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Norbert Fürstenau *Editor*

Virtual and Remote Control Tower

Research, Design, Development and Validation

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Foreword: On the Origins of the Virtual Tower

It's a pleasure to write a personal account regarding the origins of the virtual air traffic control tower as reflected in our work at the NASA Ames Research Center. This type of air traffic display is now sometimes called the remote tower, but I think there is a significant difference between the two. The virtual tower is actually a much more radical proposal and is only in the last few years becoming clearly possible at a reasonable cost. But, as I discuss later, whether it provides any additional benefit beyond the remote tower depends strongly on the specific content and application.

The Ames work on the virtual tower can be traced to a meeting I had with my boss, Tom Wempe, to whom I first reported in the late 1970s. I was a National Research Council (NRC) postdoc working for him studying pilot's eye movements looking at a newly proposed Cockpit Display of Traffic Information. This display was an electronic moving map that was intended for use in commercial aircraft cockpits to aid air traffic avoidance and to help pilots accept automatic avoidance commands. When Tom not so subtly hinted that "It would be good for me to known around here as a displays person rather than an eye movement person," I got the point. This was the first time I had ever been explicitly directed to work on something specific. Even in grad school at McGill University, I never got specific direction. Part of the education there was to be able to figure out for yourself what was important to work on.

So when Tom got even more specific and pointed out that "We were having trouble coming up with a good way to depict vertical separation on the 2D plan-view map" and that he would like me to work on this problem, I really began to worry. I didn't want to work on a display! So in some desperation I suggested, "Well, why don't we make it look like a view out the window?" At the time I drew on his blackboard a sketch of what a pilot might see out the forward window. And Tom said, "OK, why don't you work on that." But I had absolutely no idea what I would do or how I would do it.

I proposed that I should try to find some interested colleagues for this project in Professor Larry Stark's lab at Berkeley and the next week at his lab meeting suggested we find a student to work on the project. He had a new student named Michael McGreevy who was interested in the Bioelectronics Option for a graduate engineering program. He turned out to be perfect. He was an engineer with a background in art who was also interested in computer graphics, which he was then studying in a class by Brian Barsky. We began a multiyear collaboration in which we worked on the design, implementation, and testing of a perspective format for a Cockpit Display of Traffic Information (CDTI). What interested me particularly were the perceptual phenomena associated with interpreting an accurate geometric projection of the relative position and direction of targets that might be presented on a pilot's display of surrounding aircraft. Mike was beginning to program the Evans and Sutherland Picture System 2 and we initiated a design collaboration to investigate the geometric and symbolic elements that would be needed to make a perspective CDTI suitable for a cockpit. The goal was to make a traffic display useable at a glance. Before our project all CDTIs were plan-view. The perspective CDTI was eventually called VERT. It ultimately was evaluated with respect to a conventional plan-view CDTI called INTRUD (Ellis et al. 1987).

From the design and testing of prototypes, we learned many things. For example, a "God's-eye" view from behind and slightly offset was better than a forward, egocentric view as if directly out the cockpit. But most interestingly was that we found from systematic testing of pilot's direction judgments an apparent perceptual distortion we called the "telephoto" bias. It was as if when spatially interpreting the display, the users were seeing through a telephoto lens and that their visual attention would therefore not be correctly directed out the window for visual contact with traffic. It turned out that theoretical models developed from work with Mike (McGreevy and Ellis 1986), and later Arthur Grunwald (Grunwald et al. 1988), and still later Gregory Tharp (Tharp and Ellis 1990), provided several alternative but related techniques we could use to distort the display for better spatial interpretability.

It should be noted that considerable effort went into the initial design of the three-dimensional symbolic content of the perspective CDTI. In this design process, we learned that many of the difficulties of spatially interpreting perspective displays can be removed by appropriate design of its geometry and symbology. Consequently, it became apparent that simple performance comparisons of perspective versus plan-view formats could be misleading. Symbology can be introduced to remove interpretive difficulties with the perspective format. For example, segmented vertical reference lines can remove spatial ambiguities due to the geometric projection.

Later in the early 1980s after being hired as a Civil Servant at Ames, Mike McGreevy became interested in jumping into the data space of the maneuvering aircraft as seen on at CDTI, as if it were a virtual environment. He began a series of projects to develop a head-mounted display for visualization of a variety of data spaces and environments. This was the birth of "VR" at NASA in 1985. The very first real-world digital content viewed in this was a complex pattern of interacting air traffic called the "Atlanta Incident." It was a series of worrisome close encounters of aircraft generally within the Atlanta TRACON. Despite the very poor visual and dynamic quality of the early NASA HMDs, which was not reflected in the contemporary accounts of the work in the press, the reincarnation of Ivan Sutherland's "Ultimate Display" was clearly demonstrated with these air traffic data.

I was generally not directly involved with development of the virtual environment displays at Ames until the early 1990s when I began to work on the relationship of objective measures of system performance to virtual environment system usability. We studied, for example, full system latency and countermeasures for it such as predictive filtering. My principal collaborator for this work was Bernard "Dov" Adelstein. The visual environments we studied at the time for our scientifically motivated design work were generally not particularly visually interesting, so it became strategically and programmatically important to show realistic possible uses of the display format for applications that would interest NASA.

Since we were receiving support from both space and aeronautics programs at Headquarters, I felt we needed two separate demonstration environments. The "space" one was a fly-around of the Shuttle Orbiter with the task of identifying damaged tiles. The "aeronautics" one was a visualization of simulated aircraft landing at SFO. Initially, we used synthesized trajectories but later replaced them with recordings of live approach and landing data from DFW which was provided by Ronald Reisman. I called our display a virtual tower in that the head-mounted display user would appear to be immersed in the traffic pattern. I was surprised how much attention this second demo attracted. One possible reason was the high visual and very high dynamic fidelity we achieved for the 1990s, attracting attention outside our agency. This time, however, the popular representations of our system's performance were more accurate.

However, I ultimately became concerned that advocacy for a virtual tower would involve way too much technological push, so rather than pursuing a line of system development, I sought to back up and investigate the visual aspects of tower operation. I wanted to better understand the visual requirements for tower operations beyond the visual detection, recognition, and identification functions that seemed to circumscribe the visual concerns of the FAA when it came to visual tower operation. Better understanding of the visual features used by Tower controllers would help establish performance requirements for either virtual or remote towers. Two of our papers as well as six chapters in this volume ("Visual Features Used by Airport Tower Controllers: Some Implications for the Design of Remote or Virtual Towers," "Detection and Recognition for Remote Tower Operations," "Videopanorama Frame Rate Requirements Derived from Visual Discrimination of Deceleration during Simulated Aircraft Landing," "Which Metrics Provide the Insight Needed? A Selection of Remote Tower Evaluation Metrics to Support a Remote Tower Operation Concept Validation," "Model-Based Analysis of Two-Alternative Decision Errors in a Videopanorama-Based Remote Tower Work Position," and "The Advanced Remote Tower System and Its Validation," including the quasi-operational shadow mode validation) address this concern.

The virtual tower history sketched above describes work leading to a virtual tower that could be essentially worn on a controller's head as a totally immersing virtual environment. Such a format isolates its users from their immediate physical environment and probably only makes operational sense when compactness, low power consumption, and portability are important. In fact, this head-worn display format might be appropriate for use by Forward Air Controllers on a battlefield. These soldiers have a job somewhat similar to an air traffic controller, though their goal may be different. In fact, a version of such an application called the Forward Air Controller Training Simulator (FACSIM) was developed at TNO, the Hague.

But now, as can be seen in the following volume, the time for a virtual, or more properly labeled, remote tower has come. The sensors, communications links, rendering software, and aircraft electronics needed for implementation of a practical system all seem to be in place. As will be evident from the following chapters, much of the system integration work needed to complete such systems is afoot.

Moffett Field, CA Stephen R. Ellis

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Preface

The paradigmatic symbol in air traffic control (ATC), essentially unchanged since the beginning of commercial air traffic early last century, is the characteristic control tower with its large tilted windows, situated at an exposed location, and rising high above the airport. Besides the impressive 360° panoramic far view out of windows, it provides the tower controller an aura of competence and power. It actually hides the fact that tower controllers as employees of the air navigation service provider (ANSP) are members of a larger team of collaborating colleagues at different locations, including the apron, approach, and sector controllers, not all of them enjoying the exciting view out of the tower windows (for more details, see Sect. 1 in chapter "Introduction and Overview"). Only the apron controllers supervising the traffic on the movement area in front of the gates, mostly as employees of the airport operator, enjoy a similar panorama, although usually from a lower tower. The topic of this book, Virtual and Remote Control Tower, questions the necessity of the established direct out-of-windows view for aerodrome traffic control. It describes research toward an alternative work environment for tower and apron controllers, the Virtual Control Tower. It is probably no exaggeration to assert that this book is about a paradigm change in air traffic control, where paradigm in this context means a generally accepted way of thinking and acting in an established field of technology.

As explained already by Steve Ellis in the Foreword to this volume, Virtual and Remote Tower refers to the idea of replacing the traditional aerodrome traffic control tower by a sensor-based control center which eliminates the need for a physical tower building. For small low-traffic airports, the main topic of this book, the out-of-windows view will be reconstructed by a high-resolution videopanorama which may be located anywhere on the airport or even hundreds of kilometers away at a different location. This concept quite naturally leads to a new type of aerodrome control center which allows for remote control of several airports from a single distant location. It is understandable that many tower controllers are not really happy with this revolutionary idea, viewing videos instead of enjoying the reality behind the windows. The detailed research toward the Virtual Tower presented in the following chapters will show that their skepticism is partly justified, and it is the responsibility of us researchers to take their critique serious and understand their requirements in order to maintain and exceed the safety and performance level with the new system which the traditional one has achieved within nearly a hundred years of technical evolution.

After surfacing of the Virtual Tower idea, several requirements for "Future ATM Concepts for the Provision of Aerodrome Control Service" were formulated by the International Federation of Air Traffic Controllers Associations (IFATCA), such as:

The controller shall be provided with at least the same level of surveillance as currently provided by visual observation

Controllers shall be involved in the development of aerodrome control service concepts

While the first condition relates to official regulations of International Civil Aviation Organization (ICAO) concerning visual traffic surveillance on aerodromes, the second one addresses the methods for design, research and development, validation, and implementation of the proposed new human–machine systems for aerodrome traffic controllers. It appears self-evident that the introduction of a revolutionary new work environment in the safety-critical field of aeronautics which attempts to replace an established operationally optimized and validated existing one requires intensive cooperation between developers and domain experts. In Germany, most of them are employees of the Air Navigation Service Provider DFS (Deutsche Flugsicherung), cooperation partner in the recent Remote Tower projects.

While the development of any new human–machine system by definition is an interdisciplinary undertaking, nowadays involving at least experts from engineering, computer science/informatics, and engineering psychology/cognitive engineering, this book is about an especially challenging case. On the one hand, a revolutionary concept based on latest technologies is suggested which promises a significant increase of efficiency and decrease of cost. On the other hand, it attempts to replace a well-established system with a hundred years of operational experience which has to satisfy two often competing goals: safety and efficiency.

One of the problems with this kind of interdisciplinary research and development is that the field of engineering psychology and cognitive ergonomics addressing the human operator side of the system has a much weaker scientific foundation concerning established and usable formal theories as compared to the technical-engineering side. The engineers and scientists on the technical side can usually rely on a well-accepted and established basis of theoretical, mathematically founded knowledge (e.g., applied optics for the realization of a high-resolution videopanorama) and powerful software tools for simulating engineering problems and prediction of the technical system performance. The human factors experts/ psychologists on the other side usually have to work with data derived from a huge amount of statistically quantified experimental results, backed up by only a relatively small number of generally accepted formal theories of human perception and behavior (e.g., Weber-Fechner Law/Steven's Function and the Signal Detection Theory; see Appendices A and B). Moreover, there are only very few if any usable quantitative approaches and simulation tools for addressing concepts like operators "mental model," "situational awareness," or "human performance" and decision-making in a way which would allow for the numerical prediction of, e.g., decision errors. System performance under operationally relevant conditions is typically derived from human-in-the-loop simulations, with participant's responses derived from subjective questionnaires (for cost reasons often only students instead of well-trained domain experts and not seldom with questionable statistical relevance). This situation makes it difficult to obtain reliable quantitative statements about the operators' performance in the new environment. For specific questions regarding requirements and performance, experiments under more laboratory kind of conditions at the cost of reduced operational relevance can be designed which have a better chance to be comparable with theoretical predictions. Within the framework of the Remote Tower work system research, this truly interdisciplinary book contains chapters addressing, on different levels, both the technical system engineering, the human operator and (cognitive) ergonomics, and the human–system interface aspects.

At this point, we would like to acknowledge several contributions and preconditions without which much of the research work described in the following chapters probably would not have been possible, probably it would not have started at all. Starting point within DLR was the first visionary projects competition launched in 2001 by the DLR board of directors under Walter Kröll. In this novel approach to generate and support innovative ideas, the "Virtual Tower" proposal, submitted by the editor together with Markus Schmidt (one of the coauthors) and Bernd Werther (now with VW-Research), won a first prize. Well equipped with the prize money, the core team was able to start the initial 2-years concept study and engage a software engineer (Michael Rudolph, coauthor of chapter "Remote Tower Prototype System and Automation Perspectives") as fourth team member. In the years to come, he designed and wrote all of DLR's Remote Tower related software code.

We acknowledge the contributions of the growing Remote Tower staff during the following two RTO projects (RApTOR: 2004–2007; RAiCE: 2008–2012): Maik Friedrich, Monika Mittendorf, Christoph Möhlenbrink, Anne Papenfuß, and Tristan Schindler, some of them co- and chapter authors of this book. They increasingly took over workshares of the RTO research, in particular addressing simulation trials and validation. The RTO team furthermore was supported by colleagues from the DLR Institute of Optical Sensor Systems (Winfried Halle, Emanuel Schlüßler, Ines Ernst), who contributed to the image processing, movement, and object detection (see chapters "Remote Tower Experimental System with Augmented Vision Videopanorama," "Remote Tower Prototype System and Automation Perspectives"). RTO validation gained additional momentum with the start of an EC-funded validation project together with DFS within the SESAR ATM research joint undertaking, after finishing the RAiCe shadow-mode validation experiments.

The editor of this volume is particularly indebted to Steve Ellis (NASA-Ames/Moffett Field), author of the Foreword, of Chapter "Visual Features Used by

Airport Tower Controllers: Some Implications for the Design of Remote or Virtual Towers" and coauthor of chapter "Videopanorama Frame Rate Requirements Derived from Visual Discrimination of Deceleration During Simulated Aircraft Landing." As a kind of spiritus rector of the Virtual Tower idea, he demonstrated in his Advanced Displays Lab. the initial concrete realization, based on stereoscopic head-mounted displays, which inspired us for submitting our initial proposal in 2001. Nearly 10 years later, in 2010 he again advanced our research as host for the editor, spending a research semester as a guest scientist in his lab. In turn, during this period also Steve worked for two weeks as a guest researcher in the DLR Remote Tower Simulator where he introduced his profound psychophysics expertise into the methodology repertoire of the RTO research, supervising, performing, and analyzing the video frame-rate experiments described in Chapter "Videopanorama Frame Rate Requirements Derived from Visual Discrimination of Deceleration During Simulated Aircraft Landing."

At the occasion of several international Remote Tower workshops and mutual visits and meetings at DLR's Braunschweig research facilities, with the Swedish air navigation service provider LFV in Malmö, with FAA/Washington, and with companies Searidge/Ottawa and Frequentis/Vienna, we exchanged ideas and discussed problems and perspectives. I am very happy that besides Steve Ellis also several of the other colleagues and experts from external institutions and companies involved in the RTO research and development were able to contribute chapters to this book. Specifically I would like to express my sincere thanks to the following colleagues who invested a considerable amount of work and time to help this book to provide the first overview on the worldwide endeavor toward the Virtual Control Tower: Rodney Leitner and Astrid Oehme from Human Factors Consult/Berlin for Chapter "Planning Remote Multi-Airport Control–Design and Evaluation of a Controller-Friendly Assistance System" on Multiple Airport Control, Dorion Liston from San José State University and NASA-Ames as coauthor to Chapter "Visual Features Used by Airport Tower Controllers: Some Implications for the Design of Remote or Virtual Towers" on the basics of visual cues used by controllers, Jan Joris Roessingh and Frans van Schaik from NLR/Netherlands who together with colleagues from LFV and Saab/Sweden contributed chapters "Detection and Recognition for Remote Tower Operations" and "The Advanced Remote Tower System and Its Validation" on the basics of detection and recognition and on the Swedish RTO system, and Vilas Nene from MITRE/United States who provided an extensive overview on the US activities.

At this point one remark should be included concerning possible missing information and errors which may have been overlooked during the iteration of the manuscript to its final state. Most chapters are extended versions derived from previous publications, e.g., in conference proceedings volumes that underwent a selection process, usually including modest reviews, which typically, however, are less strict than journal contributions. All chapters were reviewed by the editor and all of them underwent at least one revision, some of them more. Nevertheless, we cannot exclude that the critical reader and in particular the domain experts may detect unclear, maybe even false statements or missing information. Of course, the editor and all Chapter authors will be happy about any feedback concerning errors and suggestions for improvements that may be included in a follow-up edition of this volume.

Mentioning the domain experts we certainly have to express our greatest appreciation for long years of support and cooperation by active controllers and expert managers from Deutsche Flugsicherung (DFS), the German Air Navigation Service Provider. In particular in the early phase basic domain knowledge was provided during numerous discussions and meetings with Detlef Schulz-Rückert, Holger Uhlmann, Dieter Bensch, and others which was used for a systematic work and task analysis. Later on, a formal Remote Airport Cooperation (RAiCon) was started and many more experts and managers (we would like to mention Thorsten Heeb and Nina Becker) helped in defining requirements and setting up the experimental system at Erfurt airport for performing the initial validation experiment under quasi-operational conditions.

Special thanks are due to Dirk Kügler, director of the DLR Institute of Flight Guidance since 2008. One of his first tasks was a signature under the just finished RAiCe project plan. Since that time he showed continuous interest in the RTO activities and supported the project by intensifying the cooperation with DFS, resulting in the formal RAiCon cooperation. Due to his engagement, the Virtual Tower patent was successfully licensed to company Frequentis/Austria and a cooperation agreement signed in 5/2015. A month later Frequentis won the DFS contract for realizing the first commercial RTO system in Germany to be installed and validated on the airport of Saarbrücken. After successful validation, DFS plans to set up two more RTO systems at airports Erfurt (location of the DLR-DFS validation trials of 2012; see chapters "Remote Tower Prototype System and Automation Perspectives," "Which Metrics Provide the Insight Needed? A Selection of Remote Tower Evaluation Metrics to Support a Remote Tower Operation Concept Validation," "Model-Based Analysis of Two-Alternative Decision Errors in a Videopanorama-Based Remote Tower Work Position") and Dresden (location of DLR's initial live Augmented Vision test; see Chapter "Introduction and Overview") and start with a first Remote Tower Center operation from airport Halle/Leipzig for the three remote airports.

Last but not least, we would like to express our thanks to Dr. Brigitte Brunner as the responsible science officer of the DLR program directorate. In an always supportive way, she accompanied both DLR Remote Tower projects from the beginning. She provided extra resources when there was urgent need, e.g., when the necessity of tower controller recruitment for human-in-the-loop simulations surfaced and it turned out that we had been kind of naïve with regard to the cost involved. She was tolerant and supportive also when things did not run as planned (as every active scientist and engineer knows, this is of course characteristic of any "real" research project) and when toward the planned project end it turned out that an extra half year was required for the shadow-mode trials, for initial data evaluation, and for finishing the undertaking with an international final workshop. The proceedings booklet of this event, containing the extended abstracts of the presentations, was the starting point for this book.

Finally, I would like to thank the team of Springer Publishers for their professional support, specifically Mrs. Silvia Schilgerius, Senior Editor Applied Sciences, who encouraged me to start this endeavor more than 2 years ago, Mrs. Kay Stoll, Project Coordinator, and Mrs. S. Gayathri from the technical service, who in a competent and helpful way and patiently accompanied the gradual evolution from abstract collection through repeated manuscript iterations into the present 13 chapters volume: thank you, it was fun!

Braunschweig, Germany Norbert Fürstenau
25 February 2016

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Abbrevations

2-D	Two-Dimensional
3-D	Three-Dimensional
A/C	Aircraft
ACC	Area Control Center
ADD	Aircraft-Derived Data
ADS-B	Automatic Dependent Surveillance—Broadcast
AFIS	Aerodrome Flight Information Service
AGL	Above Ground Level
AMS	Acquisition Management System
ANSP	Air Navigation Service Provider
ANT	Automated NextGen Tower
AOI	Area of Interest
APREQ	Approval Request
AR	Augmented Reality
ART	Advanced Remote Tower (EC-FP6 project)
ARTCC	Area Route Traffic Control Center
ASDE	Airport Surface Detection Equipment
A-SMGCS	Advanced Surface Movement Guidance and Control System
ATC	Air Traffic Control
ATCO	Air Traffic Control Officer
ATCT	Air Traffic Control Tower
ATIS	Automatic Terminal Information Service
ATM	Air Traffic Management
AV	Augmented Vision
CAMI	Civil Aerospace Medical Institute (US)
CAT	Category
CERDEC	Communications-Electronics Research, Development, and Engineering Center (US Army)
CHI	Computer Human Interface

CoDec	Compression-Decompression
CTAF	Common Traffic Advisory Frequency
CWA	Cognitive Work Analysis
CWP	Controller Working Position
D.C.	District of Columbia
DG-TREN	Directorate General for Transport and Energy
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
DST	Decision Support Tool
EFS	Electronic Flight Strip
E-OCVM	European Operational Concept Validation Methodology
FAA	Federal Aviation Administration (US)
FMS	Flight Management System
FOD	Foreign Object and Debris
FOV	Field of View
FSS	Flight Service Station
GA	General Aviation
GEC	Ground Executive Controller
GMC	Ground Movement Control
GMU	George Mason University
GPS	Global Positioning System
HF	Human Factors
HITL	Human-in-the-Loop (Simulations)
HMI	Human–Machine Interface
ICAO	International Civil Aviation Organization
ID	Identification
IDVS	Information Data Handling System: System for displaying weather information
IEA	International Ergonomics Association
IFAC	International Federation of Automatic Control
IFATCA	International Federation of Air Traffic Controllers
IFIP	International Federation for Information Processing
IFORS	International Federation of Operational Research Societies
IFR	Instrument Flight Rules
IPME	Integrated Performance Modeling Environment
JND	Just Noticable Difference (Webers Law)
JPDO	Joint Planning and Development Office
KATL	Hartsfield-Jackson Atlanta International Airport
KBBG	Branson Airport
KDCA	Ronald Reagan Washington National Airport
KDFW	Dallas-Fort Worth International Airport
LFV	Luftfartsverket, Swedish Air Navigation Service Provider
MANTEA	Management of surface Traffic in European Airports (EC Project)
MIT	Massachusetts Institute of Technology

MLAT	Multilateration System
NAS	National Airspace System
NATCA	National Air Traffic Controllers Association (US)
NextGen	Next Generation Air Transportation System
NIEC	NextGen Integration and Evaluation Capability
NLR	Nationaal Lucht- en Ruimtevaartlaboratorium
NT	NextGen Tower
NTA	Non-Towered Airport
OTW	Out-the-window
PIP	Picture-In-Picture
PTZ	Pan-tilt-zoom
RAiCe	Remote Airport traffic Center (DLR project 2008–2012)
RApTOR	Remote Airport Tower Operation Research (DLR project 2004–2007)
RNLAF	Royal Netherlands Airforce
ROT	Remotely Operated Tower
RTC	Remote Tower Center/Remote Tower Control
RTM	Remote Tower Metrics
RTO	Remote Tower Operation
RVR	Runway Visual Range
SA	Situational Awareness
SDT	Signal Detection Theory
SESAR	Single European Sky ATM Research
SFO	San Francisco Airport
SID	Standard Instrument Departures
SMR	Surface Movement Radar
SNT	Staffed NextGen Tower
STARS	Standard Terminal Arrival Routes
TAR	Terminal Approach Radar
TCAS	Traffic Alert and Collision Avoidance System
TEC	Tower Executive Controller
TFDPS	Tower Flight Data Processing System
TMC	Traffic Management Coordinator
TMI	Traffic Management Initiative
TRACON	Terminal Radar Approach Control
TS	Tower Supervisor
TWR	Tower
U.S.	United States of America
UNICOM	Universal Communications
VDOT	Virginia Department of Transportation
VET	Visibility Enhancement Technology
VFR	Visual Flight Rules
VFR	Visual Flight Rules
VHF	Very High Frequency

ViTo	Virtual Tower (DLR project 2002–2004)
VPA	Verbal Protocol Analysis
VR	Virtual Reality
VSATS	Virginia Small Aircraft Transportation System (SATS) Laboratory
WAM	Wide Area Multilateration
WdV	Wettbewerb der Visionen (DLR visionary projects competition)
WJHTC	William J. Hughes Technical Center (FAA)

Part I
Fundamentals and Preconditions

Introduction and Overview

Norbert Fürstenau

Abstract Since more than 10 years, an increasing interest is observed worldwide in remote control of low-traffic airports by means of some kind of virtual control tower. As outlined in the Foreword by Steve Ellis and in the Preface to this book, “Virtual Tower” depicts the idea of replacing the conventional control tower on airports by an advanced sensor-based control center. It eliminates the need for direct visual traffic surveillance and consequently the requirement for a costly tower building at an exposed location in visual distance from the runway. The virtual/remote tower idea is connected with a paradigm change in air transportation due to the growth of low-cost carriers and the corresponding increased usage of small airports which, nevertheless, require controlled airspace provided by air navigation service providers (ANSPs). Cost constraints require new ideas and concepts to meet these requirements, and the control of one or more small airports from a remote location without direct visual surveillance from a local tower is one of these visions.

After providing in Sect. 1 of this introduction some basics of air traffic control in the airport vicinity, I will continue in Sect. 2 with a personal account of Virtual and Remote Control Tower research from the DLR perspective, starting around 2000. In Sect. 3, I present an overview of goals, requirements, technical issues, achievements, and initial steps towards industrialization. The concluding Sect. 4 contains an overview of the 13 chapters and two technical Appendices.

Keywords Airport control tower • Control zone • ICAO • Remote tower operation • Virtual tower • RTO concept • RTO history • Video panorama • Augmented vision • Goals • Achievements

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1 Some Basics

The following brief overview refers to typical procedures of IFR (instrument flight rules) traffic. For VFR traffic (visual flight rules, a large part of the general aviation), the procedures may be somewhat different in detail. An in-depth presentaion of the diverse aspects of air traffic control is provided, e.g. in (Mensen 2003). Classically, airport traffic control is performed via cooperation between a group of controllers at different locations as outlined in the workflow schematics of Fig. 1. Controllers of the area control center (ACC, en route traffic, sector control) take over/hand over the traffic from/to the terminal or approach control (US terminology: TRACON, typically up to 30–50 nautical miles or 50–90 km from the airport). Approach control in turn hands over/takes over the traffic to/from the local or tower control for final approach or departure (airport environment, up to 5–10 nm from the airport).

The control functions relevant for the remote tower operation (RTO) work environment are the start-up, apron, ground, and tower control. During approach (upper part of Fig. 1), the flight is handed over from the area control center (ACC) to the approach controller. At a large airport or "Hub" the ACC until recently was often located also in the tower building, although not in the tower cab with out-of-windows view because ACC controllers are responsible for the traffic outside the control zone. Under good visibility the out-of-windows view from the tower cab allows for visual surveillance inside the control zone (i.e., < ca. 20 km). In Germany, nowadays ACC and approach usually are combined and colocated in the center. The work of the tower and ground controllers begins after the approach

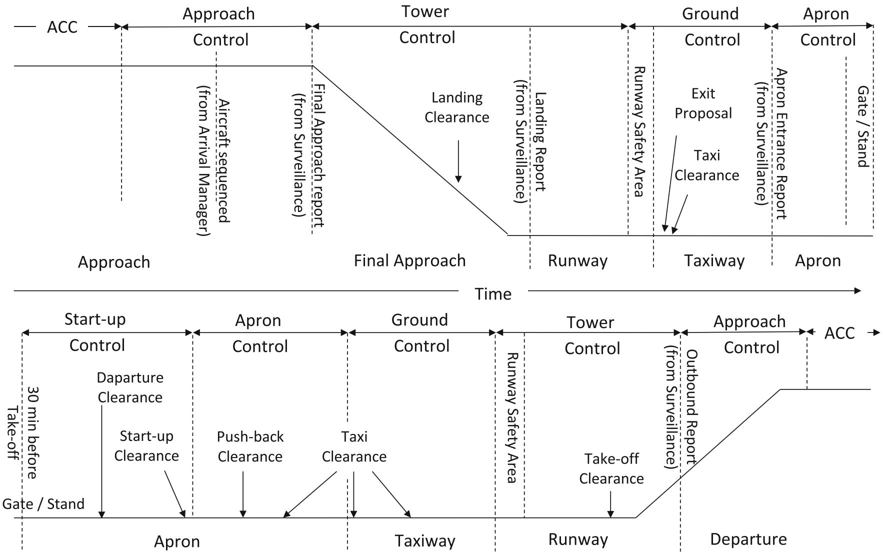

Fig. 1 Workflow schematic of the airport traffic control, separated in arrival traffic (*top*) and departure traffic (*bottom*)

controller has handed over the flight. The tower controller (tower executive, TEC) together with the ground controller (ground executive, GEC) manages the traffic on runways and taxiways. Ground executive hands over/takes over the traffic to/from APRON control (usually a separate control tower on larger airports for the traffic and activities in front of and at the gates/stands, owned by the airport operator). The tower controller is responsible for final approach and landing and hands over to the ground controller who manages the taxiing after the A/C exits the runway. The Apron controller takes over and manages the final maneuvering and docking. The mirrored procedure for departure is depicted in the lower part of Fig. 1. An additional function here is start-up control with departure clearance and start-up clearance. With small airports, the main focus of RTO, all functions within the control zone may be in the hands of only two controllers or even a single one.

In what follows, we will continue in Sect. 2 with a historic survey of the development of the Virtual and specifically the Remote Tower idea that kind of continues the personal account of Steve Ellis in the Foreword. Section 3 briefly summarizes the goals, technical issues, achievements, and industrialization aspects followed in Sect. 4 by an overview of the separate chapters of this book.

2 Background and History of the Virtual and Remote Tower Concept

This section is a personal account of the editor of the present volume from the perspective of DLR's Virtual and Remote Tower research and development. One very early proposal for a revolutionary new Virtual Control Tower work environment was put forward by Kraiss and Kuhlen (Kraiss and Kuhlen 1996) within a scientific colloquium of the DLR Institute of Flight Guidance, organized by the editor (Fürstenau 1996). In their contribution on "Virtual Reality—Technology and Applications," they proposed a VR concept for ATC, based on what they called "Virtual Holography." One proposed solution was the so-called virtual workbench, a table-like stereoscopic projection of the aerodrome traffic, allowing for viewing of 3-D trajectories with free choice of perspective for the controller. VR projection systems of this type are nowadays commercially available, but the actual research towards remote tower operation (RTO) went a more conservative way.

A couple of years after this event, the preconditions emerged for the research and development work described in the present book. The initial research environment began to take shape at the DLR Institute of Flight Guidance when the editor proposed a research topic in advanced display systems which built on 15 years of research in optical sensing technologies for aerospace applications. The idea of investigating the potential of the emerging VR technologies for aerospace applications had been presented at an internal meeting already back in 1989 after a visit of the editor at NASA Ames (Scott Fisher's VR Lab.) and at Jaron Larnier's famous VR-company VPL Research in Redwood City (Silicon Valley), where the so-called data glove had been invented as advanced interaction device for virtual environments. In 1999, the author together with coworkers of the optical sensors group (Markus Schmidt, coauthor in this volume, and Bernd Werther, now with VW-research) initiated the research on advanced VR-based human–machine interfaces and interaction systems as first step towards the Virtual Tower idea. They were motivated also by futuristic concepts and ideas which were put forward in a comprehensive study on the future of air traffic control by Wickens and others (Wickens et al. (1998)).

Two years later, it was a lucky incident which pushed the realization of Virtual and Remote Tower ideas at DLR a large step forward: the Advanced Displays team had submitted the "Virtual Tower (ViTo)" research proposal to DLR's first Visionary Projects competition in 2001 ("Wettbewerb der Visionen," WdV), initialized under the former chairperson of DLR's board of directors, Walter Kröll. Somewhat unexpected, it actually won a first prize, well endowed with 200,000 € for 2 years of initial studies and concept development. So in 2002, DLR's Virtual Tower research took off, and remembering the Kraiss and Kuhlen presentation of 1996, the team started with a basic survey on the state-of-the-art of VR technology in Europe and the USA and the shaping of an initial concept (Fürstenau 2004). The most inspiring Virtual Tower ideas, however (because based on well-founded psychophysics experiments and theories [see the Foreword to this volume and, e.g., (Ellis 1991)]), were imported in the same year after a visit of the author at Stephen R. Ellis' Advanced Displays Laboratory at NASA Ames Research Center. Steve, at that time, performed research in fundamental problems and applications of head-mounted stereoscopic displays (HMD), including virtual and augmented reality applications in aerodrome traffic control. One problem was the latency problem involved in updating high-resolution virtual environments such as an aerodrome with synthetic aircraft driven by real data in a fixed laboratory frame of reference. The operators' movements have to be tracked and time-varying HMD coordinates synchronized with the room-fixed aerodrome coordinates and aircraft positions in real-time in order to generate a 3D-VR environment, a problem that was solved with the help of predictive Kalman filtering of the movement data.

An important step towards initial experimental systems during the 2 years of the WdV study was the engagement of a software engineer (Michael Rudolph, coauthor of chapter "Remote Tower Prototype System and Automation Perspectives") who in the years to come realized all of DLR's Remote Tower software. The first realized code supported augmented vision experiments using self-made head tracking devices. Later on, the complex software environment for videopanorama reconstruction of the tower out-of-windows view, the pan tilt zoom camera control, and augmented vision functions was realized (chapters "Remote Tower Experimental System with Augmented Vision Videopanorama" and "Remote Tower Prototype System and Automation Perspectives").

This made it possible to start the initial experimental research, beginning with a focus on Augmented Vision aspects for support of tower controllers (Tavanti 2007) using wearable computing and (at that time) futuristic techniques such as the head-mounted Nomad Retinal Laser Scanning Display (HMD). One motivation for the investigation in this so-called optical see-through technology (Barfield and Caudell 2001) was the perspective to reduce head-down times in the tower so that controllers can read display information without losing visual contact to the traffic

Fig. 2 Demonstration of a laser retinal scanning display, tested by operational controllers at Frankfurt tower (2/2003). Inset: superimposed text depicts augmented vision information displayed by HMD via direct image projection onto the retina by means of a laser scanner. Wearable HMD-computing device at the back of DLR team member Markus Schmidt

situation on the movement areas (Tavanti 2006) (Pinska 2006). Figure 2 shows the first practical testing of a retinal scanning HMD at Frankfurt tower.

Another example is the transparent head-up display in the form of the holographic projection screen which was investigated by means of laboratory experiments (Fürstenau et al. 2004) and tested under operational conditions at Dresden tower as shown in Fig. 3. Here, the idea was investigated to augment the air traffic controller's direct view out of the Control Tower windows, e.g., by weather data, approach radar, and flight data information superimposed on the far view, without additional head-worn gear.

The DLR team during that time decided to turn away from the original idea of augmenting the controller's view out of the real-tower windows by means of the optical see-through technology and instead to follow the video see-through paradigm, i.e., using the video reconstruction of the environment as background for superposed additional information (Barfield and Caudell 2001). This eliminates the latency problem, i.e., the real world superimposed information delay. The augmented vision research for tower controller support using the holographic projection system was continued for a couple of years through several Ph.D. theses at Eurocontrol Experimental Center in Bretigny/France and NASA Ames Advanced

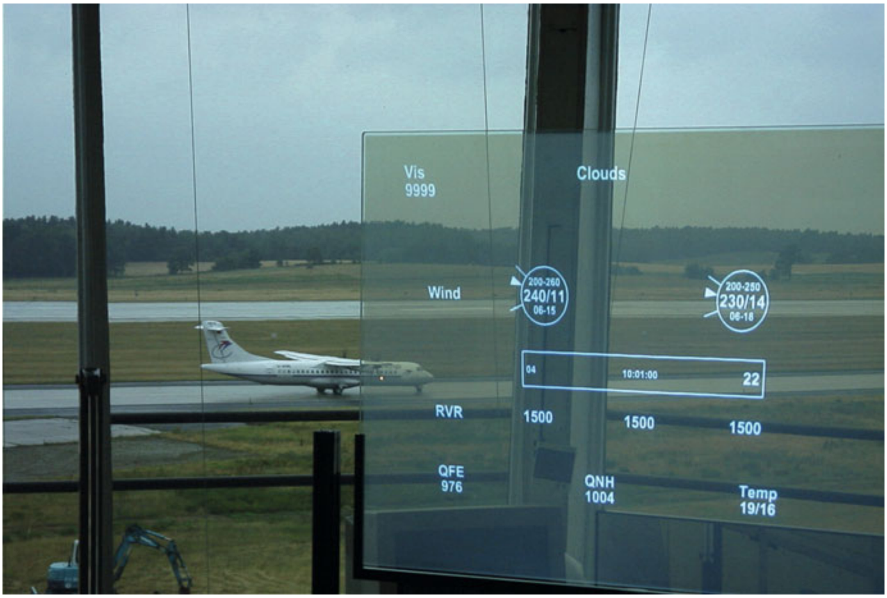

Fig. 3 Demonstration of head-up display-based augmented tower vision using a holographic projection display for superimposing live weather information on the out-of-windows view (non-collimated view: image at display distance, tower at Dresden airport, 7/2003 (Schmidt et al. 2006)

Displays Lab. under the guidance of Steve Ellis. The focus there was research in stereoscopic systems (Peterson and Pinska 2006).

One reason for this change of research direction at DLR was contacts to the Tower Section of the German air navigation service provider DFS (Deutsche Flugsicherung) which were initiated right from the beginning of the Virtual Tower research and later on evolved into formal collaborations. Many discussions with domain experts during this time led to the question if the Virtual Tower idea could provide a solution for a rather urgent requirement: cost reduction in providing aerodrome control service to small low-traffic airports. The reason was the paradigm change in air transport mentioned above: small low-traffic airports without electronic surveillance (usually surface movement radar SME) are increasingly used by low-cost carriers which, nevertheless, request controlled airspace, although often only for a few flights or a couple of hours per day. Previous "Dark Tower" experiments of DFS aiming at remote control of a low-traffic airport during nighttime (with nearly zero traffic) from the tower of a large airport, however, without transmission of visual information, had provided initial experience on the potential feasibility of this concept. This requirement for cost reduction and increase of efficiency leads to the main topic of this book: the Remote Tower as paradigm change, for low-traffic airport surveillance from a distant location, and the perspective of a single remote tower center (RTC) for aerodrome traffic management of several small airports. The original Virtual Tower idea with synthetic vision displays and VR technologies for large hub airports would remain the

Fig. 4 Initial tests (2003) of video-based far view reconstruction with standard video technology. Camera position on DLR telemetry antenna tower, ca. 25 m above ground. Camera aiming at Braunschweig airport tower on the dark roof top. White building to the right is location of initial experimental videopanorama camera system (chapter "Remote Tower Experimental System with Augmented Vision Videopanorama"). Runway visible above the camera, extending in west direction

long-term goal. "Remote Tower" was taken as the more realistic intermediate step with relaxed technological problems and as little as possible changes of operational procedures for a single RTO working position.

At this point, the idea of reconstructing the "far view" out-of-tower windows by means of a suitable assembly of high-resolution digital video cameras emerged—a "down-to-earth" solution compared with the original "virtual holography" ideas and the VR-HMD display as developed at NASA Ames Research Center. Variants of the latter, nevertheless, remain a perspective for the future as completely sensor driven synthetic vision solution for contingency centers and eventually for the actual Virtual Tower on large airports. Figure 4 depicts the initial experiments during the ViTo concept study with available standard video technology of the late 1990s for reconstructing the far view out-of-tower windows. These tests demonstrated the limits of this technology with regard to resolution and contrast and led to the requirement for the emerging high-resolution cameras (UXGA; HD) based on latest CMOS or CCD chip technology. At that time, the cost for a camera of this type was typically $>$15,000 €, without optics.

The corresponding high-quality video reconstruction of the “far view” became the main technical research topic of the Remote Tower team of the DLR Institute of Flight Guidance for the next 8 years (2005–2012), with resources provided by two internally funded projects including a budget of more than 6 M€. The first one (RApTOR: Remote Airport Traffic Operation Research, 2005–2007) as follow-up of the initial ViTo concept study started with intensive contacts between DLR’s RTO team and DFS domain experts. Detailed work and task analysis by numerous structured interviews with domain experts were performed by one of the initial core-team members who finished the first doctoral dissertation related to this field (Werther 2005). At the same time, the worldwide first digital 180° high-resolution live-videopanorama as reconstruction of the tower out-of-windows view was realized at the Braunschweig Research Airport, the location of DLR’s major aeronautics research facilities [chapter “Remote Tower Experimental System with Augmented Vision Videopanorama”, and (Fürstenau et al. 2008b)], based on a RTO patent filed in 2005 and granted in 2008 (Fürstenau et al. 2008a).

In parallel to DLR’s research and development of RTO systems, related activities continued in the USA. An experimental system for single camera based remote weather information for small airports using internet-based data transmission had been set up in a NASA–FAA collaboration (Papasin et al. 2001). Clearly, such a system could not fulfill requirements comparable to the high resolution low-latency videopanorama system of the DLR approach. Within the USA, the ATC-modernization initiative NEXTGen (an analogue to the European SESAR joint undertaking) another direction of research aimed at the so-called Stafffed NextGen Tower (SNT), addressing the integration of advanced automation into conventional tower equipment with the same long-term goal as DLR’s WdV-proposal: a completely sensor-based work environment without the need for the physical tower building (Hannon et al. 2008). An overview of the US activities is presented by Vilas Nene (MITRE Company) in chapter “Remote Tower Research in the United States”.

After realization of DLR’s experimental system, it turned out that meanwhile also the Swedish ANSP (LFV) together with company Saab had started the same kind of development (see chapters “Detection and Recognition for Remote Tower Operations” and “The Advanced Remote Tower System and Its Validation”), also targeting low-traffic airports and using more or less the same videopanorama concept. A demonstrator facility was realized in Malmö for initial verification and validation of remote control of a distant airport. This development was continued within the 6th Framework EC project ART (Advanced Remote Tower). Since 2010, under the Single European Sky SESAR Joint Undertaking (project 6.9.3), the NORACON consortium with Saab, LFV, and other partners continued the Swedish RTO development and validation. In 2006, the DLR and Saab/LFV teams met for the first time for discussing the remote tower topic at the occasion of the international mid-term assessment workshop of DLR’s RApTOr project.

Meanwhile, DLR’s Virtual Tower team kept on growing and besides submitting a second RTO patent application, they published first results obtained with the experimental RTO system and initial human-in-the-loop simulations. The most relevant achievements are reviewed and/or referenced in the subsequent chapters of the present volume. Besides technical details on the setup of the experimental system, results of work analysis, realization of a simulation environment for initial human-in-the loop simulations and initial field testing with participation of professional tower controllers are described. The initial field tests were a preparation for the so-called passive shadow-mode testing under realistic operational conditions during the follow-up Remote Tower project “RAiCe” (Remote Airport Traffic Control Center).

This second DLR-internal RTO project (Remote Airport Traffic Control Center, RAiCe) was started in 2008 and it aimed at realizing a second generation near prototype RTO system, investigating RT-center aspects and testing long distance live high-resolution videopanorama transmission. For this goal, an advanced RTO system was to be set up at a second airport. The Remote Tower Center (RTC) idea with centralized remote control of ≥ 2 airports was pursued in parallel to the experimental tested by means of human-in-the-loop simulations in an extended simulation environment (see chapters “Remote Tower Simulation Environment”, “Assessing Operational Validity of Remote Tower Control in High-fidelity Simulation”). For this purpose, right from the beginning of the new project, contacts and cooperation between the RTO team and DFS were intensified. The RTO topic was selected as one of the strategic goals of DFS and a DFS–RTO team was formed. A remote airport cooperation agreement was signed (project RaiCon, on DLR side headed by Markus Schmidt) for realizing the second system at a DFS-controlled airport that paved the way towards operational testing of the RTO system within the planned shadow-mode trials at the airport Erfurt during the final year (2012) of the RAiCe project (see chapters “Remote Tower Prototype System and Automation Perspectives”, “Which Metrics Provide the Insight Needed? A Selection of Remote Tower Evaluation Metrics to Support a Remote Tower Operation Concept Validation”, “Model Based Analysis of Two-Alternative Decision Errors in a Videopanorama-Based Remote Tower Work Position”).

The following sketch summarizes DLR’s Remote Tower research since 2002 and the gradual transition into operational systems with different air navigation service providers since 2015 (Fig. 5).

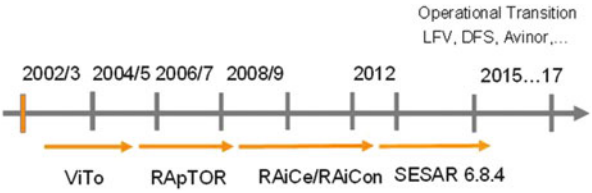

Fig. 5 Timeline of DLR-RTO projects, partly in cooperation with DFS and transition into operation with different air navigation service providers. Not shown are parallel RTO development activities since around 2006 in Sweden (LFV/Saab cooperation) and Canada (NavCanada/Searidge cooperation)

Besides the technical and engineering achievements and the advancement of human-in-the-loop (HITL) simulations, the remote tower research also generated methodological progress in experimentation and data analysis within the human–machine interaction research. Again, it was the spiritus rector of the virtual tower topic, Steve Ellis who, based on his psychophysics expertise, proposed specific two-alternative decision experiments for quantifying by means of signal detection theory (SDT) the effect of subtle visual cues used by tower controllers for their decision making [chapters "Videopanorama Frame Rate Requirements Derived from Visual Discrimination of Deceleration during Simulated Aircraft Landing", "Model based Analysis of Two-Alternative Decision Errors in a Videopanorama-based Remote Tower Work Position"; (Ellis et al. 2011a, b; Fürstenau et al. 2012; 2014)]. During a research visit of the editor of the present volume at Steve's Advanced Displays lab. in 2010, details for corresponding psychophysics experiments were worked out for quantifying videopanorama frame-rate requirements, following preparations at the DLR tower simulator facility. Steve in turn supervised and analyzed the actual experiments as part of a corresponding 2-weeks RTO-HITL simulation campaign, organized by RTO team members Christoph Möhlenbrink and Anne Papenfuß (chapter "Assessing Operational Validity of Remote Tower Control in High-Fidelity Simulation"). The same successful methods for quantifying decision making were applied later on also to the analysis of results of the shadow-mode validation experiments under quasi-operational conditions (chapter "Model Based Analysis of Two-Alternative Decision Errors in a Videopanorama-Based Remote Tower Work Position").

The results of the shadow-mode trials and the international final RAiCe workshop in December 2012 marked the beginning of an extended validation project in close cooperation between DLR and DFS, since 2012 funded by the European commission under the 7th framework ATC program SESAR (Single European Sky ATM Research). In close contact with the Swedish group, it focuses on human-in-the-loop simulations and field trials under operational conditions and is expected to help paving the way towards RTO industrialization and standardization.

In 2014, after about 10 years of successful Remote Tower research and development at DLR the Remote Tower patent was licensed to company Frequentis/Austria for product development and commercialization of the RTO concept. In the same year, the Swedish ANSP LFV received its official operating licence from the Swedish Transport Agency for implementation of the first operational system (developed by Saab/LFV in parallel to the DLR system, see chapters "Detection and Recognition for Remote Tower Operations" and "The Advanced Remote Tower system and Its Validation") with an RTO controllers' working position at Sundsval RTC for remotely controlling the traffic at the distant airport of Örnsköldsvik. The system is expected to go live during 2015 (LFV, 3 November 2014).

3 Remote Tower Operation Research: Goals, Requirements, Technical Aspects, Achievements, Industrialization

While many current towers on ASMGCS-equipped airports, even some at busy airports like London-Heathrow, can continue to operate (although with reduced capacity) totally without controllers ever seeing controlled aircraft under contingency conditions, it is clear from controller interviews that usually numerous out-of-window visual features are used for control purposes. In fact, these visual features go beyond those required for aircraft detection, recognition, and identification (Watson et al. 2009). Potentially important additional visual features identified by controllers in interviews involve subtle aircraft motion (see chapters "Visual Features Used by Airport Tower Controllers: Some Implications for the Design of Remote or Virtual Towers" and "Detection and Recognition for Remote Tower Operations"). The focus on a high-quality videopanorama reconstruction of the far view was also based on the ICAO regulations for aerodrome traffic control. Citing ICAO document 4444/section 7, no. 7.1.1.2 (ICAO 2001):

> . . .Aerodrome controllers shall maintain a *continuous watch* on all flight operations on and in the vicinity of an aerodrome as well as vehicles and personnel on the maneuvring area. *Watch shall be maintained by visual observation, augmented in low visibility conditions by radar when available*.

For large airports with "Advanced Surface Movement Guidance and Control Systems (ASMGCS)," this requirement is somewhat relaxed. On small airports with lots of VFR traffic, however, besides radio communication and possibly a direction finder, the visual information is often the controllers only information source on the traffic situation, maybe supplemented by approach radar for A/C with Mode-S transponder on board. For our goal application of small airports without expensive surface movement radar (SME) and multilateration positioning systems, the task would be to create a remote tower work environment without direct out-of-windows view which, nevertheless, should provide at least the same information and safety level, i.e., for the controller the same if not better mental traffic picture as the conventional tower work environment.

In 2006, Brinton & Atkins of Mosaic ATM Company (Brinton and Atkins 2006) had concluded that

> *"Requirements for RTO are beyond capabilities of today's electronic airport surveillance systems". however:*
>
> *"a combination of electronic surveillance, optical surveillance and advanced decision support tools may satisfy the Remote Airport Traffic Service requirements".*

An overview of the different aspects of transition from conventional tower-based airport traffic control to the new Virtual and Remote Tower paradigm is presented in the following summary which contains lists of goals, technical issues, achievements, and industrialization aspects, which are addressed in the separate chapters of the book.

General Goals

- Keep work processes as close as possible to established ones
- Keep human-in-the-loop
- Determine importance of visual cues (static and dynamic)
- Feasibility of RTO/RTC with regard to cost reduction (small airports)
- Setup of technical system for field testing
- Setup of (human-in-the-loop) simulation environment for repeatable experiments under controlled conditions
- Define appropriate methods and metrics for performance quantification
- Verification of technical system performance
- Validation: performance changes of human operator with RTO/RTC controller work position
- Safety analysis/Regulatory aspects (ICAO)

Specific RTO Goals

- Derive RTO requirements based on work and task analysis and on simulations
- Setup of RTO/RTC simulation environment for multiple airport control
- Define RTO/RTC scenarios and work environments for simulations
- Investigate and develop appropriate theoretical and methodological background for technical and human factors issues
- Development of advanced videopanorama system with necessary automation features
- Investigate possibilities of automatic movement detection, PTZ tracking, and augmented vision as specific new RTO features
- Setup of RTO demonstrator at distant airport for validation trials
- Setup and investigate high bandwidth connection (delays?) with remote airport
- Prepare and perform passive shadow-mode tests under quasi-operational conditions
- Define appropriate methods and metrics for quantifying RTO performance versus conventional tower

Technical Issues

- State-of-the-art HD camera and panorama display system
- Cameras and projection system/displays with sufficient dynamic range, resolution, and contrast
- Image compression/decompression (CODEC) algorithms
- Communication links: minimum bandwidth, cost?
- Techniques for keeping human-in-the-loop: RTO workplace design requirements
- Bayer conversion and image processing
- Optimization of contrast and resolution
- Evaluate additional sensors for integration/augmented vision (ADS-B, MODE-S,. . ..)
- Test of long distance videopanorama transmission. Delay times and stability issues

- Movement and object detection algorithms
- Augmented vision, data fusion, object tracking (PTZ-camera control)
- Tower-Lab: Simulation facilities for RTO fast-time and human-in-the-loop RTC simulations
- RTO-near prototype version for shadow-mode tests under quasi-operational conditions.

Achievements

- Close contact, information exchange, and cooperation with ANSPs DFS (Germany) and LFV (Sweden)
- Requirements determined from TWR work analysis based on domain experts' interviews and workshops
- RTO/RTC airport traffic scenarios for HITL-simulation system at DLR/Braunschweig
- Experimental systems in Braunschweig (DLR) and Erfurt
- Several fast-time, human-in-the-loop, and part task RTO- and RTC-simulation campaigns
- Development and use of advanced measurement (e.g., eye tracking) and data analysis techniques
- Establishment of theory-based data analysis for objective metrics (SDT, Bayes inference) and (cognitive) modeling approaches (information processing/time pressure theory)
- RTO dynamical cues requirements from simulation experiments (visual two-alternative discrimination)
- State-of-the-art HD technology cameras and panorama display system
- 50 Mbit connection between remote (Erfurt) camera system and 360 × 60° FOV HD-technology videopanorama, <500 ms delay
- Passive shadow-mode tests at Erfurt airport with reproducible flight scenarios using DLR test aircraft for aerodrome circling and maneuver detection tasks.
- RTO-CWP quantification by subjective and objective metrics; direct comparison tower versus RTO

Industrialization issues and international harmonization

- Support definition of RTO-specific ICAO regulations (ICAO 2012)
- Germany: DFS–DLR cooperation for (quasi-) operational trials
- 2014: DLR-RTO patent licensing/involvement of industry
- Sweden: LFV–SAAB development cooperation; 2014 operating license from Transport Agency
- SESAR Validation Project 6.9.3 (NORACON)
- SESAR Project 6.9.4 (DFS–DLR, since 2012)

4 Chapter Overview

The separate chapters of the present volume are structured into four parts: I. Fundamentals, II. RTO simulation with work analysis and Multiple Remote Tower (RT Center) aspects, III. Design, engineering, field testing, and IV. Alternative approaches. Two appendices address basics of applied optics for videopanorama design (A) and of psychophysical theories for analysis of two-alternative decision experiments used for quantifying design requirements and performance (B).

Most of the 13 chapters are reviewed, revised, and extended versions of previous publications of the DLR RTO team and of colleagues from other institutions involved in the international endeavor towards the Virtual/Remote Control Tower. They are referenced in the respective lists. They include two RTO/Virtual Tower special sessions organized by the editor as part of the IFAC Human Factors conference in Valenciennes 2010 (Fürstenau N., Virtual Tower—special sessions 1,2, 2010) and the Berlin Workshop Human-Machine-Systems 2011 (Fürstenau N., Steps towards the remote tower center—special sessions 3a, 3b, 2011). The framework for the present book originated from the collection of abstracts of the international final RAiCe workshop which took place in November 2012 (Fürstenau 2013), as a satellite event of the second EUROCONTROL SESAR Innovation days (SID 2012). Additional authors from other institutions and companies involved in Virtual and Remote Tower research were invited to contribute chapters which complete the RTO topic by outlining alternative approaches in Europe and the USA and important further aspects such as an assistance tool for multiple airport control.

Part I of the book addresses fundamental aspects of remote control tower operation and besides this introduction (first chapter) puts its focus on the visual cues relevant for object detection, recognition, and operators' decision making, in contributions by Steve Ellis/NASA (Ames Res. Center), and Frans van Schaik and Jan Joris Roessingh, both NLR (chapters "Visual Features Used by Airport Tower Controllers: Some Implications for the Design of Remote or Virtual Towers", "Detection and Recognition for Remote Tower Operations").

Part II is concerned with human-in-the-loop (HITL) simulations using the DLR tower simulator environment and with centralized multiple remote airport control. The specific RTO-simulation environment at the DLR Inst. of Flight Guidance is described by Sebastian Schier/DLR in chapter "Remote Tower Simulation Environment". Anne Papenfuß and Christoph Möhlenbrink/DLR describe in chapter "Assessing Operational Validity of Remote Tower Control in High-Fidelity Simulation" simulator studies with the new RTO/RTC work environments for investigating RTO/RTC work organization. In chapter "Videopanorama Frame Rate Requirements Derived from Visual Discrimination of Deceleration during Simulated Aircraft Landing", Ellis and Fürstenau describe a specific psychophysical two-alternative decision experiment with 13 participating controllers (as part of the larger simulation campaign, see chapter "Assessing Operational Validity of Remote

Tower Control in High-Fidelity Simulation") that provides an initial estimate of the required minimum frame rate for minimizing prediction errors with the dynamic situation of landing aircraft. In chapter "Planning Remote Multi-Airport Control–Design and Evaluation of a Controller-Friendly Assistance System," Rodney Leitner and Astrid Oehme (Human Factors Consult, Berlin) describe the development of a specific planning tool for multiple airport control.

Part III of the book covers four chapters, the core engineering part of the Remote Tower research and development: the technical Remote Tower design, development, and field testing. The basic features of the experimental high-resolution videopanorama system according to the main Virtual Tower patent (Fürstenau et al. 2008a, b), including initial verification of system performance, are described in chapter "Remote Tower Experimental System with Augmented Vision Videopanorama." Included in this chapter is the initial development phase of advanced features: augmented vision using superimposed (video see-through) information. Design and development of the second generation RTO-prototype system and work environment are described in chapter "Remote Tower Prototype System and Automation Perspectives" by M. Schmidt, M. Rudolph, and the editor. Besides the optical design, it addresses basic features of the RTO-software system for live videopanorama construction with image processing for raw-data conversion and compression, the potential of thermal imaging, and aspects of technical verification including electromagnetic compatibility. It also contains a section based on work by Winfried Halle et al. (DLR-OS, Berlin), with details on advanced movement and object detection and classification.

In chapter "Which Metrics Provide the Insight Needed? A Selection of Remote Tower Evaluation Metrics to Support a Remote Tower Operation Concept Validation," Maik Friedrich describes the RTO validation experiment of 2012, realized as final part of the RAiCe project in the form of shadow-mode testing within the DLR–DFS "Remote Airport Cooperation" (RAiCon, headed by Markus Schmidt). Like in the 2006 initial field testing, again the DLR test aircraft DO-228 (DCODE) was used to generate a statistically relevant number of reproducible operational scenarios and aircraft maneuvers during aerodrome circling within the Erfurt-airport control zone. This allowed for direct comparison of controller performance under (conventional) tower and remote conditions and for quantitative data analysis using subjective and objective metrics. A detailed analysis of a subset of decision tasks in chapter "Model Based Analysis of Two-Alternative Decision Errors in a Videopanorama-Based Remote Tower Work Position" was based on advanced objective data analysis methods for quantification of the decision errors and visual discriminability difference of TWR versus RTO conditions.

The final validation trial marked the next phase of cooperation between DLR and DFS, now within the European "Single European Sky ATM Research" (SESAR), project 6.8.4. The cooperation within SESAR also supports the international Remote Tower harmonization through close contact with the ongoing Swedish effort towards an operational RTO system within the LFV–SAAB cooperation.

In Part IV, we focus on two chapters on alternative Remote and Virtual Tower approaches. J.J. Roessingh and F.v. Schaik from NLR/Netherlands, together with colleagues from the Swedish ANSP LFV and company Saab as RTO development partners and participants in the European SESAR-funded RTO consortium "NORACON", report in chapter "The Advanced Remote Tower System and Its Validation" details of the Swedish RTO approach including its validation. In the final chapter, "Remote Tower Research in the United States" Vilas Nene (MITRE company/United States) presents a detailed overview of the US activities towards the Virtual Tower idea.

The 13 chapters are completed by two technical Appendices which are thought to support the readability of this interdisciplinary book. They provide in A (Basic Optics for RTO), for the technical-optics nonexpert, some basics of applied optics supporting the understanding of design aspects and limitations of the videopanorama reconstruction of the tower out-of-windows view, and in B (Signal Detection Theory and Bayes Inference), for the nonexpert in psychological/psychophysics methods, some basics of two (related) theories employed for the data analysis of the visual discrimination/decision experiments.

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Visual Features Used by Airport Tower Controllers: Some Implications for the Design of Remote or Virtual Towers

Stephen R. Ellis and Dorion B. Liston

Abstract Visual motion and other visual cues are used by tower controllers to provide important support for their control tasks at and near airports. These cues are particularly important for *anticipated separation*. Some of them, which we call visual features, have been identified from structured interviews and discussions with 24 active air traffic controllers or supervisors. The visual information that these features provide has been analyzed with respect to possible ways it could be presented at a remote tower that does not allow a direct view of the airport. Two types of remote towers are possible. One could be based on a plan-view, map-like computer-generated display of the airport and its immediate surroundings. An alternative would present a composited perspective view of the airport and its surroundings, possibly provided by an array of radially mounted cameras positioned at the airport in lieu of a tower. An initial more detailed analysis of one of the specific landing cues identified by the controllers, landing deceleration, is provided as a basis for evaluating how controllers might detect and use it. Understanding other such cues will help identify the information that may be degraded or lost in a remote or virtual tower not located at the airport. Some initial suggestions on how some of the lost visual information may be presented in displays are mentioned. Many of the cues considered involve visual motion, though some important static cues are also discussed.

Keywords Visual motion • Perceptual cues • Spatial perception

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1 Introduction

The visual cues necessary to fly and land an aircraft have been well studied over many decades (e.g., Gibson et al. 1955; Grunwald and Kohn 1994). In particular, the degradation in piloting performance and the consequent need to reduce airport capacity due to bad weather is fairly well understood (FAA 71010.65R 2006). The present report outlines a complementary side of the airport capacity-safety trade-off. It identifies and quantifies some of the visual features and properties used by tower controllers to monitor and enable safe landing and maneuvering on or near airports. These features are especially interesting now due to recent proposals for technology and procedures in which controllers work in towers without a direct view of their controlled space. Such towers are described alternatively as a remote or “virtual tower” (JPDO 2007). Work in these towers would be supported by controller displays of information about aircraft and the airport environment.

In general, two types of displays can be considered: one would present a plan-view, map-like computer-generated display of the airport and its immediate surroundings (JPDO 2007) somewhat like existing ASDE-X displays (Fig. 1). An alternative could present a composited perspective view, possibly provided by an array of radially mounted cameras positioned at the airport in lieu of a tower (Fürstenau et al. 2008) (Fig. 2). In either case, procedures and display techniques need to be developed which are cognizant of the current visual information used by controllers, which may be lost.

The following discussion initially points out visual elements of the control task facing the tower evident in previous task analyses of tower operations (Paul et al. 2000; Werther 2006). However, this earlier work appears to only provide very general descriptions of the specific visual features to which that the controllers attend. To the extent the visual functions that are important to the controllers are considered; they are generally limited to questions of detection, recognition, and identification. The following discussion will consider other visual features that go beyond these basic three elements and relate in specific ways to the individual

Fig. 1 ASDE-X airport map display

Fig. 2 Out-the-window camera or synthetic vision display format

decision processes tower controllers develop to do their job; in particular, we discuss the motion of the controlled aircraft. The preliminary conclusion of the discussion is that tower controllers use visual features to provide predictive position information allowing them to use *anticipated separation* to effectively and safely merge and space aircraft, maximizing airport capacity.

The visual cues used by controllers are important for several reasons. In the first place, there is FAA interest in increasing airport capacity so that current operations under nonvisual flight rules with reduced capacity may be modified to allow higher visual flight rule capacity during nonvisual operations. For this purpose, the currently used visual information needs to be provided by alternative means. Such "equivalent visual operations" described by FAA/NASA planning documents may be achieved with synthetic visual systems, i.e., with replacement of direct tower camera or sensor views with visualized electronic position data (Kramer et al. 2008). This replacement of the direct view, however, will not be fully successful, and may even be tragically misleading, if the useful visual affordances provided by the real scene are not appropriately included or accounted for. Although Equivalent Visual Operations has primarily been considered from the pilot's viewpoint in terms of flight displays which use new sensor data for synthetic vision, it has a flip side for which synthetic vision or camera-based displays could be used to present useful visual information within a remote or virtual tower.

Significantly, this information need not be provided in the form of an image, but could be provided in a more map-like plan-view format and conceivably could even come along nonvisual sensory channels, e.g., auditory or haptic. In fact, it could be based on data directly downlinked to ground displays from an aircraft indicating its state, i.e., spoilers deployed (Hannon et al. 2008).

The visual environment in an airport tower may be illustrated by considering the view from a specific tower such as that of San Francisco International Airport (SFO) (Fig. 3 top). Such tower views show significant perspective compression at the ~1 nmi range to runways and taxiways, making commercial aircraft subtend small visual angles and posing viewing difficulties due to background visual clutter. Interestingly, during low visibility CAT III operations at SFO, airport operations


San Francisco Ca Control Tower Partial Panorama

Santa Barbara Ca Control Tower Partial Panorama

Stockholm-Arlanda Control Tower Partial Panorama

Fig. 3 The variation of visibility within airport tower's immediate environments is shown from unlimited visibility (San Francisco International, *top*) through partial occlusion due to low clouds (Santa Barbara Municipal, *middle*) to complete whiteout (Stockholm Arlanda, *bottom*)

may be conducted with the controllers never actually seeing the aircraft. Thus, since it is already possible for the controllers to continue many of their control tasks without visual contact, albeit with fewer aircraft, the idea of a remote tower may have some prima facie feasibility. But without visual contact, controllers must inform the pilot and those monitoring their communications that visual contact has been lost. Significantly, at the SFO tower where the parallel runways are ~750 ft apart, continued operation without visual contact is associated with a loss (~50 %) of airport capacity.[1] In contrast at an airport such as Stockholm Arlanda, Sweden (ARN), with the parallel runways ~1 km (~3280 ft) apart, total loss of visual contact can have virtually no impact on capacity when the ground radar is fully functional.[2] Thus, there exist some operational examples of tower operation with total loss of visual contact. During low visibility operations, it is not always necessary for the controller to maintain visual contact with the aircraft, but for the aircraft to have enough forward visibility to safely maneuver the aircraft during ground taxi operations.

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[1] Personal communication, ATCO, San Francisco International Airport, 7/7/2006

[2] Personal communication, tower supervisor, Stockholm Arlanda International Airport, 4/23/2007

1.1 SFO Operations

An analysis of the role of visual features in tower control can be developed from a more detailed discussion of operations for a particular airport, SFO. A sense of the overall strategy for some aspects of usual airport operation at SFO is best obtained from plan-view maps (see Fig. 4 for SFO map). Aircraft are taxied from their gates

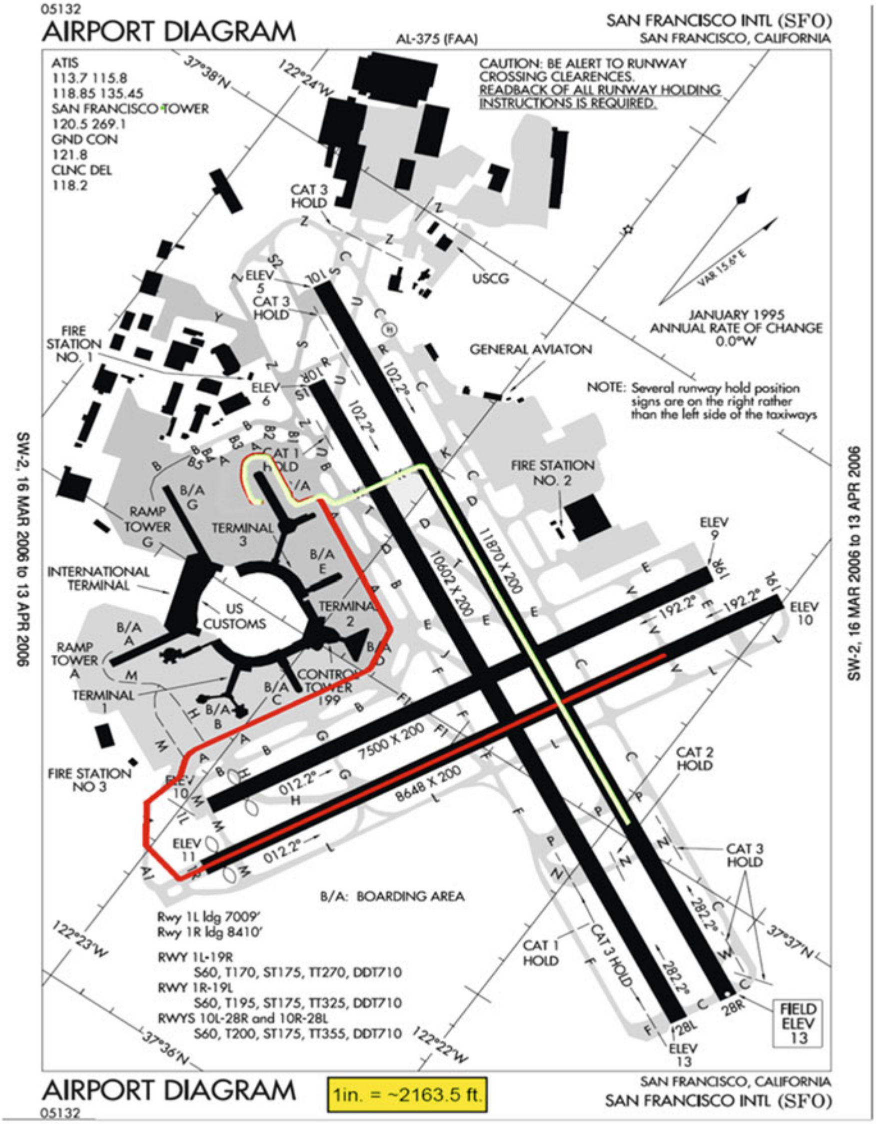


Fig. 4 SFO airport diagram showing typical movement paths for United Airlines, departures (*dark*/*red* paths), arrivals (*light green*/paths)

to the southwest ends of runways 1L and 1R and launched in staggered pairs to the northeast. Departing aircraft are interleaved between aircraft landing on runways 28 left and 28 right which also are treated as staggered pairs. Current winds, weather, and special operational requirements, of course, can significantly alter this pattern. For example, sometimes the longer 28 runways are needed for heavy, departing transpacific aircraft. Detailed descriptions of the alternative approach and departure procedures can be found in the standard instrument departures (SID) and standard terminal arrival routes (STARs) associated with the airport, but the local controller's responsibility for arriving traffic generally begins with radio contact somewhat before the aircraft crosses the San Mateo Bridge and ends for departing aircraft 1 nmi beyond the end of the departure runway. By FAA rules, the local controller is generally responsible for aircraft entering and leaving the runways, whereas the ground controllers handle, in a coordinated way, most of the taxiing to and from the gate. These two positions, in addition to that of the supervisor, are the ones that make the most use of the out-the-window information. The other two tower controller positions, Flight Data and Clearance Delivery, primarily use inside-the-tower information sources and voice communications.

2 Visual Information Used in the Airport Tower

The primary responsibility of the control tower is to ensure sufficient runway separation between landing and departing aircraft (FAA 2006). A back-propagating process may be used to understand the visual requirements supporting the tower controller's primary responsibility.

This process first identifies the visual affordances that the controllers' tasks involve. Affordances are the higher-level behavioral capacities that vision must support (Fig. 5). Controllers, for example, must be able to identify the aircraft type, company, and flight status. They must control and recognize aircraft speed, direction, and position. They must establish a movement plan involving a succession of spatial goals. They must communicate this plan to the aircraft, coordinate it with other controllers and pilots as necessary, establish whether aircraft comply appropriately, and recognize and resolve spatial and other conflicts that may arise. These higher-level elements are supported visually by a number of visual functions: detection, recognition, and perception of the static and dynamic state of the aircraft. These functions are supported by still lower-level visual mechanisms that underlie luminance, color, control, position, and movement processing. These three levels of analysis provide a basis for describing the controllers' visual task.

The tower controller's overall task has, of course, been analyzed within and outside of the FAA. It may be broken down to six different job subtasks: separation, coordination, control judgment, methods/procedures, equipment, and communication. The five of these subtasks which involve vision have been identified by boldface type in Table 1 (Ruffner et al. 2003; FAA 2006).

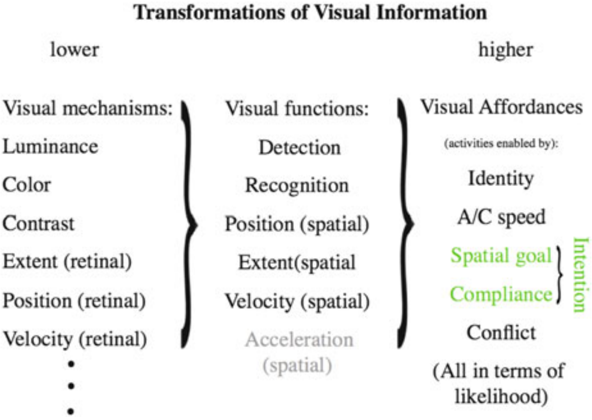


Fig. 5 Description of the dependency of the high-level spatial information needed by controllers on progressively low and lower perceptual functions and visual mechanisms

Table 1 Analysis of tower control tasks that inherently involve visual information is printed in bold

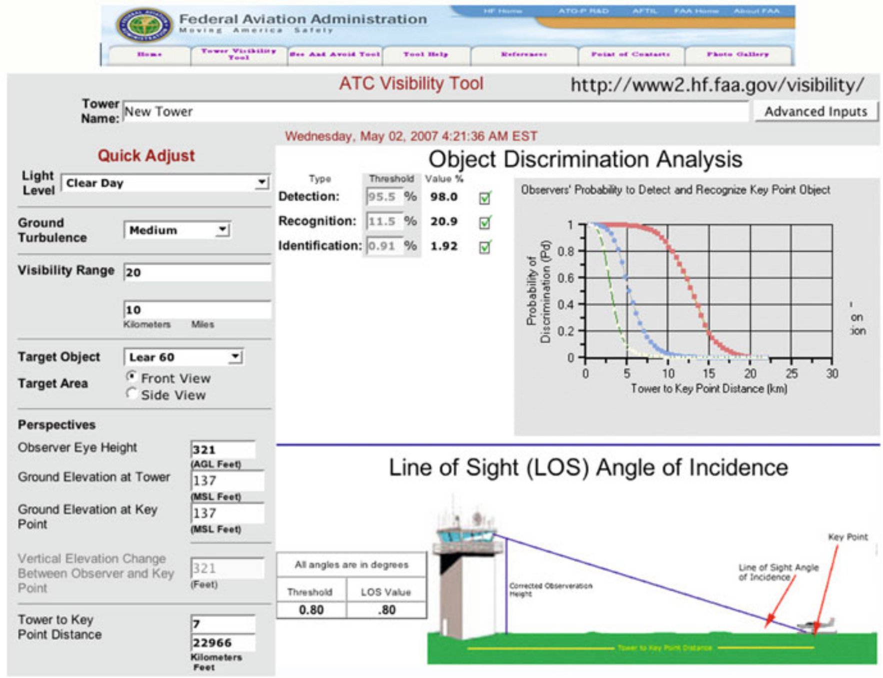
Job task	Job subtask
1. Separation	**1. Separation is ensured and maintained at all times** 2. Safety alerts are provided
2. Coordination	**1. Performs handoffs/point-outs** 2. Required coordinations are performed
3. Control judgment	1. Good control judgment is applied 2. Priority of duties is understood 3. Positive control is provided 4. Effective traffic flow is maintained
4. Methods/procedures	**1. Aircraft identity is maintained** **2. Strip posting is complete/correct** 3. Clearance delivery is complete/correct and timely 4. Letters of agreement (LOAs)/directives are adhered to 5. Additional services are provided 6. Rapidly recovers from equipment failures and emergencies 7. **Scans entire control environment** 8. Effective working speed is maintained
5. Equipment	1. Equipment status information is maintained 2. Equipment capabilities are utilized/understood
6. Communication	1. Functions effectively as a radar/tower team member 2. Communication is clear and concise 3. Uses prescribed phraseology 4. Makes only necessary transmissions 5. Uses appropriate communications method 6. Relief briefings are complete and accurate

The assurance and maintenance of spatial separation is, of course, a visual task since regardless whether separation is determined by radar or direct view, it is definitely recognized visually. Handoffs and point-outs clearly are also intrinsically dependent upon vision, though the need for the controller to adopt the pilot's spatial frame of reference to direct attention toward objects and aircraft is also a significant cognitive task. Control judgment, being essentially a mental and cognitive issue, does not have an intrinsically visual component. But its connection with maintenance of effective and efficient traffic flow does emphasize the critical importance of time in traffic control. Three general methods and procedures directly involve vision. These include establishment and maintenance of aircraft identity, posting and correct annotation of flight strips, and continual scanning of the entire control environment. Associated with these methods is the admonition to work quickly and rapidly recover from errors or off-nominal conditions. Because each tower's environment is to some extent unique, the specifics of their procedures differ from tower to tower. All control techniques are, of course, consistent with the regulations cited and described in the FAA air traffic control*, Order 7110.65R,* but unique procedures and heuristics are passed on to future controllers by on-site training. The specific visual features tower controllers use can frequently be found in these locally developed heuristic rules. Some are presented in Table 4.

The overall tower control process has been formally analyzed and modeled including visual and nonvisual components (Alexander et al. 1989; Werther 2006). For example, the MANTEA notation (Paul et al. 2000) has been applied to analyze controller activity in the tower. Some of the elements identified in the MANTEA analyses are, in fact, visual, but the visual components are only described in very general terms such as "visualize runway," "visualize meteo," etc. These descriptions really only identify the sensory modality used to gather the information and a general description of the content of the visual information, but they say nothing specific about the actual visual viewing conditions or about the specific visual stimuli. This feature is, in fact, common in other more recent and more sophisticated task analyses of visual features seen from the tower. Even the recent modeling done with Petri nets (Werther 2006) does not identify specific visual stimuli but is more concerned with estimates of time required for the precision with which various visual subfunctions maybe executed and to the logical conditions and consequences associated with the functions.

The FAA has done some analysis of the specific visual performance expected from tower controllers. The work primarily focuses on the controller's surveillance function and has been based on visual performance models developed for the military by CERDEC at Ft. Belvoir (e.g., Vollmerhausen and Jacobs 2004). These models primarily are intended to predict the probability of visual detection, recognition, and identification of known targets. "Detection" refers to users' ability to notice the presence of a particular object. "Recognition" refers to their ability to categorize the object into a general class such as a tank, light aircraft, or truck. "Identification" refers to their ability to determine the specific type of object, i.e., an Abrams tank, a Cessna 172, or a Ford refueling tanker. More modern similar visual performance models do not require same amount of calibration techniques to determine model parameters for specific visual targets and specific users (Watson et al. 2009).

The CERDEC analysis, which predicts specific object perception from towers of various heights during a variety of atmospheric conditions and object distances, has



ATC Visibility Tool http://www2.hf.faa.gov/visibility/

Tower Name: New Tower

Wednesday, May 02, 2007 4:21:36 AM EST

Quick Adjust

Light Level Clear Day

Ground Turbulence Medium

Visibility Range 20 Kilometers 10 Miles

Target Object Lear 60

Target Area ● Front View ○ Side View

Perspectives

Observer Eye Height 321 (AGL Feet)

Ground Elevation at Tower 137 (MSL Feet)

Ground Elevation at Key Point 137 (MSL Feet)

Vertical Elevation Change Between Observer and Key Point 321 (Feet)

Tower to Key Point Distance 7 Kilometers 22966 Feet

Object Discrimination Analysis

Type	Threshold		Value %	
Detection:	95.5	%	98.0	☑
Recognition:	11.5	%	20.9	☑
Identification:	0.91	%	1.92	☑

Line of Sight (LOS) Angle of Incidence

All angles are in degrees	
Threshold	LOS Value
0.80	.80

Fig. 6 The WEB interface to the FAA's tower design analysis tool that may be used by municipalities and others to test tower designs ultimately intended for FAA analysis and approval. Note website indicated in the *upper right*

been incorporated into a web tool to help tower designers ensure that specific architectural and site selection decisions for new towers will meet FAA requirements. Significantly, this tool also just focuses on the surveillance function and does not address the aspects of visual motion that tower controllers use for the information, separation, and safety tasks (Fig. 6).

In order to understand the details of the visual features used in tower control, it is first necessary to identify the range within which controllers use visual information. We can use the example of SFO. Informal voluntary discussions and structured interviews with ten active controllers and supervisors who work at this tower were analyzed for the physical locations identified as points where various types of visual references are used while controlling approaching or departing aircraft. These discussions, which were considered preliminary work, were conducted with the knowledge and approval of the SFO tower manager, his chain of command, and the local NATCA tower representative. All primary notes were taken without personally identifying markings and transcribed into secondary statistical summaries or grouped data so as to preserve the anonymity of the respondents. Primary notes were thereafter discarded.

These reported points where useful visual information could be seen primarily to include positions where visual contact with the aircraft is first or last considered to be helpful. These positions, marked in Fig. 7, include those for which aircraft come

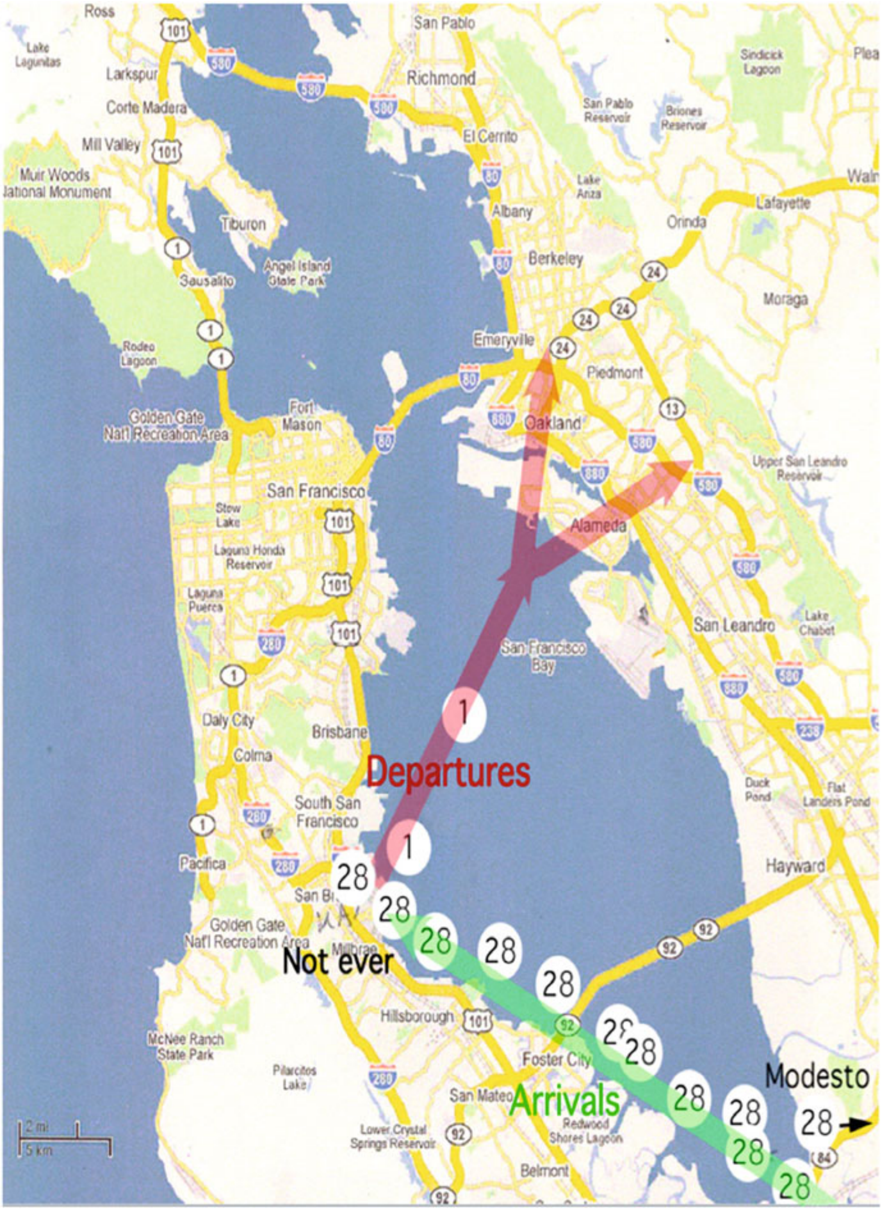


Fig. 7 The first and last positions where SFO controllers report useful visual information w/r to landing (runway 28) and departing aircraft runway 1. The *arrows* show idealized, most common approach paths (*transparent green*) to the west and departure paths (*transparent red*) to the north

under or leave tower control, where they pass important ground references or where visual contact provides other useful information. The points were determined independently from each of the controllers in response to the question, “When you are in the Local controller position, where are the aircraft when you usefully observe them visually, what visual aspects of the aircraft do you observe and why?” Controllers could designate more than one point of interest for departing and more than one for arriving traffic; only two controllers took this option. One point represents nine controllers’ overlapping responses identifying approximately the same location about 1 nmi beyond the end of the departure runway 1.

In general it is apparent from the distribution of points that controllers’ visual attention is much more spatially distributed to the aircraft approaching the 28LR runways and rather abruptly drops off about 1 mile off the end of the usual departure runways 1LR. These observations refer to the most common aircraft flow at SFO but suggest the generalization that the local controllers’ visual attention to approaching aircraft is distributed over a much large area than that corresponding to departing aircraft. A likely reason for this is that departing traffic is handed off to approach/departure control at 1 nmi beyond the end of the runway and generally not thereafter of concern to the tower.

A significant aspect of the controllers’ remarks concerning when they first start paying visual attention, or when they last pay attention, to aircraft is that they rarely mentioned the aircraft’s visual motion.[3] One reason is that for the viewing angles and distances to the aircraft approaching and departing SFO, this motion is very small in terms of degrees per second, often the azimuth rate is on the order of much less than 0.25°/s and rarely more than 0.5°/s. The visual accelerations are even much smaller and difficult to see because of atmospheric haze, thermal effects, and the visual range being beyond 5 miles. Visual rates of motion are more important for closer aircraft just seconds away from touchdown or from those on taxiways.

Probably the most obvious need for visual contact by controllers in the tower is to immediately note unusual events that are not detected by electronic sensors such as radar. Examples could be heavy bird activity or an aircraft leaking fuel onto a taxiway. But there are a wide variety of other visual features that controllers use on a more regular basis when aircraft are close enough for the visual motion to be more easily noticed. Discussions with controllers have provided a list of some that are used (see Tables 2 and 4).

A tabulation (Table 2) of the visual features mentioned in the discussions with each of the SFO controllers shows the relative frequencies with which different features were mentioned. These discussions used a “cognitive walk-through” technique in which the controllers were asked to imagine representative approaching, departing, and taxiing aircraft under a variety of visual conditions and to report what they looked for visually to assist their control tasks. The consequent discussions were guided by the elements outlined in Ellis and Liston (2011, Appendix).

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[3] Visual motion is defined as the angular rate of change of the line of sight angle to an aircraft from the tower.

Table 2 Visual features identified by interviews with ten SFO tower controllers

Feature	Times mentioned	Commentary	Feature	Times mentioned	Commentary
1. Relative visual motion used to interleave takeoffs and landings	5	Controllers **verify predicted separation** using relative motion w/r stationary references to plan clearances	7. Visible wing dip predicts coming turn	3	Visible banking quickly confirms conformance to turn clearance
2. Visual check for obstacles or other A/C to verify a clearance	5	Obstacle checks include ground vehicles, aircraft, birds, and people	8. "Mike and a mile" rule for interleaving takeoffs and landings	3	**Predictive rule:** Departing A/C must be rolling across taxiway Mike on RW1 when matched landing A/C on RW28 is at least 1 mi out for required separation
3. "Taxing with authority" helps attention allocation	4	Fast and confident A/C motion allows controllers to distribute attention to pilots who maneuver hesitantly allowing **anticipation** of future problems	9. Engine smoke or heat confirms takeoff start	2	Currently less useful since modern engines don't smoke much and have cooler exhaust
4. Aircraft attitude/altitude predicts a "go-around"	4	Controllers anticipate "go-around" by checking A/C passage through various approach gates defined by altitude and attitude	10. Onset of navigation lights predicts a tower call requesting service	2	Controllers can **anticipate** coming workload
5. Visually apparent acceleration, speed, or turn rate anticipates taxiway selection	4	Controllers mentally integrate motion features to anticipate taxiway and ground route selection	11. Visual resolution of motion and position is better than by radar at airport	1	1–2 nmi from the tower; the "visual display" of the real world has more "pixels" than associated radar displays
			12. Visual double check on A/C tail to verify company	1	

(continued)

Table 2 (continued)

Feature	Times mentioned	Commentary	Feature	Times mentioned	Commentary
6. Coordinate/ cross-check visual and radar data	4	Specific visual landmarks are selected to cross-check radar	13. Check landing gear	1	Probably an isolated comment because it's checked routinely; "Gear down" isn't a problem for major airlines

Boldface marks the predictive aspect of specific visual features

The most frequently mentioned features were relative motion between landing or departing aircraft and obstacles that could be on the runway. The first of these features is probably prominent because SFO has intersecting runways commonly used for takeoffs and landings. An assessment of all of the features mentioned, however, shows what may be a more general element. Seven of the 13 features identified in the interviews note that the feature helps the controller anticipate future activity. This information provides insight into pilot intent, knowledge, and likelihood of aberrant behavior. These predictive cues help the controller with the short-term trajectory planning needed for *anticipated separation* and help them allocate their attention to pilots either unfamiliar with the airport or maneuvering in unexpected ways.

3 Visual Features at SFO

In order to examine the generality of the visual features and produce a list as complete as possible, structured anonymous interviews were conducted with controllers from an additional seven airports. Because we were not able to obtain timely agreement from the national NATCA office for the participation of line controllers, these additional discussions were limited to supervisory personnel. Anonymity was maintained since all written notes were taken without personally identifying markings, and formal questionnaires were not used. To insure anonymity, original notes were transcribed into statistical or grouped secondary notes, and the originals were thereafter discarded insuring that no personally identifiable information was recorded or could be reconstructed post hoc. In all cases, tower visits to US airports were conducted with the knowledge and approval of the specific tower's manager and FAA headquarters. US airport towers in addition to that of San Francisco International Airport (SFO) that were visited were Boston Logan International (BOS) MA; Golden Triangle Regional (GTR) MS; Santa Barbara Municipal (SBA), Santa Barbara, CA; and Norman Y. Mineta San Jose International (SJC), San Jose, CA. Supervisory controllers from Denver

Table 3 Airport tower environments discussed and evaluated

Airport tower environments discussed	Number of controllers or supervisors	Notes
Stockholm Arlanda ARL	1	Discussions were held, but visual features from the ARL tower were not analyzed
Boston Logan International (BOS)	3	Supervisors only
Denver International (DEN)	1	Supervisors only without airport view
Golden Triangle Regional (GTR)	1	Supervisors only
LaGuardia International (LGA)	1	One supervisor without airport view
Philadelphia International (PHL)	1	One supervisor without airport view
Santa Barbara Municipal (SBA)	2	Supervisors only
San Jose International (SJC)	3	Supervisors only
San Francisco International (SFO)	11	One supervisor, 10 controllers
Total	24	

International (DEN) Denver, CO; LaGuardia Airport (LGA), New York City, NY; and Philadelphia International (PHL), Philadelphia, PA, were included in the multi-airport analysis. They visited the first author at NASA Ames and provided information regarding the nature and location of visual features used by controllers while viewing airport diagrams and regional maps. The tower at Stockholm Arlanda (ARN) in Sweden was the only foreign airport tower visited but was not included in any quantitative analysis. For a summary of the airport towers considered and the personnel interviewed, see Table 3.

Figures 8 and 9 illustrate how the visual velocity of aircraft viewed from the tower could be determined for moving aircraft at or near the airport and those that were farther away in the airport vicinity but still visible. Figure 10 provides a breakdown of various classes of features as 14 general categories that were used to organize the features. Counts on the numbers in each category give some idea of their relative frequency of mention. At this stage of investigation, no systematic attempt was made to determine the relative operational importance or frequency of use of the various features. Investigations are currently underway in collaboration with Jerry Crutchfield of the Civil Aerospace Medical Institute (CAMI) to determine the frequency of use and criticality of the visual features that have been

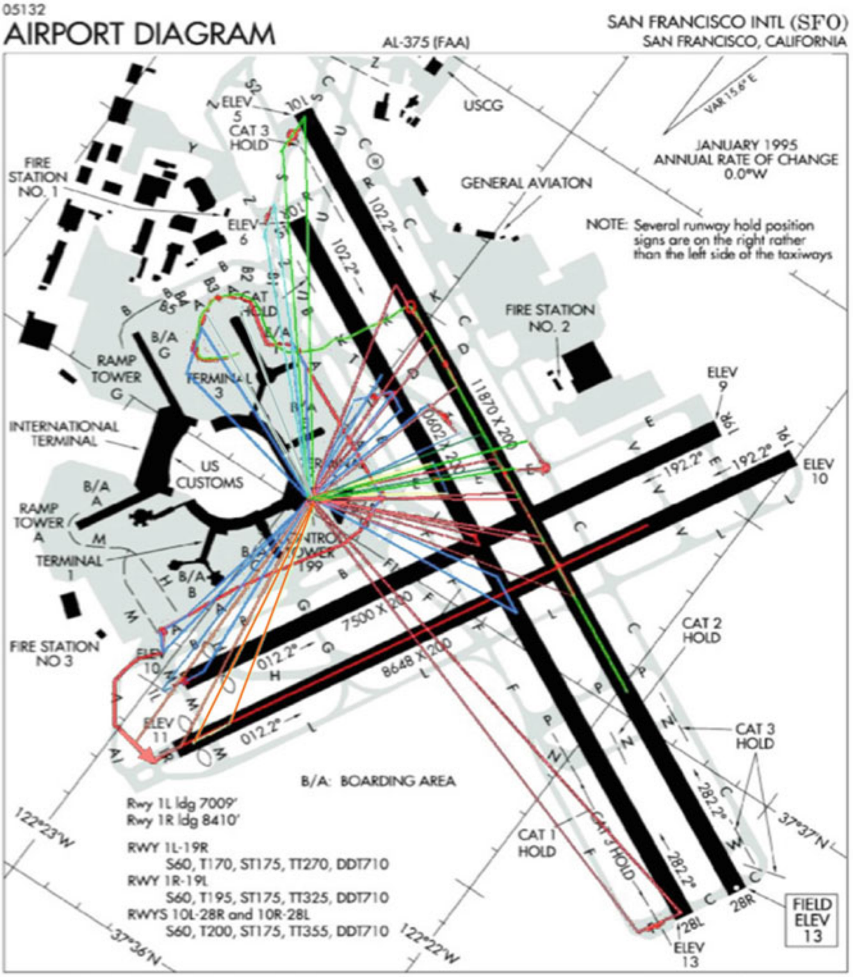

Fig. 8 Lines of sight from the San Francisco International Airport tower to positions on the airport where the visual motion was analyzed. Simple geometry allows calculation of rates of change of lines of sight from the tower to aircraft from knowledge of tower and aircraft position and aircraft velocity

identified[4] [also see van Schaik et al. (2010) and chapter "Detection and Recognition for Remote Tower Operations"]. In particular, the high frequency of mention of the points of the first and last useful visual contact is undoubtedly an artifact of their mention in the structured interview as an example of the kind of visual information

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[4] The project is called Concurrent Validation of AT-SAT for Tower Controller Hiring (CoVATCH). AT-SAT stands for Air Traffic Selection and Training test battery.

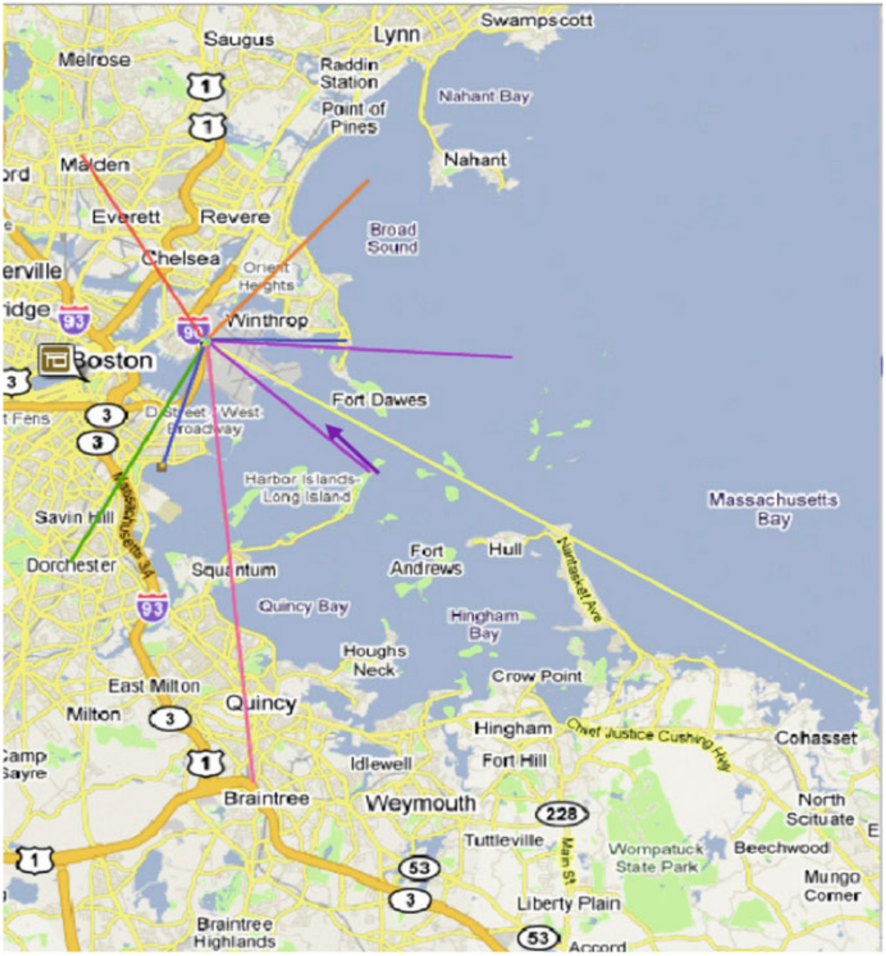

Fig. 9 Lines of sight from the Boston Logan International Airport (BOS) tower to positions in the airport region where the visual motion of moving aircraft were analyzed

being sought. The point of the investigation was to collect as broad a range of visual features as possible for further analysis in subsequent studies.

When a visual feature was identified by a controller, its location was plotted on an appropriate map. Afterward, the direction of flight and speed was determined from the appropriate airborne traffic pattern or ground path. Simple geometric analysis was then possible to determine the apparent visual rate of the aircraft as seen from the tower at the time the visual feature would have been noted. Because actual aircraft speed was not actually measured, speed was estimated

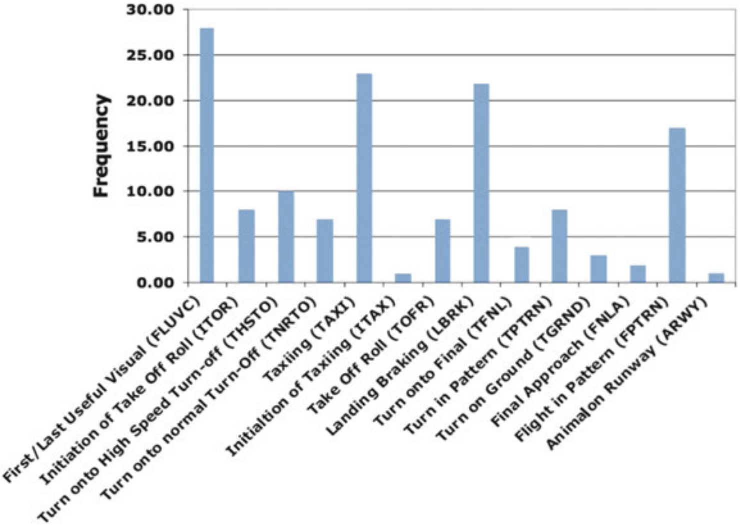

Fig. 10 Frequency of report of the use of various visual cues

from typical rates mandated by approach procedures or estimated by controllers and pilots familiar with the airport and typical air and ground aircraft motion. Some reflection on the geometry shows, however, the aircraft speed to have a comparatively small influence on visual motion. Its impact is dwarfed by the effect of relative direction of flight. An aircraft flying directly toward the tower can have virtually 0 °/s visual velocity! The relative direction of flight used for analyses was determined from the interviewees and the typical patterns of motion at and around the airport if the original notes did not include the needed information. Once the approximate visual velocity associated with each visual feature was determined, a spectrum of visual velocities associated with each of the 14 feature categories could be determined. These are shown in Fig. 11 and summed to give an overall total. These spectrums of visual velocity for each of the categories of features reflect some of the physical aspects of each category. The first and last useful visual contact rates are slowest because these are in general the farthest from the tower. Visual rates during landing deceleration are high because the aircraft are generally closer to the tower yet still moving relatively fast compared to taxiing.

For the purposes of the present inventory, the most important aspect of the distribution of motions is not its shape or arithmetic mean but its mode and range. As can be seen in Fig. 11, the vast majority of visual rates are less than 1 °/s with the mode at a small fraction of a degree per second. These visual rates are quite slow compared to those typically studied in visual psychophysics. If a concept of operations for a remote or virtual tower is to include visually presented targets that provide the information that controllers currently pick up from aircraft motion, the display techniques need to be able to represent this range of slow motion for visual cues that controllers currently use. It is important to note that the useful

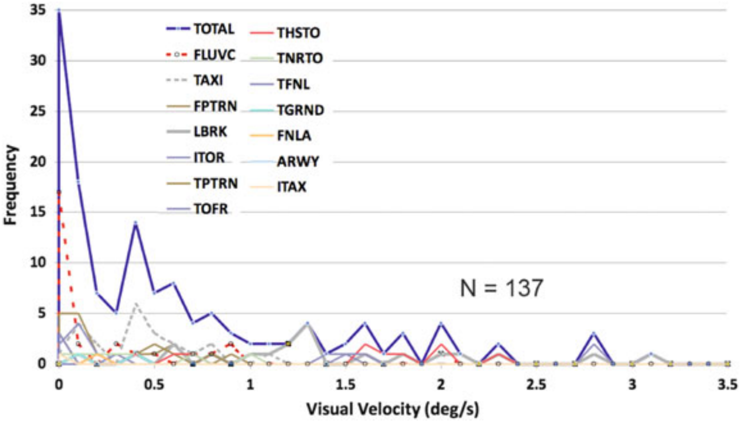

Fig. 11 Frequency distribution of rates of visual movement associated with a variety of different visual cues coming from moving aircraft. See Fig. 10 for the meaning of the letter codes of the variety visual cues identified

presentation of aircraft motion therefore benefits significantly from the use of very large-format displays. To the extent that the display scales down visual motion due to screen size, the displayed visual rates, which are already very slow, could well become imperceptible and require special signal processing to be operationally useful. An example of such processing could be the computational detection of the slow motion and its denotation by introduction of or changes in visible symbology. A second important caveat is that the visual rates are not seen in isolation but have a temporal context; in fact, the change in visual velocity itself can be an important cue which is identified for some visual features in Table 4 and discussed in more detail in the final section.

Table 4 provides a summary of all the visual features identified from discussions with controllers from all analyzed airports. It lists the identified visual feature, the information the feature provides the controller, and suggests some general information support characteristics that would be necessary to provide equivalent information on alternative displays that might be used in a virtual or remote tower: (1) A map-like display that could be driven by ground radar or other comparable positions information, e.g., ADSB. (2) An image-like display that resembles the out-the-window view from a tower and could be driven by airport cameras or other sensors and computer graphics providing synthetic vision (Figs. 1 and 2).

A better understanding of exactly how some of these cues can be used can come from examining them quantitatively. An example of such analysis is presented below with respect to landing deceleration at SFO.

Table 4 Visual and other perceptual features that aid tower air traffic control

Visual feature A/C = aircraft	Visual information provided	Information and display techniques: map-like displays	Information and display techniques: out-the-window image-like displays
Status			
1. A/C is prepositioned with an anticipatory rotation for a turn while holding short of a taxiway or runway	Pilot is correctly expecting to be cleared for a specific turn	Current and static A/C orientation should be shown on electronic map	Visual resolution of display should be sufficient for user to recognize A/C pose at crossing points
2. A/C type	Predicts likely ground acceleration, e.g., the difference between turbine and constant speed propeller. A/C type determines separation techniques used	A/C type should be indicated by icon shape or data tag to relieve controller memory load	High-resolution visual image required to support existing visual performance requirements for tower design
3. Dust up or thermal optical distortion from thrust	Applied power can confirm compliance with takeoff or other clearances that require engine spool up	Downlinked indications from A/C of engine spool up should be displayed A/C icon	Evidence of spool up should be visible on display, or A/C icon associated with the power-up should be displayed based on downlinked information
4. Smoke or spray from wheel indicates ground contact and touchdown point	Touchdown indicates landing likely unless a touch-and-go is planned. Helps to identify likely taxiway to be used to exit runway	Downlinked information from wheel sensors indicating touchdown should be displayed on A/C icon to indicate touchdown point	Visual evidence of wheel contact should be visible or downlinked information from wheel sensors indicating touchdown should be displayed on A/C icon
5. Navigation lights being turned on	Call to tower is imminent, usually to the clearance delivery controller at a big tower	Navigation lights when A/C at gate should be visible. Downlinked information regarding A/C before engine start should be displayed if visibility is insufficient before pilot calls tower	Navigation lights when A/C at gate should be visible. Downlinked information regarding A/C before engine start should be displayed if visibility is insufficient before pilot calls tower
6. A/C relation between A/C attitude and altitude	The visual relationship between A/C attitude and altitude is predictive of pilot intent such as landing or executing a missed approach	A/C pitch attitude should be displayed geometrically or numerically for comparison with speed display with short delay < ~1 s	Pitch attitude and speed need to be perceivable on display with short delay < ~1 s

(continued)

Table 4 (continued)

Visual feature A/C = aircraft	Visual information provided	Information and display techniques: map-like displays	Information and display techniques: out-the-window image-like displays
7. Reflected "lights" on the water. Visible reflections of A/C lights-off ground features such as bodies of water or a runway surface that confirm normal or indicate deviant flight path	At some airports reflections of landing lights-off surfaces like water can independently confirm normal lateral position and orientation of landing A/C. Such information is similar to pilot reports of passing the outer marker	Provide indication of A/C passing over "virtual" markers along approach route and outer or inner marker shown on display, possibly sourced from data downlink	Visual fidelity of image of approaching A/C should include large specular reflection of landing lights
8. A/C mechanical status, gear, flaps, spoilers, and reversers	Confirms appropriate aerodynamic status of A/C. Confirms intention to land. Can be used to indicate onset and intensity of braking, predicting the A/C deceleration profile	Downlinked data from A/C should provide data for display of status of gear, flaps, spoilers, and reversers to confirm commitment to landing	Aerodynamic configuration of A/C should be visually evident or enhanced by graphic overlays based on downlinked data
11. First/last visual acquisition. The position where an approaching aircraft is normally first usefully visible or where visibility is typically lost for a receding aircraft	Confirm location of radar contact, spacing w/r to A/C in pattern	Display A/C icon corresponding to initial and final radar contact	Provide sufficient visual contrast and resolution to allow visual contact at times and positions comparable to view from a real tower
12. Movement during taxi	Verifies compliance with taxi clearance and/or detects violation	A/C motion and position need to be observable. Note: because of reduced display size and map scale, the physical motion on the display may be below perceptual thresholds	A/C motion and position need to be observable. Note: because of reduced display size, the physical motion on the display may be below perceptual thresholds

(continued)

Table 4 (continued)

Visual feature A/C = aircraft	Visual information provided	Information and display techniques: map-like displays	Information and display techniques: out-the-window image-like displays
13. Animal obstructions or intrusions	Need to issue obstruction warning and modify approach, departure, or ground movement; offending animal could be as small as a snapping turtle or as large as a bear or alligator	Airport sensor data (e.g., motion sensors or cameras) should be used to provide timely displays of obstructions' locations and movement	Visual displays should have sufficient resolution and contrast to match out-the-window views. Airport sensor data (e.g., motion sensors or cameras) could alternatively be used to provide timely iconic or text overlays
14. Birds, flocks, large birds	Need to issue bird activity warning and modify approach, departure, and ground movement	Airport sensor data (e.g., motion sensors or cameras) should be used to provide timely iconic and/or text displays of obstructions' locations and movement	Visual displays should have sufficient resolution and contrast to match out-the-window views. Airport sensor data (e.g., motion sensors or cameras) could alternatively be used to augment display to provide timely iconic or text warning overlays
15. Inanimate obstacles on runway/taxiway	Need to issue obstruction warning and modify approach, departure, ground movement, and possible communication with user-operated vehicles	Airport sensor data (e.g., motion sensors or cameras) should be used to provide timely iconic and/or text displays of obstructions' locations and movement	Airport sensor data (e.g., motion sensors or cameras) should be used to provide timely iconic and/or text displays of obstacles or displays making them visually detectable
16. Unexpected/unanticipated event	Visual observation of event requiring non-standard/emergency procedures	Not handled well without sensors designed for unanticipated dangers consequently rare but dangerous events could be missed	High visual fidelity wide field of view surveillance with high sample rate and low latency required for unanticipated events, which likely have a visual component

(continued)

Table 4 (continued)

Visual feature A/C = aircraft	Visual information provided	Information and display techniques: map-like displays	Information and display techniques: out-the-window image-like displays
Acceleration/deceleration			
17. A/C beginning visual acceleration of takeoff roll	Confirms compliance with clearance to takeoff	Detection of onset of takeoff roll by low-latency motion sensors needed. Downlink from A/C or other sensors needed to provide information with delays comparable to current view of the A/C. NB: physical size of map display will make initial A/C motion harder to see than direct out-the-window view (see text). A map onset of motion signal, such as making the A/C symbol double bright, would greatly assist controllers	High resolution, bandwidth, low-latency view of A/C starting takeoff roll are required for visual confirmation of compliance. Such a display could provide information equivalent to the current out-the-window view
20. A/C pitching after landing braking	Predicts landing, length of landing roll, and taxiway to be used to exit runway and is related to confirmation of understanding of assigned gate	Downlink from A/C or other sensors would be needed to provide information with delays comparable to current view of the A/C. A visual indication on the icon of the landing A/C to indicate wheel contact could provide comparable information	High resolution, bandwidth, low-latency view of A/C landing roll are required for visual detection of pitching. Since this pitch cue is smaller than that at touchdown, its visibility on out-the-window displays should be verified
21. A/C pitching during initiation of takeoff (especially B757)	Confirms compliance with clearance to takeoff	This information is redundant with the indication of onset of takeoff roll (see above)	High resolution, bandwidth, low-latency view of A/C starting takeoff roll are required for visual detection of pitching. Since this pitch cue is smaller than that at touchdown, its visibility on out-the-window displays should be verified

(continued)

Table 4 (continued)

Visual feature A/C = aircraft	Visual information provided	Information and display techniques: map-like displays	Information and display techniques: out-the-window image-like displays
22. Banked wing predicts turn faster than change in A/C position	Confirms compliance with clearance	Aircraft symbol or data tag needs to indicate A/C pose	High resolution, bandwidth, low-latency view of A/C banking are required for visual detection of pose
23. A/C initiating turn onto taxiway, especially cue from nose wheel angle	Confirms clearance to turn onto taxiway, nose wheel angle predicts turn	Downlink from A/C or other sensors would be needed to provide information with delays comparable to current view of the A/C. A visual indication on the landing A/C icon of nose wheel angle and A/C pose w/r to taxiway and runway could provide comparable information	High resolution, bandwidth, low-latency view of A/C taxiing are required for visual detection of pose and nose wheel position
24. Timing of visible plume effects of thrust reversers and spoilers. Note: these cues are distinct from the visibility of the mechanical deployment of these devices	Predicts landing deceleration, length of landing roll, and taxiway to be used to exit runway and is related to assigned gate	Downlink from A/C or other sensors would be needed to provide information with delays comparable to current view of the A/C. A visual indication on the landing A/C icon of deployment of thrust reversers could provide comparable information	High resolution, bandwidth, low-latency view of A/C landing roll are required for visual detection of deployment of reversers and spoilers (see text)
Speed			
25. Visual deviation of glide path seen as relative motion against stationary reference. Relative motion of an A/C seen against stationary ground references, allowing its glide path to be more easily perceived	Confirms correct approach/departure paths	Graphical display of flight path against a ground-referenced map could provide some comparable visual information, but the 3D element would require ground-referenced altitude data tag for the A/C icon	High-resolution visual image is required based on existing visual performance requirements for tower design

(continued)

Table 4 (continued)

Visual feature A/C = aircraft	Visual information provided	Information and display techniques: map-like displays	Information and display techniques: out-the-window image-like displays
26. Relative motion of visually overlapping targets. Relative motion of visually, partially overlapping objects that allow them to be perceptually separated, e.g., two aircraft along approximately the same line of sight. This cue is especially helpful at night when A/C are seen as light patterns	Breaks visual clutter, aids perceptual separation of otherwise confusing objects	Relative motion can also be displayed on a map, but the sampling rate degrades and delays motion perception. De-clutter algorithms can be employed to remove clutter. The usual plan-view format minimizes clutter due to perspective compression as seen from a tower	High resolution, bandwidth, low-latency view of visually overlapping aircraft and background are required for visual judgment of relative motion. Current specifications for tower design provide adequate visual requirements for the perception of relative motion (see text)
27. Relative motion of aircraft on crossing trajectories with respect to a fixed ground reference such as a lamp pole	Confirms correct approach/departure paths, allows estimation of safe passing through runway intersections such as those at SFO	Stationary ground reference symbols should be introduced to map displays to make the relative motion of moving symbols easier to perceive	High resolution, bandwidth, low-latency view of visually overlapping aircraft and reference objects are required for visual judgment of relative motion (see text)
28. A/C speed during taxi, "taxing with authority"	Speed indicates level of pilot familiarity with airport, and likelihood of clearance conformance improves distribution of controller's attention, unusually slow speed indicates need for special attention	Ground speed data tags should be associated with aircraft symbols. If such data tags are not provided, the physical map size needs to be large enough so that high and low speed taxiing can be distinguished by controllers	High resolution, bandwidth, view of taxi area are required for visual judgment of motion. The physical size of the display needs to be sufficient for discrimination of high and low visual rates of taxiing (see text)
Sound[a]			
29. Sound of takeoff power	Confirms compliance with takeoff clearance	Directional sound cues provided by 360° radially mounted directional microphones should be provided within a remote tower	Directional sound cues provided by radially mounted directional microphones should be provided within a remote tower
30. Sound of engine run-up	Preparing for takeoff	Directional sound cues provided by 360° radially mounted directional microphones should be provided within a remote tower	Directional sound cues provided by radially mounted directional microphones should be provided within a remote tower

(continued)

Table 4 (continued)

Visual feature A/C = aircraft	Visual information provided	Information and display techniques: map-like displays	Information and display techniques: out-the-window image-like displays
31. Loud unexpected sound	Attention directed to source, possible explosion, bomb attack, etc., is an important adjunct to visual information	Directional sound cues provided by 360° radially mounted directional microphones should be provided within a remote tower	Directional sound cues provided by radially mounted directional microphones should be provided within a remote tower
Additional observation			
32. General surveillance	Some airport towers are strategically placed so as to provide useful, excellent visual surveillance outside of the airport and relevant airspace		The field of regard may be usefully made larger than that needed for aircraft control for airports where general surveillance is needed, e.g., Boston Logan

[a] In discussions of visual features used to aid control, so many controllers spontaneously mentioned the importance of sound cues, we have included them in this table

4 Deceleration During Landing at SFO

In order to analyze the deceleration of aircraft landing at SFO, digital video images of the initial braking were recorded after touchdown. Recordings of a wide variety of landing aircraft were made to examine a wide range of decelerations. The 45 observed and reported aircraft included 747–400s; a variety of models of 767, 757, 737, A319, A320, and CRJs; and small twin turboprops. The weather was clear with light winds from the west. The landing data from all the aircraft have been aggregated as there was no intention to make a more detailed analysis by type but rather to understand the range of visual rates and visual decelerations that would be visible from the airport tower as discussed below.

The following analysis begins to determine the magnitude of this visually sensed deceleration and how it could be used by controllers. Through this process we identify one of the dynamic visual features used in traffic control from the airport tower: the change in speed evident during a single glance a controller might make toward a decelerating landing aircraft.[5] In thinking about what specific aspects of

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[5] During normal vision, people make from 3 to 5 fixations per second (Rayner and Castelhano 2007). However, when studying some aspect of an ATC image, fixation duration can increase but rarely grow longer than approximately 1.3 s (e.g., Remington et al. 2004). Consequently, a reasonable constraint for modeling the duration of a controller's glance would be to insure that they are 1.3 s or less.

the visual stimulus to which the controllers might be attending, it is helpful to remember that perceptual discriminations of commonly experienced magnitudes of sensory quantities such as velocity are fairly well described by Weber's Law, which states that the just-noticeable difference (JND) is a constant proportion of the quantity's magnitude. This so-called Weber fraction is roughly constant for a variety of psychophysical parameters, but under the best conditions is ~6 % for changes in velocity viewed within a typical 0.5 s time period. For stimuli with random mixtures of spatial frequencies, i.e., mixtures of contours of different sizes, the JND grows to about 7.5 %. Very significantly for the very slow visual velocities less than 1 deg/s such as those commonly seen from the control tower for landing and departing aircraft, the JND can climb up to ~10 % (McKee et al. 1986).

It is therefore important to understand that controllers may not be directly sensing the visual velocities per se even though they may claim to do so. They may, in fact, develop alternative viewing strategies allowing them to translate speed into displacement during relatively fixed time intervals, thus making the detection of unusual rates of change easier. Additionally, alternative visual cues to quantities such as deceleration could be used. For example, aircraft pitch while moving along the ground could be equally well a clue to the onset or offset of braking.

It is not so much the visual aspect of the visual information that is important as it is the fact that the information revealed by vision is relevant, real, direct, unmediated, immediate, and continuous that makes it possible for the best possible anticipation of future action. This is why the visual input could be critical. Replacements for it need to capture the same predictive, informational features as suggested in Table 4.

In order to begin to analyze the visual features actually present in real landing in more detail, we have initially focused on the deceleration profile of aircraft landing on the 28 left and 28 right runways at SFO. Controllers report that they use their sense of degree and timing of this specific deceleration to anticipate which taxiway would be needed for the aircraft to exit the active runway. Their decision is time critical during heavy runway use since landing aircraft are staggered in pairs and interleaved with departures on crossing runways 1R/1L.

We have made 15 frame/s video recordings at 1024 × 768 resolution of the braking phase of 45 aircraft landing on 28L and 28R and processed the recordings to measure changes in visual velocity. We have used a custom MATLAB image processing technique that isolated the moving contours across a set of two frames and averaged them to localize the aircraft and provide their screen velocity in degrees per second. Using the viewing geometry described in Fig. 12, we have recovered the aircraft braking profile and computed the changes in its visual velocity as viewed from the control tower by re-projecting the movement, as it would have been seen from the tower. Thirty of these velocity profiles (low-pass filtered with a 1 Hz cutoff) are shown in Fig. 13.

Because of the noise present in our current recording technique, we were unable to obtain velocity and acceleration values with acceptable noise levels. We were,

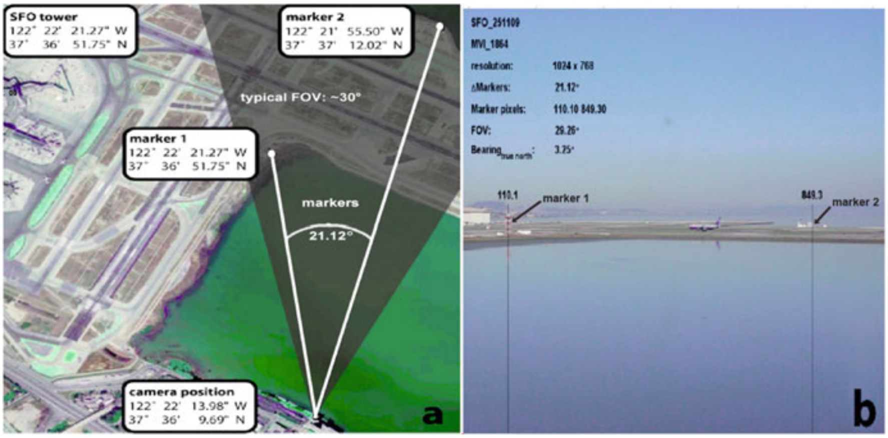

Fig. 12 Camera parameters and view at SFO. Markers at known ground positions determined from Google Earth ground images were used in combination with the known geometry of the runway to convert line of sight angles to aircraft from the camera position into position along the runway, thereafter into line of sight angles from the airport tower and thereafter into visual velocities as seen by controllers

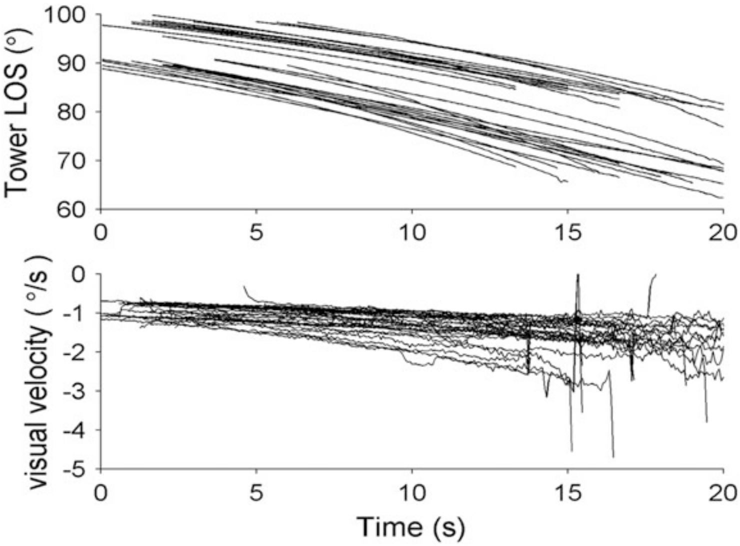

Fig. 13 Line of sight direction change and visual velocity

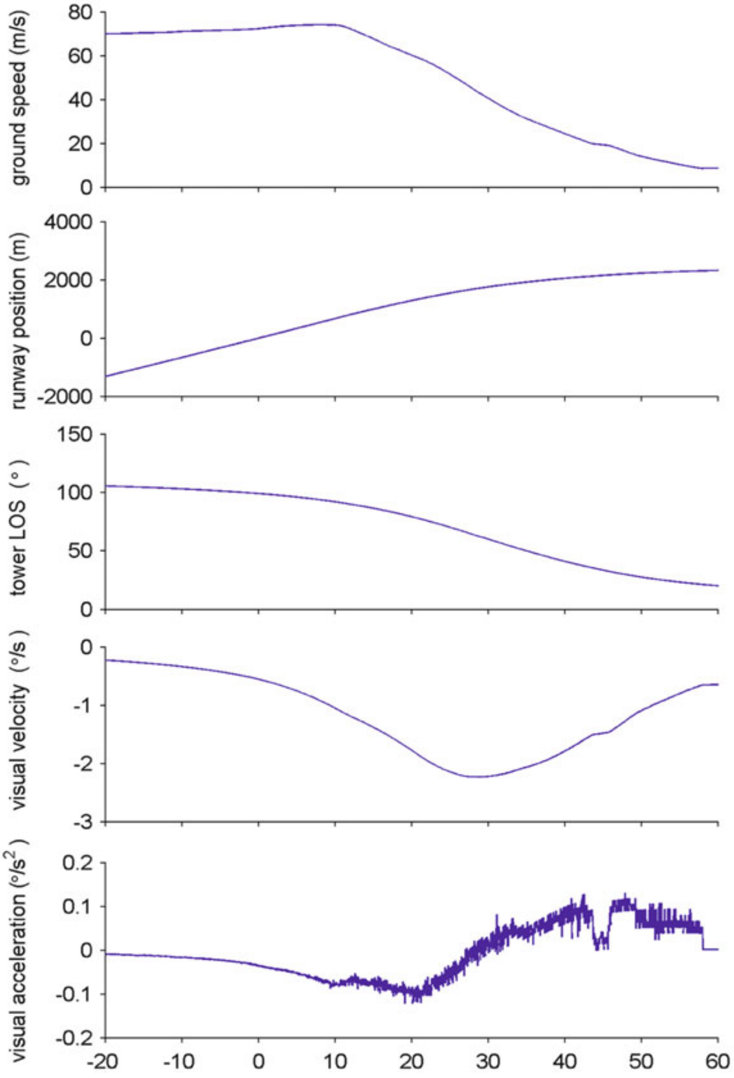

Fig. 14 Line of sight (LOS) changes

however, able to obtain a directly recorded braking deceleration profile[6] for another A319 aircraft landing on runway 28L from the same company, comparably loaded and flying in the same wind and weather conditions as one of the aircraft we had recorded visually. Since we knew the touchdown points for these two A319 landings, we've combined the two trajectories to produce what we believe to be a fairly accurate landing profile as seen from the tower (Fig. 14).

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[6] The aircrafts' deceleration was recorded just after touchdown using an arm rest-stabilized iPhone in airplane mode running an application called Motion Data with sampling rates at 30 Hz.

The deceleration profile in Fig. 14 shows the aircraft approaching and passing the tower as it decelerates. In fact, during the approach the visual velocity actually increases during the deceleration because of the decreasing distance between the aircraft and the tower. It is clear from the deceleration profile that there are several phases of braking due to deployment of the thrust reversers, spoilers, and mechanical brakes and further data collection and processing needs to be done to more precisely identify these periods. However, the very smooth velocity plot in Fig. 14 (third panel from top) already shows that the amounts of velocity change in the braking within any short-time window 2 s or less are well less than the ~6 % usual Weber fraction for a just-noticeable difference of midrange psychophysical quantities such as perceived speed. This level is defined by convention to be that difference in a sensory quantity that can be detected correctly 75 % of the time and is therefore not evidence of a very strong sensory stimulus. This observation leads to some skepticism that the controllers are detecting velocity change per se because controllers would likely wish to be more certain regarding their judgments than 75 % correct. Accordingly, they may have developed a strategy to detect speed change by some other means, perhaps by comparing displacement for approximately equal time periods. Such a timing strategy might be evident in eye-tracking records of controllers judging aircraft deceleration. Of particular interest will be future analyses and experiments to determine how well the controller's sense of aircraft deceleration can be maintained with airport imagery spatially degraded by pixilation and sensor noise and temporally degraded by low sampling rate. The sampling rate issue has been addressed by research first published by Ellis et al. (2011) and more extensively analyzed in chapter "Videopanorama Frame Rate Requirements Derived from Visual Discrimination of Deceleration During Simulated Aircraft Landing" of this volume.

5 Summary

1. Airport tower controllers use visual features observed during aircraft operations to provide information beyond simple detection, identification, and recognition of aircraft.
2. Twenty-eight useful visual features have been identified from discussion with 24 controllers and supervisors. Some involve the static pose of the aircraft of interest, but many of the most useful involve aircraft motion, especially aircraft acceleration and deceleration.
3. The visual features provide predictive or lead information regarding future aircraft position, pilot intention, and pilot airport familiarity that enable controllers to appropriately distribute their attention during operations and to anticipate possible conflicts.
4. The very slow rates of visual motion in terms of subtended visual angle suggest that the change in velocity reported by controllers is not directly sensed but must be observed by learned viewing strategies developed from tower experience.
5. Directional aircraft sounds audible in the tower are also used to assist operations.

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Detection and Recognition for Remote Tower Operations

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Abstract Remote control of airports implies application of cameras to replace direct visual observation from airport control towers by projection of the airport and its traffic in a remote control centre. Surprisingly, hardly any literature can be found to list the required visual objects and phenomena for tower control, i.e. the visual cues that need to be seen for tower control. The composition and validation of the so-called visual cue list for tower control is the subject of this study. Tower controller task analysis was used to compose a 'long-list' of visual features. The long-list has been presented to a group of operational air traffic controllers to test the need and the circumstances to observe these visual cues. Our analysis shows that most of the visual cues are useful for operational tower control but are not strictly mandatory for applying the rules of the International Civil Aviation Organisation. The requirement for visual image resolution of remote tower control is the second subject of the paper. Our analysis leads to definition of a 'shortlist' of important safety-related visual objects and phenomena for tower control and the conclusion that state-of-the-art media are just able to provide the required image resolution for visual *detection* but not for *recognition*.

Keywords Remote Tower • Tower Control • Visual cues • Detection • Recognition

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1 Introduction

In Europe, the first prototypes of remotely controlled airfields have emerged. Dedicated airfields are equipped with cameras, such that the air traffic controller (ATCO) can control the airfield from a distant virtual visual control room. The view on the airfield is displayed in real time on a display in this room. From here, the airfield can be surveyed and the traffic movements can be controlled. This concept is particularly suitable for a group of relatively quiet airports at geographically dispersed locations, such that the control of multiple airfields can be centralised, thus making efficient use of air traffic controller resources.

The topic of this study focuses on two aspects:

1. The visual 'features' (cues, objects, phenomena) that air traffic controllers should be able to see for safety reasons in a remote tower
2. The minimum resolution requirements for remote tower control

A list of visual features to be seen from the control tower is of interest because it strongly influences the requirements on the surveillance cameras, the data-communication links and the display system. In this study, such a list of items, e.g. a flock of birds or debris on the runway, and the circumstances under which these items must be detected and recognised has been created. The basis for this list was established by considering the task requirements of the air traffic tower controller.

Minimum required performance specifications are needed to determine the ability of camera surveillance and display systems to sufficiently display visual features. To see those features under widespread viewing conditions (day/night, sun/overcast, etc.) is key to the tower controllers' tasks and hence aviation safety. This means, that, in order to detect, for example, birds at the runway, parameters such as the visibility range from the tower, the resolution of the image and the contrast between object and its background must exceed certain threshold values. This paper will discuss the establishment of the resolution threshold values.

This small study was made possible in the context of the Advanced Remote Tower (ART 2006) project. ART is a 6th Framework Program project funded by the European Commission and run under project lead by Saab AB in Sweden and the Swedish Air Traffic Control organisation LFV.

The properties of tower control may not be well known to readers. Therefore, the next section is included to explain the procedures and systems used in state-of-the-art tower control. The focus of this contribution, i.e. the analysis of tower control visual features and resolution requirements for remote projection, is found in last sections.

2 Tower Control

2.1 *Basic Duties*

The ICAO task definition for air traffic controllers is (ICAO 2005a) to:

- Prevent collisions between aircraft and on the manoeuvring area between aircraft and obstructions. The manoeuvring area is the section of the airport to be used for take-off, landing and taxiing excluding aprons.
- Favour an expedite flow of traffic.

These tasks have to be performed by visual observation. The procedures change when visibility conditions change. Definition of visibility conditions can be found in ICAO (2005b). If the tower controller cannot exercise visual control over all traffic, e.g. because of fog, a special procedure called procedural control is applied. It means that an aircraft is cleared via radio telephony to a point at the airport, where the pilot has to report when reaching that point. Procedural control and its safety depend largely on the quality of the VHF communication channel and the situational awareness in the cockpit. Procedural control implies much lower throughput capacity for the airport (often only one aircraft can be moved at the time). ICAO does not specify how visual surveillance from control towers shall be implemented in detail. ICAO does not specify what objects or visual cues have to be seen.

2.2 *Airport Radar and Surveillance Systems*

Air traffic control in the towers of airports is thus based on visual surveillance tasks. However, for low-visibility conditions, Airport Surface Detection Equipment (ASDE) with radar screens and information from the Terminal Approach Radar

(TAR) are available at the larger airports. This kind of equipment serves the tower controllers, but controllers are allowed to take decisions based on the ASDE and TAR only in visibility conditions 1 and 2 (ICAO 2005b).

3 Analysis of Visual Features

3.1 Analysis of Tower Tasks and Visual Needs

We identified visual needs of the tower controller from our task analysis of tower operations (ART 2008), based on expert elicitation and task observation. The tower tasks were structured according to the time phases in ATC handling of arriving and departing aircraft. Also general tasks (such as collecting weather information) and abnormal events (e.g. crash, bird strike, overrun of the runway) were taken into account. Our interest concerns the visual features at and around the airport which have to be surveyed as part of the task, such as specific features of aircraft (e.g. its apparent ability to land during final approach, flocks of birds, etc.). To make a more fine-grained assessment of the quality with which visual features can be viewed, different visual tasks can be distinguished:

- Visual detection (you may or may not detect that an object is at a certain location)
- Visual recognition (once you have detected the object, you may be able to recognise it, e.g. that an object is indeed an aircraft)
- Visual identification (verify observed information, such as an aircraft at a particular position with other information, such as a flight plan)
- Visual judgment (concerns a more abstract relationship, e.g. a potential conflict between aircraft or an unusual descent rate of aircraft)

These different visual tasks put different requirements on human visual characteristics (e.g. visual acuity; see, e.g. Stamford Krause 1997) and therefore lead to different system requirements when displaying these features in a remote tower. Moreover, visibility conditions, such as fog, may affect these visual tasks differently.

3.2 List of Visual Features

The list of visual features that was derived from the task analysis includes the following items:

1	Large-size bird (e.g. goose) on the manoeuvring area or vicinity of the runway
2	One smaller bird (like a seagull) on the manoeuvring area or vicinity of the runway

(continued)

3	Flock of smaller-size birds (e.g. small-type seagull) on the manoeuvring area or vicinity of the runway
4	Animal, like a deer or a dog, on the manoeuvring area/runway
5	Vehicle on the manoeuvring area
6	Aircraft entering the control zone of the tower
7	Stationary obstacles on the manoeuvring area
8	Aircraft in the circuit
9	Descent rate of aircraft
10	Aircraft undercarriage (main gear and nose wheel)
11	Aircraft position on final
12	Airspace for missed approach/go-around
13	Foreign objects on the runway (e.g. plastic bag, pieces of metal, pieces of exploded tyre)
14	Aircraft flare at landing (judgment)
15	Aircraft touchdown inside touchdown zone
16	Detect smoke or water spray from tyres when touching down
17	Aircraft slowing down on runway (judgment)
18	Taxiing aircraft follows designated route
19	Water, snow or slush on runway
20	Aircraft acceleration during take-off run (judgment)
21	Aircraft lift-off (judgment)
22	Aircraft climb (judgment)
23	Cloud base
24	Clouds (type and coverage)
25	Visibility range (as judged from visibility of objects with known distance)
26	Aircraft lining up on the runway
27	Number or logo on skin of aircraft
28	Aircraft starts to move
29	Aircraft starts to turn
30	Aircraft landing lights
31	Precipitation (type) (judgment)

4 Method and Results

A questionnaire was presented to a group of seven controllers. This questionnaire referred to the visual features listed above. The controllers were asked to give their safety-related experience about the maximum viewing range (detection range) for each of the features. Subsequently, they were asked to state the importance for safety reason to detect or judge a feature on a scale from 0 (not important for safe control) to 6 (very important for safe control). If it was not required to see the feature, the controller should indicate ‘0’.

The controllers had to indicate at which distance they would detect a feature in good visibility and daylight. Figure 1 summarises the estimates of the seven

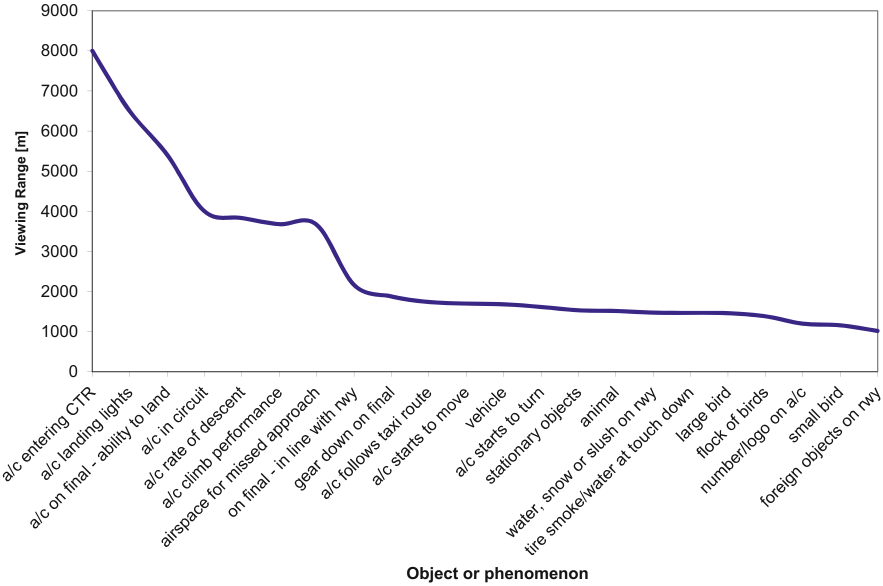

Fig. 1 Viewing range for detection at which tower controllers see objects or phenomena in good visibility and in daylight

controllers. With these distances, it should be considered that tower controllers often use binoculars to better see certain objects or phenomena, but this was not allowed for answering the questions. The middle section of the runway on the airport where these controllers are active is about 700 m away from the tower with the runway thresholds located at about 1100 and 1400 m from the tower. Note that the distances to the runway and to the runway thresholds lead to many responses close to these values. It is clearly important for safety that the runway is free of obstacles, wildlife and birds and that the monitoring of aircraft landing and take-off requires a visibility range of up to 2 km from the tower. The 'plateau' in Fig. 1 at approximately 3800 m distance is explained as a typical value for monitoring of the circuit.

It must be realised that these visual features are not equally important for the tasks of the tower controller. Therefore, it was attempted to impose an order on the list of features in accordance with the importance for the job. Figure 2 depicts the importance to *detect* objects in order to do the job with emphasis on safety, on a scale from 0 to 6.

There was a high level of agreement among the controllers about the most important objects to detect. It should be considered that there is considerable variance in the importance ratings of objects that are on average considered less important, sometimes depending on the way controllers interpret their job. Some controllers indicated that detection of certain objects (such as foreign objects on the runway) is not part of the tower controllers' tasks, but rather that of other airfield personnel, such as those responsible for runway inspection between flights.

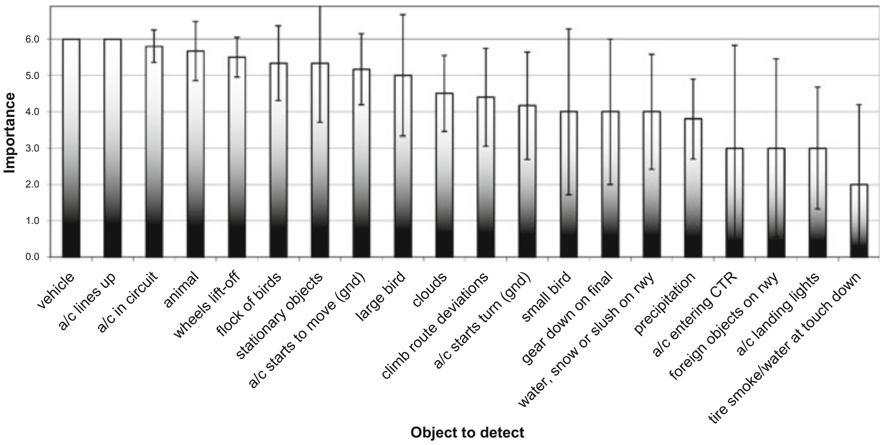

Fig. 2 Rated importance to detect objects (6 is high importance). Standard deviations ($n = 7$) in the rating are indicated

Figure 3 depicts the importance to *recognise* objects in order to do the job, on a scale from 0 to 6.

The five least important objects to detect are:

16. Tyre smoke/water when touching down
30. Aircraft landing lights
13. Foreign objects on the runway
6. Aircraft entering the control zone
31. Precipitation

The five most important objects to detect are:

5. Vehicle on the manoeuvring area (1700 m)
26. Aircraft lining up (1400 m)
8. Aircraft in circuit (4000 m)
4. Animal on the manoeuvring area and runway (1500 m)
21. Aircraft lifts up wheels from runway (1000 m)

The five least important objects to recognise are:

13. Foreign objects on the runway
6. Aircraft entering the control zone
10. Gear down on final
2. Small bird
24. Type of clouds

The three most important features to recognise are:

26. Aircraft lines up on runway (1400 m)
8. Aircraft in circuit (4000 m)
5. Vehicle in the manoeuvring area (1700 m)

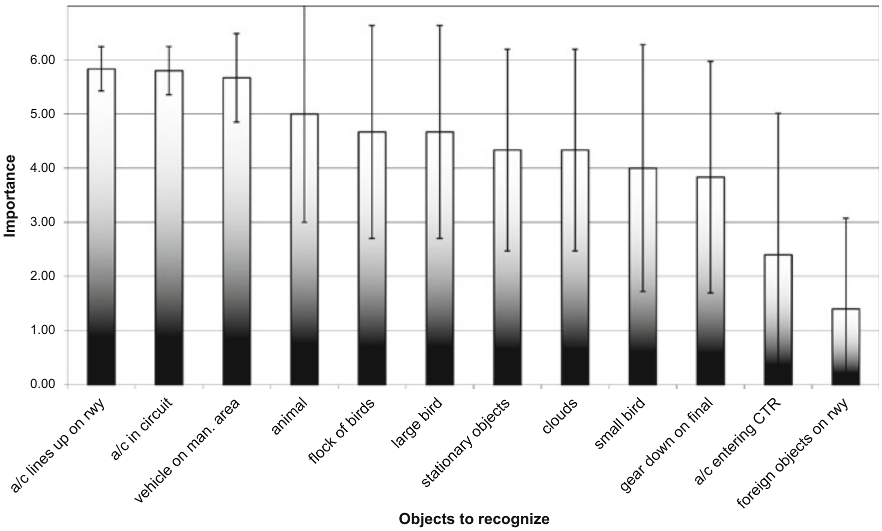

Fig. 3 Rated importance to recognise objects. Standard deviations ($n = 6$) in the rating are indicated

Again, there was a high level of agreement among the controllers about the three most important objects to recognise. It should be noted that recognition of objects requires a higher visual acuity (and imposes higher system requirements for displaying these objects) than detection.

Subsequently, controllers were asked to rate the importance to judge phenomena. The ratings are depicted in Fig. 4.

There is a moderate to good level of agreement among controllers about the importance of phenomena to be judged. The controllers are unanimous in the rating of importance that they must be able to visually judge the availability of (conflict free) airspace in case an aircraft has a missed approach and must make a go-around.

Finally, the controllers were asked to rate the importance of making an identification of an aircraft on the basis of logo or number visible on the skin of the aircraft. This importance was however rated as low.

Controllers were asked how they would rank the safety-related importance of being able to see the features during night. Their answer was unanimous: no feature can be surveyed by visual observation in the dark unless it carries lights. Lights provide a high contrast and resolution against a dark background, making visual observation during night different from daylight conditions. Therefore night operations have not been further analysed in this paper.

The five least important phenomena to *judge* visually are:

26. Aircraft flare
19. Water, snow or slush on the runway
23. Cloud base
11. Aircraft position on final
9. Descent rate of aircraft

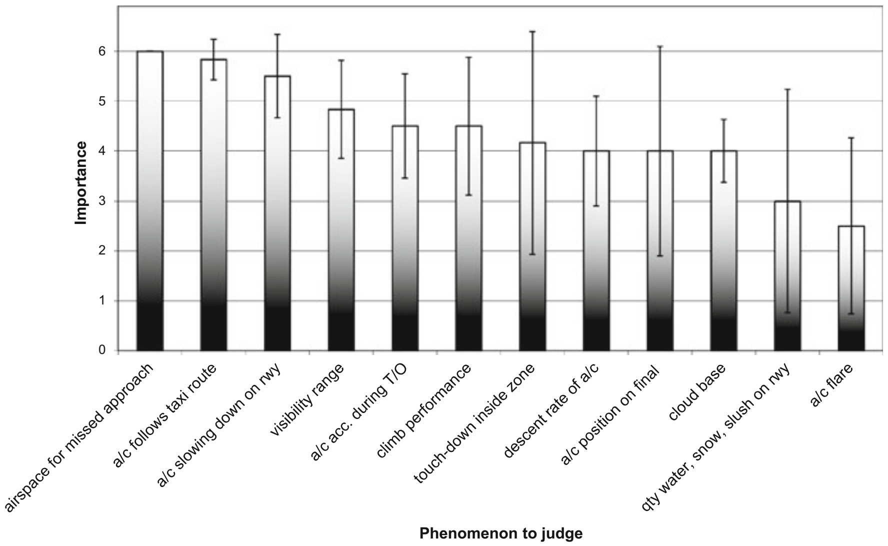

Fig. 4 Rated importance to judge phenomena (6 is high). Standard deviations ($n = 7$) in the rating are indicated

The five most important phenomena to *judge* visually are:

12. Conflict-free airspace that must be available for approaching aircraft in case such an aircraft has a missed approach and must make a go-around (at approx. 3700 m maximum)
18. Whether aircraft follow or deviate from a designated taxi route (at approx. 2300 m)
17. Whether aircraft slow down sufficiently after touchdown (at approx. 1500 m)
25. The visibility (range) from the tower
20. Aircraft acceleration during take-off (at approx. 1000–1500 m)

5 Discussion and Effect on Image Resolution

This study was performed to investigate the features that benefit safety if observed under good visibility conditions during the day. A long-list of features was extracted from a tower controller task analysis. This list was presented to operational controllers in a questionnaire about the importance of these features for safe tower control. The responses to the questionnaire were ordered with respect to importance for the tower controllers' job, distinguishing between features that are important to be detected, to be recognised or to be judged with emphasis on safety. More expensive visual systems would be able to detect the smallest objects at the largest distances and even recognise and assist in judgment, but it would not be cost beneficial. Therefore, we removed the features from the list that are ranked the least important either for detection, recognition or judgment. For daylight these are (2) smaller birds; (6) aircraft entering the control zone; (9) descent rate of aircraft; (10) aircraft gear down; (11) aircraft position on final; (13) foreign objects; (14) aircraft flare; (16) smoke or water spray; (19) water, snow or slush; (23) cloud base; (24) type of clouds; (30) aircraft landing lights; and (31) precipitation. The reasons for controllers to find these features less important are obvious; these features are too small, too remote or not very important at all for safe control of aircraft. Off course, aircraft and vehicle lights are very important for night operations, but this investigation focused on daylight operations in good visibility. The low importance rating for item 27, number or logo, was not expected. This result might stem from the typical traffic at a small airport with well-known users. This feature and result was therefore excluded from further analysis.

The results were translated to image resolution requirements. For the surveillance of objects at large distances, the capability of a display system to make small details visible (i.e. the resolution) is critical. The resolution depends on the camera, the addressable resolution of the graphics processor (expressed in pixels per degree visual angle in horizontal/vertical direction) and the resolution of the display (which in turn depends on such factors as pixel size and video bandwidth).

The size and distance of small objects determine the required limiting resolution of the image system and display. Ideally the limiting resolution of the image system should at least be equivalent to the ATCO's ability to perceive detail. Perception of detail is expressed as visual acuity (i.e. the inverse of the smallest perceptible object angular detail) in arcmin^{-1} (1 arcmin, or minute of arc, equals 1/60°). ATCOs might have a minimum separable acuity between 10 and 40 arcsec^{-1}, when tested in the laboratory (e.g. Boff and Lincoln 1988). However, to set a minimum requirement for the 'noisy' tower environment, we shall assume that the ATCO has a visual acuity of only 1 arcmin^{-1}, which is reached by 85 % of the population. On this basis, we assume a limiting resolution of 60 lines per degree. This would ideally correspond to an 'addressable' resolution (i.e. addressable pixels of the image generator) of 60 pixels per degree. However, to account for the loss of resolution in a system, we should divide the latter addressable resolution by 0.7 (the so-called Kell factor, Padmos and Milders 1992). Hence, dividing the addressable resolution of 60 pixels per degree by 0.7 results in the *required* addressable resolution of 86 pixels per degree.

In this context, only the visual features for detection and recognition are contributing to the requirements. Table 1 is an inventory of remaining visual features that play a role in safe conduct of tower operations. These features are ordered according to importance in Fig. 2 for detection and Fig. 3 for recognition. For each feature, cross-sectional area and typical size were estimated. The distance at which the features are observed comes from the data in Fig. 1.

For features for which a visual judgment is required, the resolution requirements are not specified and would need further investigation. These features are (12) airspace for missed approach/go-around, (15) aircraft touchdown capability,

Table 1 Selected important visual features for visual tower control with their typical dimensions, observing distance from the tower and the consequences for remote projection in pixels per degree both for detection and recognition (daylight conditions, good visibility)

	Important visual feature	Cross section	Characteristic size	Range	Vis. angle	Resolution for detection	Resolution for recognition
No.		(m^2)	(m)	(m)	(arcmin.)	(pixels/deg.)	(pixels/deg.)
1.	Large-size bird	0.50	0.71	1500	1.7	51	289
3.	Flock of smaller-size birds	20.00	4.47	1400	11.1	8	43
4.	Animal	1.00	1.00	1500	2.3	37	210
5.	Vehicle on the manoeuvring area	4.00	2.00	1700	4.1	21	118
7.	Stationary obstacles	1.00	1.00	1500	2.2	38	215
8.	Aircraft in the circuit	6.00	2.45	4000	2.1	41	229
12.	Airspace for missed approach/ go-around	See text		3700	See text		
15.	Aircraft touchdown inside t-down zone	See text		1500	See text		
17.	Aircraft slowing down on runway	See text		1500	See text		
18.	Taxiing aircraft follows designated	See text		1700	See text		
20.	Aircraft acceleration during take-off	See text		1500	See text		
21.	Aircraft wheel lift-off	1.00	1.00	1000	3.4	25	140
22.	Aircraft climb	See text		3700	See text		
25.	Visibility range	See text					
26.	Aircraft lining up on the runway	6.00	2.45	1400	6.0	14	80
27.	Number or logo on skin of aircraft	See text		1200	See text		
28.	Aircraft starts to move	1.00	1.00	1700	2.3	37	210
29.	Aircraft starts to turn	See text		1700	See text		

(17) aircraft slowing down on runway, (18) taxiing aircraft follows designated route, (20) aircraft acceleration during take-off, (22) aircraft climb and (25) visibility range. Feature (29) aircraft starts to turn will probably be preceded by (28) aircraft starts to move and is thus expected to bring similar requirements.

For recognition of objects, we can use the criterion that at least eight image lines overlay a recognisable object. Under optimal conditions in the tower, ATCOs may be able to recognise high-contrast features subtending a visual angle of 2 arcmin. This would mean that we need a limiting resolution of 240 lines per degree (343 pixels per degree). However, taking into account more realistic conditions, Padmos and Milders (1992) propose a more relaxed guideline for the required addressable resolution (in pixels per degree):

0.14 × object distance/object size (expressed in the same unit of length)

Thus, to *recognise* an object with a characteristic size of 1 m at a distance of 600 m requires 84 pixels per degree visual angle. The required visual subtended angles from the controller responses have been translated in the last two columns of Table 1 in to the calculated resolution for detection and recognition using our literature references given above. When traffic is labelled, such that detection and recognition of traffic are facilitated, the requirements listed in Table 1 may be lowered.

The visually most demanding task is to recognise a large bird at 1500 m, which is on the edge of what can be detected and recognised with unassisted eyesight. However, tower controllers will expectedly use binoculars if they detect distant objects or movements, for which an equivalent camera/display system, such a separate pan-tilt-zoom (PTZ) camera, may be used in remote tower operations.

Most of the other features will be viewed with a minimum subtended visual angle of 2–6 min. The resolution required for detection and recognition of a flock of smaller-size birds would need additional investigation, since it will obviously depend on the actual size of each bird and the number and distribution of birds. Typical camera and projection systems provide about 30–40 pixels per degree viewing angle. From the table it can be concluded that resolution is sufficient to provide *detection* of the most important features for visual tower control. For detection of small features, for example, when a steady aircraft start to move (nr. 28), binoculars (zoom camera) and (automatic) tracking would be required. If features have to be recognised, 5–6 times the number of pixels per degree that are needed for detection will be needed. Video image enhancement techniques may be required to achieve resolution and contrast for recognition, therewith providing cost-beneficial solutions to the requirements.

This survey was our first attempt to derive optical requirements for remote tower operations. It is planned to include more air traffic controllers (including military air traffic controllers) in the survey in order to fine-tune the analysis. Further analysis will also address minimum contrast requirements for remote tower control. For the ability to detect objects in a complex scene, contrast sensitivity of the human and hence image contrast in the projected image are at least as important as visual acuity/image resolution (e.g. Streid 2007).

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Part II
Remote Tower Simulation and Remote Tower Center

Remote Tower Simulation Environment

Sebastian Schier

Abstract Remote tower operation (RTO) research faces a lot of challenges. Working processes of the tower controllers need to be revised just as well as working place design and regulations. In accordance to this great bandwidth of design and adaption works, a development and validation platform is of substantial need. Among the validation tools recommended by the European Operational Concept Validation Methodology (E-OCVM), simulations play a crucial role. Within the present chapter, three aspects of simulation experiments are presented and discussed which are specific for RTO research: (1) the different usage of scenarios in fast- and real-time simulation tools, (2) new and specific requirements for RTO simulations, and (3) development of the specific resilient simulation setups for RTO research as driving force, with emphasis on the redesign of human-in-the-loop simulations.

Keywords Simulation • Human-in-the-loop • Remote tower • Air traffic management

1 Introduction

In the first section of the present chapter, the possibilities and the current usage of simulations throughout the procedures of the European Operational Concept Validation Methodology (E-OCVM) are described. Thereby the different usage scenarios for fast- and real-time tools will be shown. Because real-time simulations and their possibilities for bringing the controller into the loop play a major role for remote tower research, the principles of tower human-in-the-loop (HITL) simulations will be explained in detail.

Remote tower operation (RTO) research differs with respect to its solutions significantly from other tower research fields. For instance, research on assistance systems or new ways of communication between the controller and pilot never requests to rearrange or adapt the size and the resolution of the outside view. This

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problem has to be solved when using simulation tools. In the second section of this chapter, these new requirements involved in RTO simulations will be summarized.

The third section will describe the development process at DLR with the goal of resilient simulation setups for remote tower research. Starting with a small console for working place design up to the simulation of a whole remote tower center including multi-airport working positions, a process of more than ten years development will be shown.

As a conclusion in section four, a brief view on advantages and disadvantages of the current simulation methods as well as an outlook into planned expected future developments will be given.

2 Methods and Scenarios

2.1 Method Selection

Starting the research on remote tower, the main objective was to determine whether tower and ground controllers are able to work in an arbitrary distance from their airport, without the conventional direct view out of windows, i.e., without the physical control tower. Primarily, this is a matter of feasibility because in the beginning it was not clear if remote tower operation would be possible at all. The limiting factor within this feasibility subject is the human operator. If some of the information provided in a conventional tower is not available (e.g., acoustic emissions from the airfield) or available only with reduced quality (e.g., video image versus real out-of-windows view), it has to be analyzed if the error probability of the operator's decision-making increases under RTO conditions.

Selecting the appropriate methods for the remote tower validation, the European standard of air traffic system validation E-OCVM [cf. (EUROCONTROL 2010)] needs to be considered. E-OCVM defines a process model from the initial idea to the final operational system. Within this model, the stage V2 addresses feasibility questions (cf. Fig. 1). Eurocontrol suggests to take a case-based approach on this V2 stage including the human performance case. For this human performance case, the tools gaming, fast-time simulations, real-time simulations, and shadow-mode and live trials are suggested.

Gaming can be eliminated for remote tower research from the suggested methods. As defined in the E-OCVM, gaming focuses on interaction between different parties which is clearly not the major challenge of remote tower.

Fast-time simulations (FTS) offer ideal conditions to run numerous scenarios and thereby determine effects. But for human performance issues, FTS design is challenging. As human operators can only work in real time, their behavior needs to be modeled compatible to fast time. These models can only be as precise as the knowledge about the human performance in the examined case. Because simulations were performed in the initial phase of remote tower research, models were

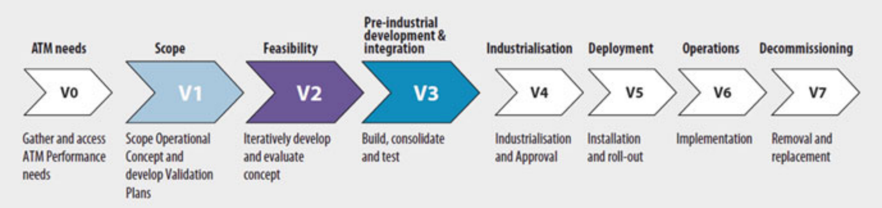

Fig. 1 E-OCVM lifecycle model [(EUROCONTROL 2010), p. 16]

expected to be only rough approximations of reality. Of course this is the usual case in the early development phase of any advanced human–machine systems.

Real-time simulation (RTS) is in fact an imprecise term. E-OCVM defines: “Real-time simulation techniques are important in providing human-in-the-loop experience of a proposed concept” [cf. (EUROCONTROL 2010), p. 49]. In this understanding, human-in-the-loop (HITL) simulation is the adequate term as this is a hyponym of RTS. HITL simulations are not in need of an abstract model, but put the human into the loop, so that human performance issues can be examined in detail. For feasibility assessment on remote tower operations, this is expected to deliver reliable results.

Shadow-mode and live trials do also own the advantage of including real human performance. Nevertheless the given scenario is not under full control of the experimenter. Human performance can only be observed during situations that happen to occur at the moment of observation. Generating specific conditions and examining those are possible only with very specific effort and usually involve much higher cost than simulations. In any case shadow-mode/live trials may not show all effects and challenges of remote tower, and it is very difficult—often impossible—to design repeatable experimental conditions in order to generate statistical significance of the results. Nevertheless, for the RTO system also, live experiments and shadow-mode trials were realized with a test aircraft under operational conditions in order to quantify the performance of the near prototype system (see chapters “Remote Tower Experimental System with Augmented Vision Videopanorama” and “Remote Tower Prototype System and Automation Perspectives”).

In conclusion, it follows that HITL simulations are the most adequate tool for initially determining the effects and challenges of remote tower operations. Nevertheless HITL simulations do own several disadvantages which request an elaborate scenario retrieval process in advance of the HITL simulations. The difficulties and the defined process will be shown within the following section.

2.2 Scenario Retrieval

HITL simulations are an optimal tool to assess human performance in new work environments. This advantage includes the fact that all experiments have to run in real time. It follows that in comparison with fast-time simulations, the possibility is limited to examine a large variety of different scenarios. Consequently HITL simulations are generally used to validate a certain known effect, rather than searching for unknown effects. Because for remote tower operations, many human factor-related effects of the new work environment were unknown at the beginning of the research, and an appropriate scenario retrieval process had to be determined.

Regarding this problem, E-OCVM suggests to use fast-time simulations:

> They [FTS] are best used to test the sensitivity of a proposed concept to different assumptions and scenarios. [source (EUROCONTROL 2010), p. 49]

But as stated above, FTS is in need of a sufficient human performance model to examine remote tower scenarios. Sophisticated simulation environments for human performance models are available [e.g., (Fowles-Winkler 2003)] based on Wickens' multiple resources model (Wickens and Hollands 2000) and the human information processing/time pressure theory (Hendy et al. 1997), and initial tests were performed (Mahmoudzadeh Vaziri and Fürstenau 2014). However, the usage of this kind of performance modeling within FTS requires a coupling between the environment and process simulation on the one hand and the specific human performance simulator on the other which is a development task in its own. Moreover, for obtaining absolute workload data based on this kind of sophisticated models and combined simulation, a separate validation of the performance tool for each specific scenario is required. This requirement would be somewhat relaxed when the focus is on relative comparison between different versions of a specific work environment or HMI.

Facing this challenge, the following process was defined for the RTO/RTC simulations which combines the advantages of FTS and HITL simulations [cf. (Schier et al. 2011)]:

1. A rough remote controller model is implemented in FTS.
2. Numerous scenarios are analyzed by FTS.
3. Scenarios with interesting effects are selected and brought into HITL simulation.
4. HITL simulation analyzes the interesting scenarios in detail and by real human performance.

Additional to this four-step scheme, a fifth step was optionally defined, integrating results of HITL simulation into the rough remote controller model of FTS, improving it for upcoming validations.

For the RTO center scenario retrieval, this process was started by defining a rough controller model [cf. (Walther 2010)]. The model was based on the assumption that tower controllers' performance is limited to the fact that one command per time can be given. As such controlling two airports remotely includes the possibility that upon parallel events on both airports, one event is delayed. This happens, for instance, if aircrafts want to take off on both airports at the same time (cf. Fig. 2). The controller is only able to give one takeoff clearance at a time instant. Following this constraint, one takeoff needs to be delayed.

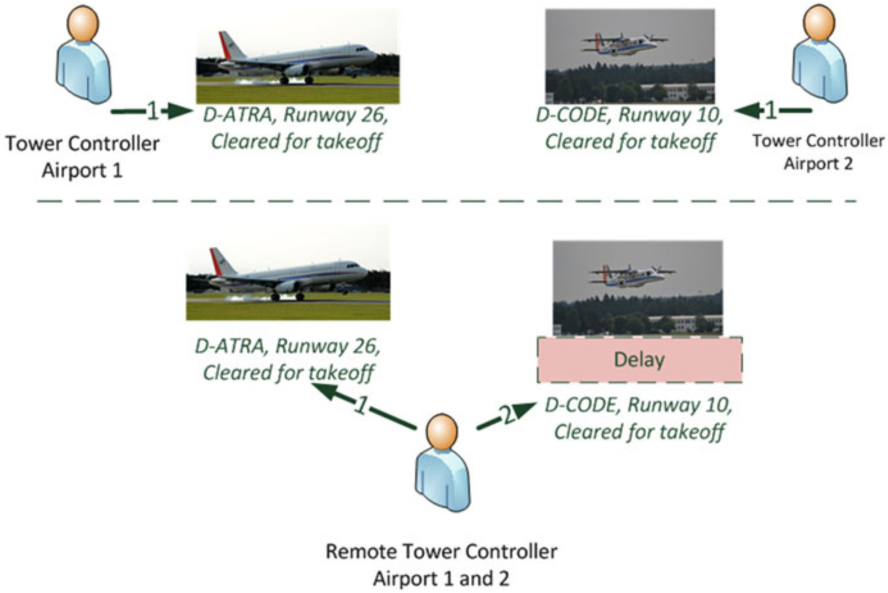

Fig. 2 Challenges of parallel events in remote tower operations

Situations like these could be determined within numerous fast-time simulation runs using the rough controller model that implements only the radio communication behavior. Retrieving those situations, a defined process was initiated to model exactly the same situations in a HITL simulation (cf. Fig. 3). In this way high-fidelity situation remodeling in HITL simulations should be achieved.

One metric for quantifying the quality of scenarios within HITL is the accuracy by which traffic events are modeled. In the environment of tower simulations, traffic events are defined as clearly identifiable actions of an aircraft (e.g., landing, takeoff, etc.). The accuracy refers to their occurrence in time. As such, the above shown modeling process could be evaluated by the time difference between modeled event occurrence in the fast-time simulation and actual ones in HITL simulations. Two specific RTO-HTIL simulations which were performed according to the abovementioned procedure are described in the following sections "Case Study: RAiCe1" and "Case Study: RAiCe 2." These experiments were analyzed with regard to the timing precision of the events. As a result it was determined that 123 of the defined events took place within a time precision of 60 s which was defined as the acceptable threshold (cf. Fig. 4). With about three events per scenario [cf. (Schier et al. 2011)], this was accepted as sufficient for the conducted 38 HITL trials.

Following the HITL simulations, first findings (e.g., radio communication times for different clearances) were transferred back to the FTS controller model. By this process the FTS quality could be improved for further scenario retrievals.

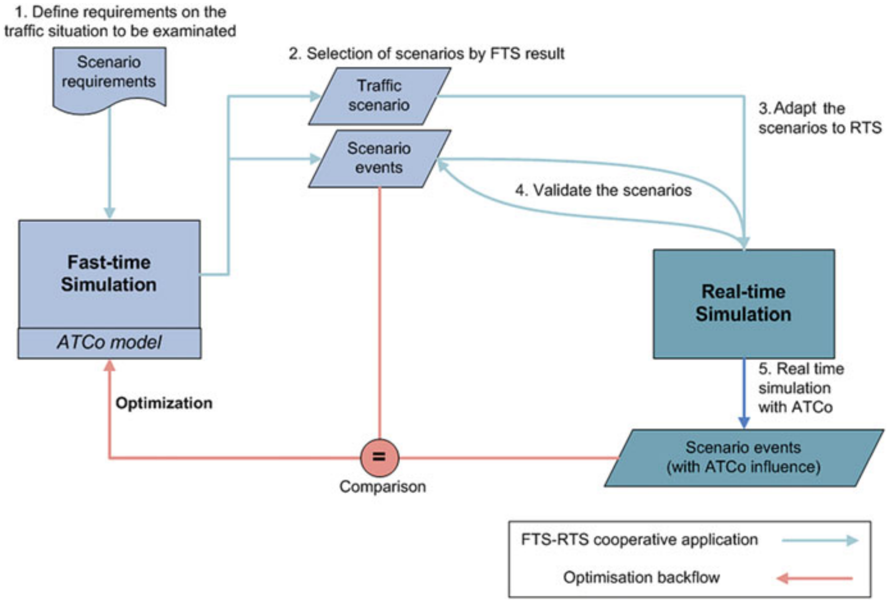

Fig. 3 Scenario definition process [cf. (Schier et al. 2011)]

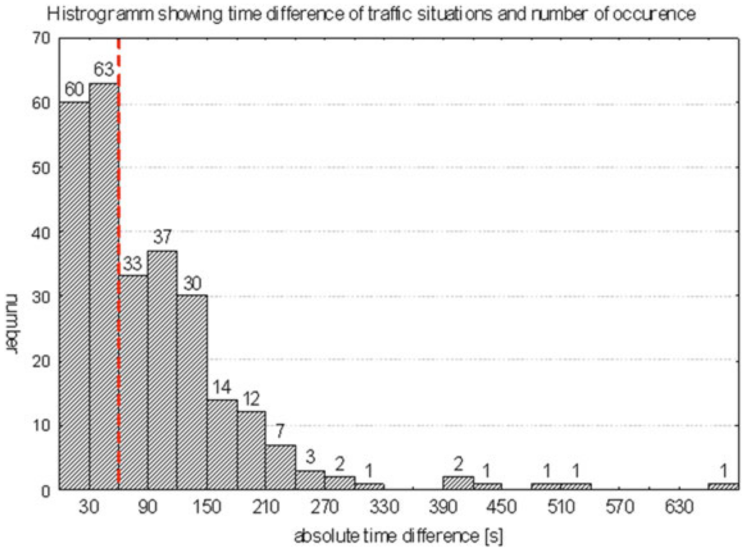

Fig. 4 Histogram showing time difference of traffic situations and number of occurrences [see (Schier et al. 2011)]

3 Initial HITL Simulation Design

3.1 Case Study: RAiCe1

Simulation based research on remote tower, taking humans into the loop was initiated by a DLR project called RAiCe (Remote Airport Traffic Control Center, campaign name RAiCe1 [cf. (Fürstenau 2011)]). The general objective of the RAiCe1 simulation experiment was to examine the differences between work under remote tower conditions and work under normal tower conditions. Twelve air traffic controllers were invited for this purpose.

The simulation setup for this campaign relied on two work environments (cf. Fig. 5). One of these was the Apron and Tower Simulator at the DLR Institute of Flight Guidance. For the experiment a 200° projection system including simulation software and multiple working positions was available for validation trials. The second work environment was a remote tower console and HMI, designed by the RTO team within the first RTO project Remote Airport Tower Operation Research [RAPTOR, cf. (Schmidt et al. 2007)]. This console consisted of a desk with integrated screens (e.g., for flight strips, camera control, radar, etc.) and a back projection system for the simulated remote out-of-windows view. A special software interface simulated a live camera input so that the standard live video panorama software could be used for the output of the simulators image generator output. The panorama system in this way can easily be switched into the alternate live camera mode.

The data analysis of the successfully conducted simulations revealed some of the major challenges for remote tower control. Moreover it was found that the simulation setup employed for the experiments had potential for some optimizations:

1. *360° projection*: Due to the limited panorama viewing angle of 200°, effects of traffic pattern observation in the back of the controller could not be analyzed. In consequence a 360° projection system should be available for further simulations.

Fig. 5 RAiCe1 setup: remote tower console (*left*) and 200° projection system (*right*)

2. *Console integration*: The console was an inflexible wooden design which was adapted for a single screen size and specific systems. In consequence integrating tower tools like flight strips and approach radar was a challenging and time-consuming task.
3. *Remote tower video panorama*: The video panorama was provided by a back projection system consisting of five UHD projectors. This system was not adaptable to any changes of the working position or any requests for other projection size and resolution.

These simulator design deficits were taken into account later on when the Apron and Tower Simulator underwent a major redesign (cf. Sect. 4).

3.2 Case Study: RAiCe 2

As a follow-up of the first simulation study (RAiCe1), the second one (RAiCe2) focused on the effects of so-called multi-remote tower (MRT) or RTO center (RTC) conditions [cf. (Moehlenbrink et al. 2010)]. Specifically, the simulation experiment addressed the question of how two controllers would organize their work under simultaneous control of two airports. Starting with the assumptions that two controllers are available and two airports are RTC controlled, several distributions of this work are possible. For instance, each controller can control one airport, or one controller takes the role of the coordinator[1] and one controller the role of the executive controller for both airports in parallel.

For this setup again a mockup console was used (cf. Fig. 6). This wooden-shaped console was equipped with two rows of five displays each for simulating the outside view of two airports. Additional approach radar, weather information, and paper-based flight strips were integrated. The simulations were driven by two different software applications due to a change of the simulation engine. The first airport (Braunschweig—EDVE) was available in an earlier software version [UFA's Towsim [cf. Sood et al. 2015)]. The second airport (Erfurt—EDDE) was modeled with the new Narsim engine [cf. (Have 1993)] which was dedicated to become the new simulation software.

The simulation experiments were successfully conducted with twelve air traffic controllers working in six teams. Two major conclusions were drawn from this experiment:

1. *Console integration:* The wooden design impeded the integration process of the numerous tower tools and utilities. Screen sizes could not be adapted, and only very limited space for the flight strips was available. Due to the fixed shape of the console, extensions were not possible.

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[1] Coordinator: In air traffic control, controllers are sometimes supported by a so-called coordinator. This role includes organizing the flight strips and taking phone calls to coordinate with airport and approach control.

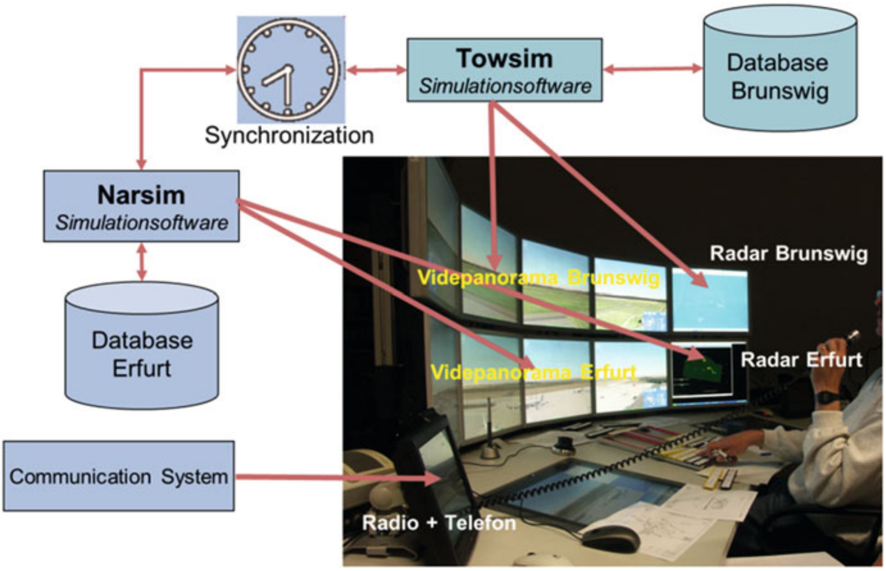

Fig. 6 RAiCe2 setup: remote tower console for Braunschweig and Erfurt

2. *Synchronization*: Synchronization of the simulations and their recording appeared as a major issue. Analyzing parallel events and special situations, voice, and aircraft data had to fit together with an accuracy of a second.

Again these findings were taken into account for a redesign of the simulation facilities as described in the following section.

4 RTO Simulation Requirements and HITL Simulation Redesign

4.1 ATS360 and TowerLab

In 2010 a major redesign of the air traffic simulation facilities was started. The reason was on the one hand outdated technology and software. On the other hand, requirements for the HITL simulation had changed [cf. (Schier et al. 2013)]. As such also the experiences made in the RAiCe1 and RAiCe2 experiments were taken into account.

The redesign process was preceded by a major requirements analysis. Not only former simulation campaigns, but also the design of other simulation facilities and future project demand was analyzed. Summarizing the results of this requirement analysis, it became clear that two major trends could be found for tower HITL simulation. One trend leads to a most realistic environment with the objective of

Fig. 7 ATS360: the new close-to-reality Apron and Tower Simulator of DLR

optimizing the current controller working position. This trend includes, for instance, the above-stated demand for a 360° projection system requested by RAiCe1. The second trend aims at a most flexible environment suitable for the design of futuristic working positions. Several findings within the RAiCe2 experiment supported this trend [cf. (Schier et al. 2013)].

A final conclusion was drawn that both trends could not be satisfied by one single facility. Consequently a new 360° system was realized (ATS360) offering maximum realism with regard to the simulated environment and scenarios (cf. Fig. 7). The ATS360 includes a 360° high-resolution projection system and mockups of operational systems such as the DFS electronic flight strip system (Tower Flight Data Processing System—TFDPS) and the weather and information system (information data handling system—IDVS).

Additionally a very flexible facility called TowerLab was designed (cf. Fig. 8). To provide an adaptable outside view system, allowing for modifications with regard to size, resolution, and alignment, a loose connection of monitors was constructed. This construction can be changed within minutes if other setups are needed. Additionally a generic console called MoToKo (modular tower console) was constructed. This console tried to encounter all of the experiences made with the remote tower consoles. Fixed display cutouts predetermining the screen size were avoided. The console is extensible and adaptable by a standard construction kit and allows for easy movement to other positions.

TowerLab and ATS360 were used within numerous simulation experiments, from research on advanced surface management systems [cf. (Carstengerdes et al. 2013)] to analysis of tower controller visual sequences. In the following sections, the application within three more remote tower studies will be described.

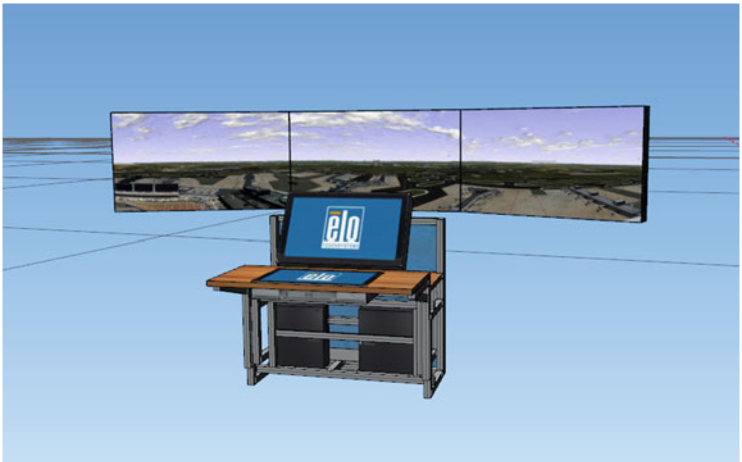

Fig. 8 TowerLab: design drawing of MoToKo with outside view system

4.2 *Remote Tower Human Factors Study*

The "Remote Tower Human Factors Study" (RTC-HFS) as a contract research for the Deutsche Flugsicherung GmbH (DFS) was the initial use of the new TowerLab design. The goal was to analyze task load limits of controllers in remote tower controller working position (CWP) [cf. (Papenfuß et al. 2012)].

To a large extent, the simulation design was driven by requirements defined by DFS for remote tower CWPs. As such a specific screen size and resolution had to be provided for the simulated out-of-windows view. Additionally DFS lookalike controller tools were requested. The flexible TowerLab infrastructure including the display wall was adapted to these needs. A MoToKo console was configured according to the requirements of DFS CWP, including TFDPS mockup (the DFS flight strip system), DFS weather display, and approach radar (cf. Fig. 9).

Six air traffic controllers took part within this successful first TowerLab simulation campaign [cf. (Papenfuß et al. 2012; Moehlenbrink and Papenfuss 2014)]. Besides primary data collection, feedback of the air traffic controller was again requested in the simulation. Specific improvements of the hardware setup were not requested. The TowerLab design was accepted and additionally proved its advantages by the very short construction and adaption phase. The comments provided by the domain experts primarily focused on the software:

1. *Synchronization*: Further improvement of data synchronization between simulation engine and all connected systems (e.g., flight strip and radio emulation system) appeared desirable.
2. *Helicopter model*: the situations displayed within this campaign included several helicopter missions. The used model was a very rough one adapting fixed wing

Fig. 9 RTC-HFS: remote tower controller working position (CWP) design

models. For further campaigns it was suggested to implement an improved helicopter model.

The integration of these optimizations was initiated for the following simulation campaigns.

4.3 Remote Tower Center (RTC) Study

As the second part of the RTC human factors study, an investigation in the remote tower center concept was performed. This campaign focused on the possibility to set up a center for controlling multiple airports remotely from a single location. Within this center it is possible for the controllers to work one shift at one airport and change to another airport on the next shift. It was the goal to investigate constraints and challenges of these airport changes [cf. (Moehlenbrink and Papenfuss 2014)].

The simulation design made use of the experiences gained in the first RTC-HFS campaign and multiplied the designed working positions for three airports (Dresden, EDDC; Erfurt, EDDE; and Braunschweig, EDVE) as shown in Fig. 10. Additionally a CWP for a ground coordinator was constructed. He/she is in charge of coordinating startup and air route clearances as well as initiating flight plan for flights following visual flight rules.[2] In contrast to the executive controllers, he/she

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[2] In contrast to flights following instrumental flight rules, flights following visual flight rules do not need to post a flight plan before initiating the flight. As a consequence this leads to the task that air traffic control has to record and write all relevant flight information upon initial call of the aircraft.

Fig. 10 Remote tower center (RTC) design for controlling three airports from afar. Foreground, ground coordinator; back, three airport CWPs for executive controllers

was not in need of an outside view, but advanced flight plan systems and communication devices had to be provided.

The simulations were successfully conducted with 12 air traffic controllers shifting through the different working positions. Collected comments of the controllers and the ATM experts showed significant improvement on the data synchronization requested within the remote tower human factors campaign. Again the missing helicopter model was addressed.

4.4 Multi-remote Tower Study

The latest RTC simulation campaign was conducted within the European SESAR (Single European Sky ATM Research) framework. Again in a DFS–DLR cooperation, the multi-remote tower (RTC) concept was addressed. Air traffic controllers were given a high amount of traffic at a single remote tower working position, observing one airport. The results of this condition were compared with a multi-remote tower condition. This means that scenarios with the same amount of traffic were applied to two airports to be controlled by the operator in parallel [cf. (Moehlenbrink and Papenfuss 2014)].

The simulation design combined the experiences made in RAiCe2 with multi-remote tower working positions and the latest results of the remote tower center study (cf. Fig. 11). The single working position was slightly improved as compared to the center study by an advanced camera control and weather display. The multi-remote tower CWP was built on the same basis, but encountered several additional challenges. Especially the requirement to not have displays of radar or flight strips within the line of sight to the outside view had to be solved by the construction process. The simulated out-of-windows view in this case was based on the latest

Fig. 11 Multi-remote tower setup (*left*, single working position; *right*, multi-remote working position)

videopanorama prototype version (using HD technology, see chapter "Remote Tower Prototype System and Automation Perspectives").

A final design for the multi-remote tower console was retrieved, and the simulation with 20 controllers was successfully finished. The synchronization process between simulation, voice system, flight strips, and eye-tracking system could be established.

5 Conclusion and Outlook

In ten years of remote tower research including extensive validation efforts, human-in-the-loop simulations have proven their potential to gain substantial knowledge about future remote tower processes and to support the design of advanced air traffic control technology. Nevertheless it was shown that the role of a major validation tool could only be achieved by elaborate adaption and evolution of the facilities as well as the corresponding processes.

For further development and usage of the HITL facilities in validation trials, this development and adaptation process needs to be continued. As such, the DLR simulation staff focuses on three major topics to further support remote tower research:

1. *Integration of head- and eye-tracking systems*: Within all remote tower trials, the investigation of visual attention of the controllers was a major focus of research. Taking this into account, the head- and eye-tracking systems will be permanently integrated into the simulator and connected to the central data recording

system. Moreover head-/eye-tracking systems will be integrated in a way that a usage for operational systems might also be possible. Offering a real-time interface, warning and caution systems, as well as additional system functionalities can be integrated into the remote tower working position [cf. (Manske and Schier 2015)].

2. *Adaption of the visualization system:* Until now, the requirements for tower simulation projection system followed the simple recipe that higher resolution leads to a better projection system. In terms of remote tower, this paradigm is no more valid, as cameras deliver pictures with limited resolution and certain configurations for the field of view. DLR will encounter these possibilities within their simulation design and enable remote tower simulation facilities to be adapted to the camera performance parameters. In consequence valid statements about air traffic controller performance under certain remote tower system configurations can be given.
3. *Future Visualization Systems:* Current tower control as well as tower simulations consider the real view on the airport as state of the art. With remote tower this state of the art seems to change to a more artificial view or synthetic vision. For future development this could lead to a trend showing the air traffic controllers completely synthetic views within a virtual reality environment. As these technologies will be a matter for validation again, DLR prepares its simulators to also show virtual reality data. Therefore, initial technical tests and research work have been carried out to connect the flight dynamics simulation to so-called virtual labs showing 3D computer-generated environments as depicted in Figs. 12 and 13.

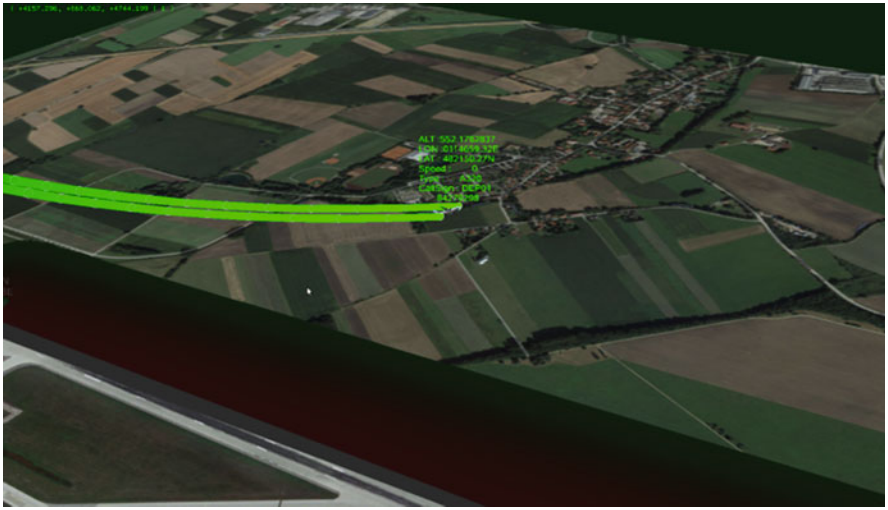

Fig. 12 DLR flight dynamic simulation in a virtual environment

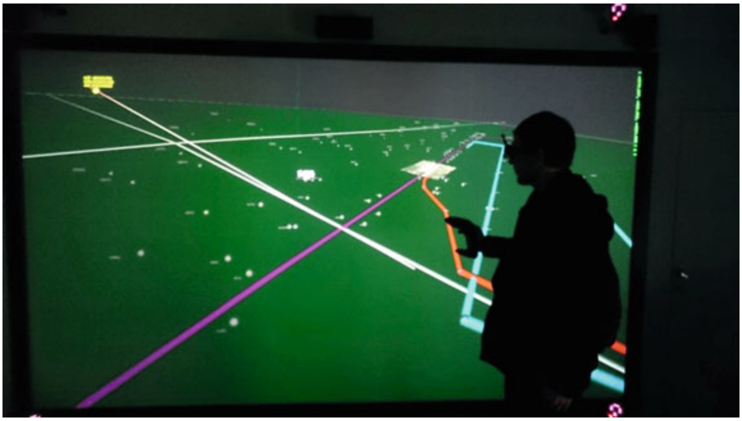

Fig. 13 Controller interaction tests in DLR's virtual reality lab

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Assessing Operational Validity of Remote Tower Control in High-Fidelity Simulation

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Abstract In this chapter, results from simulation studies are presented which were conducted to assess the operational validity of the remote tower concept at a very early maturity level. The goal was to gain empirical evidence to lead further developmental activities and to learn about the critical design issues and human factors of the remote tower control concept. A high-fidelity simulation study with 12 tower controllers was conducted to assess the operational validity of an experimental workplace for remote tower control. The core of this workplace is a panoramic display, presenting high resolution video data of the remotely controlled airport. Besides the feasibility of the concept, the study addressed the relevance of the view outside the tower window and the benefit of information augmentation. Eye tracking, questionnaire, and interview data were gathered. Results indicate that the concept is valid for control of smaller airports with little air traffic. The augmentation of callsigns onto the video panorama reduced head-down times for the radar display.

Keywords Human factors • Validation exercise • Feasibility • Eye tracking • Information augmentation

1 Introduction

1.1 Motivation

Remote control of smaller airports with little traffic is a concept for future air traffic control. It has the potential to reduce the costs of providing air traffic control to these airports. However, the concept implicates significant changes regarding the controllers'[1] work environment, as the controller shall move from the tower to

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[1] In this chapter, the term controller refers to both male and female operators. For ease of reading, the male personal pronoun will be used.

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another location, up to hundreds of kilometres away. One key challenge is the substitution of the view out of the tower window (far view). Yet, controllers can be assisted by replacing the far view with a panoramic video transmission which further allows for novel automated support (Fürstenau et al. 2008; van Schaik et al. 2010).

One objective within this context of developing a replacement of the far view relates to "what" information in general, and specifically of the far view, an air traffic controller uses, in order to guarantee safe operations on the (remotely controlled) airport. Until now, there is no conclusive evidence which information tower controllers specifically use from the view outside to control air traffic and which information is not used. Nevertheless, for smaller airfields with little sensor technology, the view outside certainly is the most comprehensive source of visual information. From the human factors perspective, it is of interest to understand, in how far the substitution of the far view causes changes on the tower controllers' working methods.

For this reason, operational validity of this novel concept means that the controller sees everything he needs to. The function of and the information derived by the far view, therefore, is a central topic in this study. In addition, another focus is set on the examination of the utility of controller assistance at the remote working position through information superimposition and a zoom camera with a semi-automatic tracking function. A high-fidelity simulation set-up was chosen to represent the essential changes for the work environment and to assess its impact on air traffic control operations (see also previous chapter "Remote Tower Simulation Environment").

1.2 Related Work

From 2002 to 2004, the concept study "Virtual Tower" was conducted at German Aerospace Center (DLR) that initialised research concerned with remote control of small airports (Fürstenau et al. 2004a). Within the project RApTOr (Remote Airport Tower Operation research), first steps of the idea were realised, and an experimental remote tower operation controller working position (RTO-CWP) was developed (Fürstenau et al. 2008; Schmidt et al. 2007). Based on a task analysis, it was concluded that the far view is a crucial information source. Nevertheless, there is still discussion going on, what information from the outside view controllers really use for their decisions and what information is not relevant. Therefore, the core of the RTO-CWP is a reconstruction of the far view by means of a live stream of high resolution videos and an additional zoom camera. For demonstration and evaluation of the technical concept, an experimental system was set up at the research airport of Braunschweig-Wolfsburg (EDVE). For a more detailed technical description of the camera system and the configuration of the RTO-CWP, see the references mentioned above and chapters "Remote Tower Experimental System with Augmented Vision Videopanorama", "Remote Tower Prototype System and

Fig. 1 The experimental workplace for remote tower operations (RTO-CWP) [1] integrated within the infrastructure of the conventional tower simulator [2] (IEEE copyright)

Automation Perspectives" of the present book. The experimental RTO-CWP is depicted in Fig. 1.

In a preliminary simulation study, this experimental work place was tested with two controllers from the research airport Braunschweig-Wolfsburg; the airport also chosen for the simulation study. The study was concerned with questions regarding the feasibility of this novel concept in general and specifically with the usability of the workplace and its novel assistance functionalities (Möhlenbrink et al. 2010). Results of this study were promising with regard to the controllers' acceptance of this approach to remotely controlling air traffic, as well as operational feasibility of the workplace. The gaze behaviour of the controllers was recorded during the simulations in order to describe the information search process of tower controllers in an objective way. There was a clear influence of the working position on the gaze behaviour. Due to the small sample size, questions regarding the influence of the information augmentation could not be answered.

1.3 Aerodrome Control Work Environment

The tower controller is responsible for safety of operations within the aerodrome. The most fundamental tasks are the control and surveillance of traffic on the runway, taxiways, and park areas as well as the surveillance and coordination of the whole aerodrome. Usually, at regional airports, an executive controller (EX) and a coordinator (CO) work together in a team to control the aerodrome. The executive controller is in contact with the pilots via radio, while the coordinator is more concerned with coordinating the arriving and departing traffic with other sectors and assisting the tower controller with the documentation on the flight strips. Both controllers share the responsibility for the safety of the operations.

Nevertheless, the executive is the team leader and makes the final decision about the sequence of aircraft. In comparison to other air traffic control working positions, tower controllers do permanently have to react upon changes in the environment (Dittmann et al. 2000). Therefore, they mentally have to integrate a variety of different information and cues, which enables them to take proactive actions (Tavanti and Bourgois 2006). The direct view on the airport is the most specific visual information source for aerodrome control, in contrast to the en route controller. Additional visual information sources are flight strips, radar, and a weather display. Additionally, the controller is using radio for communication with the pilots, ground radio, and telephone. There are further information sources, especially assistance systems, which are not available at all airports (Papenfuß and Möhlenbrink 2009).

1.4 Characteristics of Regional Airports and Consequences for Air Traffic Control

In general, regional airports do not possess a wide range of sensor technology due to the high costs of these systems. Approach radar information is provided that covers the aerodrome traffic but not traffic on the ground. The traffic at a regional airport typically is a mix between flights operating under conditions of Visual Flight Rules (VFR) and Instrumental Flight Rules (IFR), with a high percentage of VFR traffic. Even though these rules refer to different meteorological conditions, they also characterise features of the pilots. IFR traffic is mainly operated by commercial airline pilots. In contrast, flights operating under VFR conditions are mainly flown by private pilots and pilot trainees. Whilst IFR traffic is relatively predictable as a flight plan is scheduled hours in advance, VFR traffic does not require a prior flight plan. Therefore, its occurrence is rather unpredictable for the air traffic controller.

These boundary conditions implicate several consequences for air traffic control at regional airports. The VFR traffic cannot be anticipated like IFR traffic and demands flexible reaction of the controllers. The fact that pilots of VFR traffic are usually less experienced has influences on the air traffic control service. It is likely that there are more deviations from the standardised controller–pilot radio communication, and there is less confidence that the pilots follow the commands from the tower correctly. Thus, the control of the mixed traffic is one contributor to mental workload (Vogt et al. 2006) as the controller has to pay more attention to some traffic situations and has to cross-check the actions of pilots more closely, compared to IFR traffic only.

1.5 Controller Assistance via Information Superimposition and Automatic Zoom Camera Tracking

The replacement of the outside view by a live video offers new possibilities for controller assistance that could compensate for the missing sensor equipment of regional airports. The live video can be used for automated information extraction and information augmentation. Motion detection algorithms can detect moving objects like aircraft (AC), vehicles, or bird swarms. This information can be used for assistance like highlighting these objects on the panorama, to use this object data for the control of the zoom camera (automatic tracking), or to use the data for further data procession, e.g. fusing radar position and video image position of AC for conformance checking. Furthermore, information gained through data fusion of other sensors can directly be superimposed onto the outside view of the tower controller. It is assumed that in the future also, at regional airports, the means are provided to get position and identifier data (callsigns) from all aircraft. Data of a multi-lateration system or ADS-B sensors can directly be superimposed at the respective position on the video panorama (Fürstenau et al. 2008). Thus, information presented to the controller in the conventional workplace separately on his radar display and the flight strips will be integrated into the outside view of the RTO-CWP.

1.6 Research Questions

In order to evaluate the concept of providing remote tower services via a controller working position with a video panorama (in the following called “RTO-CWP”), three different research questions were addressed in the study. (1) In how far are the RTO-CWP and the solution for replacing the far view (video panorama) suitable for a team of air traffic controllers in order to control air traffic at a regional airport. Where are the limitations of the concept? How is the workplace rated by controllers regarding acceptance and usability?

As pointed out above, the far view is a crucial part of aerodrome control. Therefore, besides the new work environment, a second research question deals with (2) the relevance of the far view and what information the controller uses from this information source. As the concept of a video panorama allows for novel assistance functions, the study investigates a third research question (3) in how far the superimposition of different information provides a benefit for the controllers.

2 Method

2.1 Subjects

Twelve tower controllers from six German airports participated in the high-fidelity simulation study. The sample was rather heterogeneous regarding age (Range: 24–59 years, mean $M = 39$, standard deviation $\mathrm{SD} = 12$) and job experience as tower controller (Range: 2–37 years, $M = 17$, $\mathrm{SD} = 11$). All controllers were used to work with simulated traffic on high-fidelity simulators because it is part of their education and training as a tower controller.

2.2 Experimental Design

A 2×3 factorial experimental design was tested with the within-subject factors weather (good visibility, low visibility) and work place variant (conventional tower simulation baseline TO-BL, RTO-CWP baseline RC-BL, RTO-CWP, and information augmentation RC-MD, RC-CA). After a series of three simulation runs for each team of two controllers, roles (executive, coordinator) and weather condition changed, resulting in three runs per team constellation. Weather condition and work place variant were varied between the groups in order to control learning effects regarding the use of the new workplace.

2.3 Simulation Setting

The RTO-CWP was integrated into the high-fidelity simulation environment at DLR in Braunschweig and equipped with all necessary displays and HMI in order to represent a quasi-operational workplace. The simulated airport was Braunschweig-Wolfsburg. For the tower simulator, a 4-projector front projection (each 768×1024 pixel) on a 200° spherical surface was used, imitating the view out of the window without reduction of visual angles and proportions (life-size). The RTO-CWP was equipped with a 4-projector rear projection system ($30''$ diagonal, 1050×1400 pixel resolution) that realised the 180° panorama of the corresponding four simulated cameras within a reduced operator viewing angle of ca. 125°. Due to the smaller distance of the projector to the rear projection and the better quality of the devices, the video on the RTO-CWP was brighter, had a higher contrast, saturation, and acuity in comparison to the tower simulator. The simulation set-up of both, the tower and RTO simulation, comprises an operator's position for executive and coordinator, as well as working positions for two pseudo pilots and a supervisor.

2.4 Experimental Task

The controller team had to manage air traffic in 30-min simulation runs at the airport Braunschweig-Wolfsburg according to published legal guidelines from the DFS. They divided their tasks into executive and coordinator. The traffic scenarios were designed with the same demand (12 AC in 30 min) and overall traffic mix of 60 % VFR traffic. In order to reduce learning effects, the callsigns of the AC differed between the simulation runs. This traffic rate of 24 AC/h had to be chosen significantly higher than usually expected for the small low-traffic airports in order to understand to create challenging situations for the controllers to understand, in how far the remote tower concept influences the working methods of the controllers and if there are limitations to the concept.

2.5 Experimental Conditions

As a methodological approach for validation of the novel work environment, working in a common 200°-tower simulator is compared with working at the RTO-CWP. In the human-in-the-loop simulations, four different conditions of the workplace were realised.

1. *Tower Simulator Baseline (TS-BL)*
   In this condition, controller teams worked on the conventional high-fidelity airport tower simulator with life-size 200° projection of the outside view. This condition was instructed as working in a real tower at the airport Braunschweig-Wolfsburg.
2. *RTO-CWP Baseline (RC-BL)*
   Controller teams were working at the new experimental workplace RTO-CWP with video panorama and zoom camera. This experimental condition served as a baseline to compare working in the conventional tower simulator with working at the RTO-CWP. Compared to the TS-BL, this working environment was introduced as being 200 km away of the airport.
3. *RTO-CWP and Movement Detection (RC-MD)*
   Compared to the RC-BL condition, image processing algorithms are realised for the detection of moving objects. Moving objects were superimposed with a coloured frame. It was further possible for the tower controller to direct the zoom camera on a moving object or start the automatic tracking of that object by manually clicking on a detected moving object.
4. *RTO-CWP and Callsigns (RC-CA)*
   In this condition, the callsign of each AC was superimposed next to the respective AC. The position of the AC was gathered from the simulator in order to place the callsigns onto the video panorama. Moreover, semi-automatic tracking function was available, like in the RC-MD condition.

5. *Weather (Good Visibility Versus Low Visibility)*
   There were two weather conditions, both in the range of conditions to operate VFR flights, which differed in the range of sight. In the good visibility condition, the viewing distance was unlimited, and in the low visibility condition the viewing distance was diminished to 3.5 km (about 2.17 miles).

2.6 Controllers Working Positions

The two controller positions (executive and coordinator) were equipped with a generic approach radar application, a weather display, paper-based flight strips, radio, and the far view, displaying the visual scenery as seen from the tower position. Within the tower simulator, two identical radar applications were placed in front of each of the tower controller position. It was necessary because of the large distance of the coordinators operating position to the radar display placed in front of the executive.

At the RTO-CWP, there is an additional control display in front of the executive for controlling the zoom camera and its functions, but just one radar right in front of the coordinator's operating position. Nevertheless, the spatial dimensions of the RTO-CWP allow the executive to sufficiently check the radar display. The configurations of the working positions are depicted in Figs. 2 and 3.

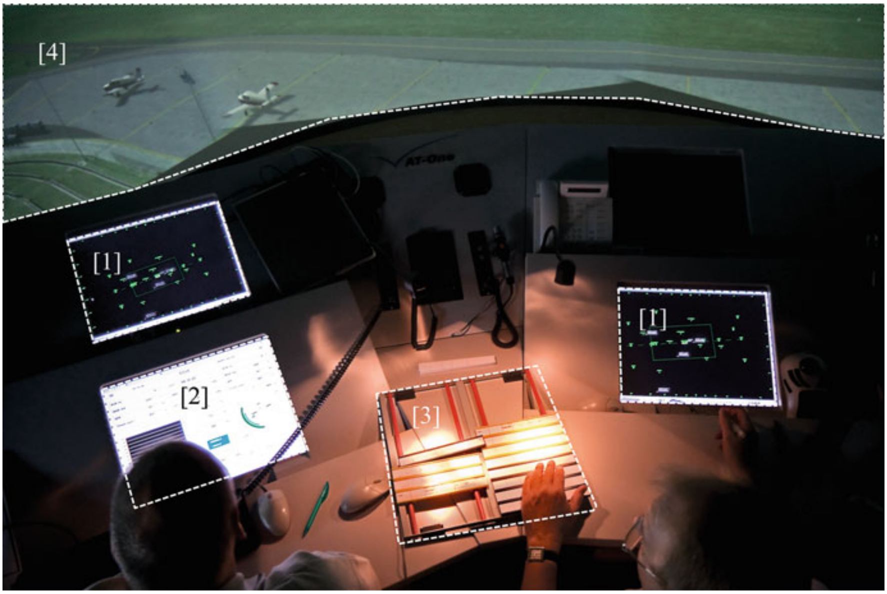

Fig. 2 Design of working positions in the tower simulator encompasses [1] two radar displays, [2] weather display, [3] flight strips, and [4] far view (200° life-size projection). The executive is positioned to the left and the coordinator to the right of the flight strips

Fig. 3 Design of the RTO-CWP with [1] radar, [2] weather display, [3] flight strips, [4] far view (video panorama), and [5] control display for zoom camera. The executive is positioned to the left and the coordinator to the right of the flight strips

At the two pseudo pilot working positions, located in a separate room, two trained pseudo pilots controlled each AC via command pad and mouse clicks, according to the radio advices given by the tower controller. They translated heading, speed, and altitude commands and clearances advised by the tower controller into inputs for the simulation software.

3 Dependent Variables and Data Analysis

3.1 Feasibility, Acceptance, and Usability of the Workplace

In this study, questionnaires and interviews were used to assess usability, feasibility, and acceptance of the experimental workplace and the assistance tools in order to gain insights about operational validity. The study took part on an experimental workplace; therefore, it was expected that handling issues with the human–machine interfaces might occur. After each simulation run, both controllers had to fill out a set of questionnaires, addressing the relevant aspects of human–machine interaction with regard to feasibility and acceptance. Questions from the EUROCONTROL SHAPE questionnaires (Eurocontrol 2008) were used. Ergonomic concepts addressed with the questionnaires were mental workload and the impact of automation (SHAPE-AIM), trust in automation (SHAPE-SATI), and situation awareness (SHAPE-SASHA). Only items concerning the experimental workplace and the new components like information augmentation, zoom camera, touch pen, and tracking function were selected. Each item was rated on Likert scales ranging from 5- to 7-point scales, depending on the original questionnaire. Further questions from the system usability scale (SUS) were used to access subjective rating concerning the usability of the controller working positions on a five-point Likert scale (Brooke 1996). Sum scores were calculated for each scale, and negative items were inverted beforehand according to the manuals (Eurocontrol 2008).

Furthermore, after each simulation run feedback of the controllers concerning the usability of the RTO working environment and the different information augmentation variants was gathered in semi-standardised interviews. The traffic situations of the simulation runs were used as triggers for the controllers, to comment on operational requirements for remotely controlling an airport. The feedback of the controllers was clustered in two main topics: usability of the workplace and feasibility of the concept. Comments of the controllers are reported in an aggregated manner.

3.2 *Assessing the Relevance of the Far View*

As outlined, the far view is the most distinct information source of the tower controllers' work place. Even though its relevance in general is rated high, it stays unclear what specific information is used from the far view. For validation of the new work environment that aims at replacing the outside view, it is crucial to understand what information controllers need from the outside view in order to ensure that this information is available at the new workplace, as well. The radar display of the en route controller, as the main visual information source, presents a synthetic, integrated graphical representation of several radar sources. It contains information about the three-dimensional position, velocity, and heading of AC in the airspace. In comparison, the far view is more complex and less explicit regarding the information the controller perceives by "looking outside". Information claimed to be derived by tower controllers ranges from the position and velocity of AC to the visual range at the airport and animals on the runway (Papenfuß and Möhlenbrink 2009). Although the far view is not clearly understood, it is argued that it is a necessary element in the safety chain for tower air traffic control (Möhlenbrink et al. 2010). As a general rule, in order not to miss any unexpected event, tower controllers are expected to look outside as often as possible. Therefore, the so-called head-down times (i.e. when the controller is not looking outside, but on other information sources) should be minimised in order to minimise the risk of not detecting unpredictable events, as well (Hilburn 2004). The head-down and head-up times of tower controllers have been investigated by means of using objective metrics, like controllers' gaze position, in order to derive percental dwell times (e.g. Pinska 2007). Different publications report controllers using between 20–54 % of time for the far view (Pinska 2006; Oehme and Schulz-Rückert 2010; Lange 2014) and 51–80 % for head-down times, respectively. Even though these studies provide indicators for the frequency of use of far view, this metric is not explaining what information controllers do actually perceive when they look outside in order to collect information for their decision making.

The relevance of information or data is an essential feature to assess and evaluate human–machine interaction. For instance, the psychological concept of situation awareness that is known to have an impact on human–machine performance (Durso et al. 1999) refers to the "perception of the relevant information in the environment"

(Endsley 1995, pp. 34). In order to better understand the relevance of the far view and the acquired information in this study, a multi-method approach is used. Durso et al. (2008) suggest that relevance of information can be quantified and computed on three dimensions—number of tasks which require the information, task frequency, and the criticality or importance of the tasks that use the information.

In order to achieve an applicable approach, in this simulation study, relevance of an information source is defined as frequency (percentage) of use and uniqueness and criticality of information. Accordingly, eye tracking is used to gain objective metrics that describe the distribution of visual attention. Because of the spatial limitation of the head tracking unit, only one working position, RTO-CWP or tower simulator, could be used for eye gaze measurement. It was decided to measure eye gaze behaviour at the RTO-CWP. As this metric is derived in a simulation setting, furthermore, a ranking of information sources regarding the perceived importance for the daily work of the tower controller is used. In a questionnaire, controllers were asked to rank the information sources they use in their daily work according to their importance. The list consisted of 20 different information sources. The rank of the information sources is calculated as the mean ($N = 12$), where the first rank is weighted with the score 20 and the last rank with the score one. To identify the severity of situations, where information of the far view is needed, a questionnaire was used, as well as free interviews. In the final questionnaire, controllers were asked to remember situations they had perceived as critical. Out of those situations, they were asked to choose one they remembered particularly well and to describe this situation and what they did to solve this situation. Afterwards, they were asked to select all those information sources out of a list from which they derived relevant cues for the specific situation that triggered their actions. By means of interviews, controllers were further asked to specify what information they use from the far view that is not available through other information sources.

3.3 Benefit of the Assistance Tools and Analysis of the Eye-Tracking Data

The concept of the assistance tools investigated in this study aims at supporting the tower controller by providing relevant information within the main visual information source, the far view. Initial approaches used a transparent display to superimpose relevant information for tower control (Fürstenau et al. 2004b; Peterson and Pinska 2006); see also chapter "Introduction". In one approach, wind information was superimposed over the runway (Schmidt et al. 2006). Controllers have to submit wind information to the pilot when they give a landing clearance. Additionally, they visually have to scan the runway to make sure that it is not occupied. Normally, the wind information is provided on an additional display. It is assumed that by superimposition of relevant data, head-down times of the controllers can be minimised (Peterson and Pinska 2006).

To assess the benefit of the assistance tools used in this study, a multi-method approach was used. The introduced augmentation assistance tools (movement detection, callsigns) were evaluated by means of a dichotomous scale (“Yes”, “No”), asking for usability, benefit, and reliability. Additionally, during the simulation runs at the RTO-CWP, eye data was recorded as an objective measure of the information acquisition process and the head-down times of the controllers.

The head-mounted eye-tracking system in combination with an optical head tracker via infrared cameras allows a parallel tracking of both controllers in the complex simulation environment (Möhlenbrink et al. 2010). Dwell times for the different information sources were determined as an index for the visual attention distribution. The analyses of this data focussed on the differences of this index between the roles controller and coordinator, as well as the differences between RTO-CWP baseline and information augmentation conditions. For these analyses, a 3d-model of the RTO-CWP was generated, which includes the position of the screens of the visual information sources (compare Fig. 3). Based on that 3d-model, the eye gaze is transferred during the measurement into position data on the screens. After eye data recording, the Eye-Tracking Analyser (EyeTA) was used to calculate fixations and respective dwell times for defined areas of interest (AOI). In this study, the AOIs were identical to the information sources at the RTO-CWP (compare Fig. 3), thus being far view, flight strips, radar display, weather display, and zoom camera. The EyeTA tool was developed at the Institute of flight guidance for semi-automatic analysis of large eye-tracking data sets. For calculation of fixations, the dispersion threshold algorithm suggested by Salvucci and Goldberg (2000) was implemented with minimum fixation duration of 100 ms Fixations are used as indicators for conscious information acquisition; so in combination with the AOIs they represent the information controllers gathered during the simulation run in order to make decisions.

4 Results

4.1 Feasibility, Acceptance, and Usability of the Concept

The scores for all questionnaires in the four conditions are shown in Fig. 4. The four graphs show the scores for mental workload (AIM, Fig. 4a), trust in automation (SATI, Fig. 4b), situational awareness (SASHA, Fig. 4c), and system usability (SUS, Fig. 4d). The dotted lines refer to the minimum and maximum values of the scales, as well as the mean. First, the absolute values for the scores are described. For the AIM scale, a lower score is better, as it refers to less negative impact of the new automated system on mental workload. The scores for all four experimental conditions are relatively low, indicating no major negative influence on mental workload. The SASHA scale is interpreted in the same way; a lower score means less negative influence on operators’ situation awareness. The scores

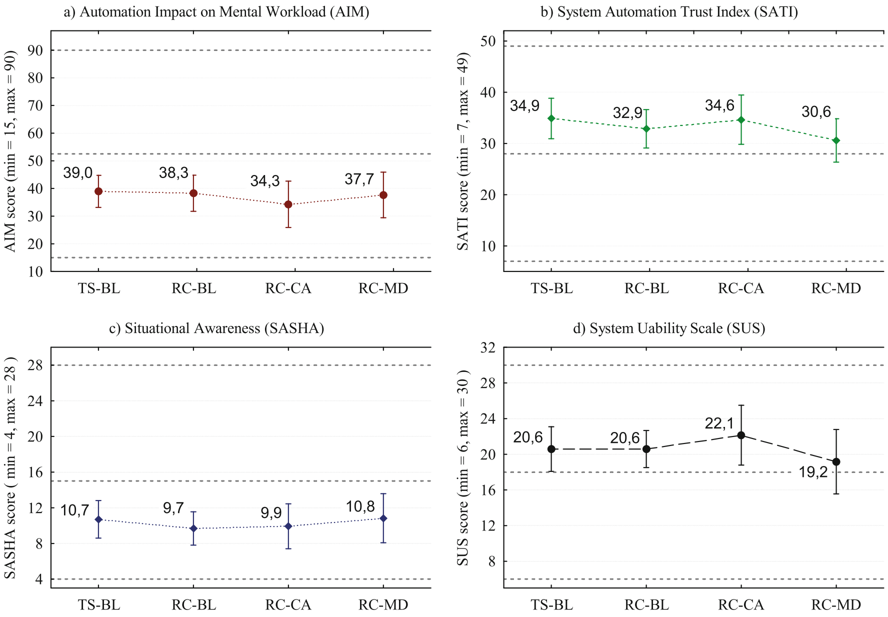

Fig. 4 (**a**–**d**) Mean values for the operational feasibility questionnaires; *vertical bars* indicate 0.95 confidence intervals. (**a**) Impact of automation on mental workload (AIM, min = 15, max = 90) (**b**) Trust in automation index (SATI, min = 7, max = 49). (**c**) Situational awareness (SASHA, min = 44, max = 28). (**d**) System usability scale (SUS, min = 6, max = 30). *X*-axes indicate experimental conditions: TS-BL = conventional tower simulator, RC-BL = RTO-CWP Baseline, RC-CA = RTO-CWP Callsign Augmentation, RC-MD = RTO-CWP Movement Detection Augmentation. *Dotted grey lines* indicate minimum, maximum, and medium scores for each of the scales

for all four experimental conditions are also relatively low, indicating no major negative influence on situation awareness. The scales of SATI and SUS indicate a higher trust in automation and usability, corresponding to higher score values. For all four experimental conditions, the scores are located for SUS, as well as SATI slightly above the middle of the scale, indicating a slightly larger than medium trust in the automation and a slightly larger than medium usability of the work places. The AIM score for the callsign condition also is the lowest for all four conditions; the highest was measured for the conventional tower simulator ($M_{\text{TS-BL}} = 39.0$, $\text{SD}_{\text{TS-BL}} = 13.7$). The trust in automation index tended to be highest for the TS-BL condition compared to the lowest value for the RC-MD condition ($M_{\text{TS-BL}} = 34.9$, $\text{SD}_{\text{TS-BL}} = 9.3$, $M_{\text{RC-MD}} = 30.2$, $\text{SD}_{\text{RC-MD}} = 6.8$, 7 items, 7-point Likert scale). Regarding the situational awareness, the RC-BL had the best (lowest) score compared to the RC-MD condition ($M_{\text{RC-BL}} = 9.7$, $\text{SD}_{\text{RC-BL}} = 4.2$, $M_{\text{RC-MD}} = 10.8$, $\text{SD}_{\text{RC-MD}} = 4.6$, 4 items, 7-point Likert scale). There is a nonsignificant effect for the usability scale that the condition RC-CA is rated more usable than the condition

RC-MD ($M_{\text{RC-CA}} = 22.3$, $\text{SD}_{\text{RC-CA}} = 5.5$, $M_{\text{RC-MD}} = 18.4$, $\text{SD}_{\text{RC-MD}} = 5.9$, 6 items, 5-point Likert scale).

As the high standard deviations show, inter-individual differences were quite high. None of the four questionnaires used to assess feasibility and usability of the workplace did show in a paired t-test a significant difference between the real tower simulator baseline (TS-BL) and the RTO-CWP baseline (RC-BL). Regarding the two types of information augmentation, two subsamples were created for the "Callsign" and for the "Movement Detection" condition. t-tests were conducted to analyse whether the two subsamples rating the RTO-CWP had similar ratings in the RTO-CWP baseline condition (RC-BL). The results showed that both subsamples did not differ significantly, but for the situation awareness questionnaire SASHA. Here, the controllers taking part in the MD condition tended to rate the negative impact on situational awareness less than the controllers taking part in the CA condition ($\text{MBE} = 7.37$, $\text{SD} = 3.02$, $\text{MCA} = 11.0$, $\text{SD} = 4.31$, $t(20) = -2.09$, $p = 0\ .05$). In a next step, a Repeated Measures ANOVA of the influence of the information augmentation on the SHAPE questionnaire scores was conducted. Bonferroni post hoc test was used to check for significant differences between the conditions. No significant differences could be found between the RTO-CWP baseline RC-BL and the motion detection condition RC-MD. The comparison between the RC-BL and the callsign condition (RC-CA) revealed a significantly decreased mental workload (AIM scale) when augmenting callsigns into the far view ($M_{\text{RC-BL}} = 41.8$, $M_{\text{RC-CA}} = 34.4$, $F(1,15) = 5.43$, $p < 0.05$).

One general usability issue of the RTO-CWP is that it transforms the tower workplace into a sole computer work place. This can cause new ergonomic issues. A feared feeling of "loss of reality" on this computer work place was not rated as critical, because the en route controller also only uses a computer work place. Compared to the set-up of the real tower (TS-BL), controllers reported that they could not use the head position as an indicator for the position of an AC on the airport or the traffic pattern, whilst working on the remote tower workplace. The change of those dimensions in the experimental remote tower work place (RC-BL) was reported to lead to some initial problems with the judgement of distances. All controllers described differences in working at the RTO-CWP compared to a real tower regarding the possibility to detect far away AC due to the resolution of the video cameras (see chapter "Which Metrics Provide the Insight Needed? A Selection of Remote Tower Evaluation Metrics to Support a Remote Tower Operation Concept Validation"). This effect was especially apparent for VFR traffic in the traffic pattern. Furthermore, controllers reported that the area of the approach that was visible on the 180° video panorama was too small. They would start to search the AC earlier in a real tower with real far view.

The workplace and its features, like the zoom camera, were rather intuitively to use. In general, the controllers wanted personalised settings for the assistance tools; for instance, switching information augmentation on and off, selecting single AC that should only be augmented, or defining a set of fix positions for the zoom camera, which can be accessed via shortcuts.

In general, the concept of replacing the view outside the tower through a high resolution video was commented as sufficient in normal operations for small airports with a simple layout and a medium traffic amount. Most controllers rated this concept as suitable for low traffic situations (start and end of day of operation) or contingency purposes. High accuracy and reliability of the video pictures are mandatory. Additional sensor solutions for night and bad visibility operations were mentioned as necessary and helpful. Some controllers raised the concern of liability, when something causes an incident or accident that could have been detected with a real far view but not with the video panorama. There were comments that some relevant information is only available by being present at the airport, e.g. precise information about weather and the runway surface status. Furthermore, controllers mentioned that especially for dealing with VFR traffic precise knowledge of the vicinity of the airport is necessary, e.g. landmarks used for navigation or the location of hospitals. There were concerns that this knowledge and experience get lost whilst working on a remote working position.

The controllers were confronted with an experimental workplace, which displayed only 180° of the aerodrome. Controllers had divergent opinions about the missing backside view. Some preferred to see it permanently; some preferred to have the possibility to see these areas via a moveable camera. Others mentioned the possibility to adapt procedures to ensure safe operations in this area, e.g. not to use the backside traffic pattern or to allow only one AC in the backside traffic pattern at a time. In general, new procedures or changed working styles were both reported as possibilities to overcome those limitations introduced by the RTO working position. For example, controllers stated that they would use more extensively position reports of the pilots to control air traffic.

4.2 Relevance of Far View

Eye-tracking data of the simulation runs are used as an objective metric, to describe the attention distribution of controllers during their control task. Eye-tracking data are available only for the RTO-CWP, so all data refer to the attention distribution whilst working remote. Eye-tracking studies regarding the attention profile in a conventional tower at a small- to medium-sized airport have been conducted by Lange (2014), Oehme and Schulz-Rückert (2010), and Pinska (2006). Altogether, 43 eye data files containing 30-min simulation runs could be gathered: 22 from the executive and 21 from the coordinator's operating position. Seventy-two percent of the recorded eye gaze position data could be matched to one of the predefined AOIs ($SD = 13\,\%$).

Both roles show a comparable profile for using information sources with the highest rank for the far view ($M_{\mathrm{FarView}} = 44\,\%$, $SD_{\mathrm{FarView}} = 12\,\%$); compare Fig. 5.

For the executive position, the ranking is (1) far view, (2) radar, (3) flight strips, (4) zoom camera, and (5) weather; for the coordinator, this ranking is (1) far view, (2) flight strips, (3) radar, (4) zoom camera, and (5) weather. In order to understand

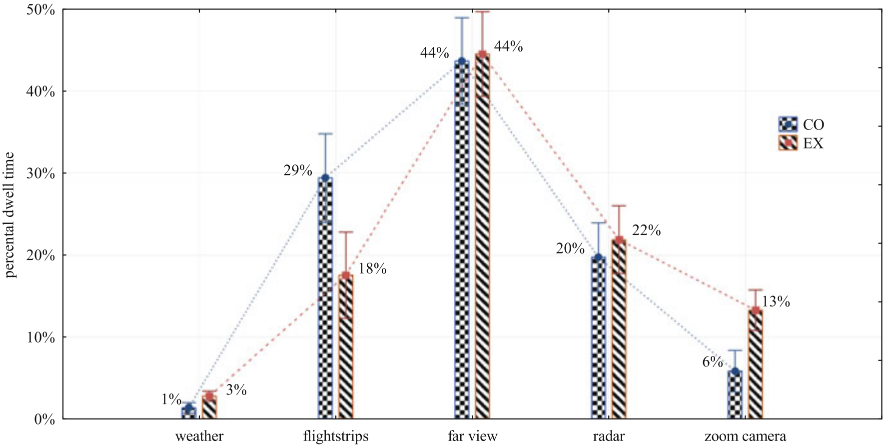

Fig. 5 Mean percental dwell times M of the visual attention on the different visual information sources of the RTO-CWP, separated for the two roles executive (role EX, $n = 22$) and coordinator (role CO, $n = 21$). *Vertical bars* indicate 0.95 confidence intervals

if the role (executive, coordinator) influences the distribution of the visual attention, a repeated measurement ANOVA was conducted, with the factor role (executive, coordinator) and visual information sources as repeated factor. The results indicate a small effect for the interaction of role and display ($F(4,164) = 5.18$, $p < 0.001$, $\eta^2 = 0.11$). The post hoc Bonferroni test shows that there is a significant difference for the attention distribution on the flight strips ($M_{\mathrm{EX}} = 18\,\%$, $\mathrm{SD}_{\mathrm{EX}} = 9\,\%$; $M_{\mathrm{CO}} = 29\,\%$, $\mathrm{SD}_{\mathrm{CO}} = 15\,\%$; $p = 0.01$) (cf. Fig. 5). The coordinator spends about 10 % more visual attention on the flight strips compared to the executive, which can be explained with the share of tasks between the operators.

The result of the ranking of the information sources for the top ten information sources for the aerodrome working position is depicted in Fig. 6. This ranking differs significantly from a corresponding one obtained through a work analysis for the conventional tower workplace of a large international airport (see (Papenfuß and Möhlenbrink 2009) and chapter “Remote Tower Prototype System and Automation Perspectives”, Sect. 2). Direct communication means the face-to-face interaction with team members in the tower. The information source IDVS resembles an integrated data processing system mainly used for weather data and operational data (e.g. runway in use). The information source monitor stands for additional cameras for surveillance of the airfield that are presented on additional monitors in the tower cab. According to this ranking, the far view is seen as the second most important information source ($M = 18.4$, $\mathrm{SD} = 1.4$) followed by the radar ($M = 17.6$, $\mathrm{SD} = 1.4$); only radio communication is ranked more important ($M = 19.6$, $\mathrm{SD} = 0.8$). Standard deviation for the ranking of these information sources is rather small, compared to the large standard deviations for the lower ranked information sources, e.g. flight strips, IDVS, and telephone. This means that

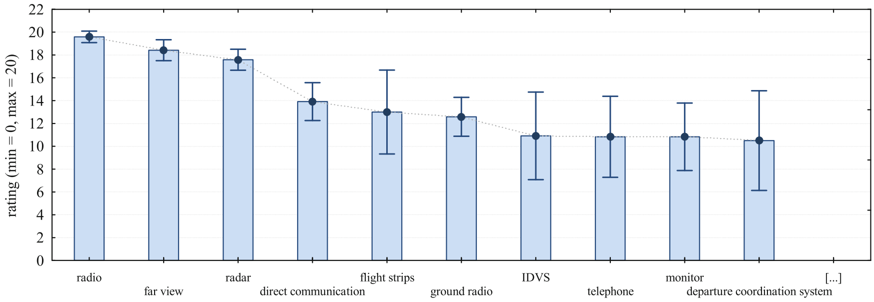

Fig. 6 Top ten of the most relevant information sources for the aerodrome working position, data from $N = 12$ controllers. *Bars* resemble the mean rating (minimum = 0, maximum = 20); whiskers indicate 95 % confidence intervals

all controllers had a rather similar ranking for the first three information sources, but strongly differed in their individual ranking for the following information sources.

The results of the analysis of the critical situations are shown in Table 1. In 10 out of the 12 described situations, the far view provided the relevant information used for decision making. Both radar and radio communication provided relevant information in 7 cases, and telephone and ground radar were named each in one case. The other information sources like displays, monitors of video cameras, and alerts were not selected.

For the 10 situations, where the far view provided relevant information, controllers were further asked to specify what information they got from the far view. These answers ($n = 10$) were analysed and grouped into four functional categories of information: anticipation of abnormality ($n = 2$), discovery of abnormality ($n = 2$), composition and verification of the traffic picture ($n = 5$), and unspecified/all ($n = 1$), compare Table 2.

Within the free interviews, controllers were asked in which operational situations the far view provides information that is not provided by any other information source. Accordingly, one of the most critical information is whether the runway is occupied or not. Furthermore, the far view is used to timely verify whether pilots executed the commands given by the controller. The controllers need this verification to estimate if AC will be separated properly or if further control steps are needed to ensure safe operations. One situation identified by controllers is the timing of the base turn (turn base clearance) of a VFR AC. Controllers mentioned that it can be hard to timely decide only with the help of the radar whether the pilot already followed the command (to turn), because the update rate of the radar is relatively low. A change in the attitude cannot be detected, and a change of the position will be visible with recognisable delay. In the far view, the change of the aircrafts' attitude can be verified more precisely, sometimes by reflections on the aircrafts' surface that are clearly visible to the controllers.

Another situation that was mentioned by controllers is the cross-checking of, especially, VFR pilots action on the ground. It might be of interest to check whether

Table 1 Use of information sources in critical situations

Information source	Response ($N = 12$)	Frequency (%)
Far view	10	83
Radar	7	58
Radio	7	58
Telephone	1	8
Ground radar	1	8
Other displays	0	(0)
Monitors of video cameras	0	(0)
Alerts	0	(0)

Table 2 Overview of functional categories and samples of information

Id	Category	N	Description
1	Unspecified/all	1	All information
2	Anticipation of abnormality	2	AC performs “swing” manoeuvre, rapid change of attitude
			Collision risk (Turn-off + next landing)
3	Discovery of abnormality	2	Observation of military jets and small AC
			Observation of motion track of AC
4	Composition and verification of traffic picture	5	Strength and location of smoke
			Identification truck/vehicle on ground radar
			Verification of information
			Precise and timely information of position, speed, and separation of AC

the pilot took the correct taxiway, because confusions can happen if a pilot is new to an airport. Controllers rate the experience of pilots through cues derived by radio communication. If a pilot sounds unsure or has problems to follow the phraseology, controllers will check the pilot in the far view more closely, e.g. if the pilot takes the correct taxi way.

4.3 Benefit of Assistance Tools

The controller rated the assistance tools by means of a specific questionnaire. Questions are structured into three categories—regarding the tracking functionality of the zoom camera (questions 1–3), the usability of information augmentation of either “callsigns” or “automatic movement detection” (questions 4–6), and the potential of these functionalities to provide operational benefit (questions 7 and 8). Results are presented for both roles executive and coordinator separately. Question 3 was only answered by the executive role, because the coordinator did not have had the means to directly interact with the zoom camera. Additionally, the two augmentation types “Callsigns” and “Movement Detection” are contrasted for category 2. The results are shown in Tables 3 and 4. The first number indicates the times the question was answered with “Yes”; the number in braces indicates, accordingly, the times answered with “No”.

With regard to the tracking functionality (questions 1–3), controllers’ ratings are relatively clear that this functionality is a sensible feature. There are issues regarding the handling and reliability of the feature, where controller’s ratings provided no clear results or tendencies. In the free interviews, some usability issues were further specified. The tracking functionality of the zoom camera was regarded as useful for traffic in the traffic pattern to detect the AC type, to determine whether AC has left the runway, or in critical situations in general, where usually one extra controller follows the critical objects with his glasses. In the experimental set-up chosen in this study, the tracking was not reliable enough. Furthermore, the tracking was sometimes too slow to follow the AC. The usage of the zoom camera was rated as “intuitive”, although too sensitive, especially in high zoom levels. The amount of training for precise manual control was rated “high”. Controllers described desirable advanced control options. One is to select a specific AC in the approach radar display, and the coordinates of the AC position will be used to automatically position the zoom camera.

The augmentation type “callsigns” was rated as reliable, the controllers used the information that was provided, and the information was rated as correct. There was no clear opinion regarding the operational benefit of the assistance tool or whether it changed the work routines fundamentally.

Table 3 Answers regarding tracking functionality

			EX Yes (No) $N = 12$	CO Yes (No) $N = 12$
Tracking	1	Is the tracking functionality a sensible feature?	11 (1)	11 (1)
	2	Did the tracking functionality work correctly?	4 (8)	6 (6)
	3	Was it possible to use tracking functionality without handling problems?	7 (5)	–/–

Table 4 Answers regarding information augmentation

			Callsigns CA		Movement detection MD	
			EX $n = 6$	CO $n = 6$	EX $n = 6$	CO $n = 6$
Usability	4	Was the additional information a reliable assistance?	4 (2)	5 (1)	1 (5)	1 (5)
	5	Did you use the additional information?	5 (1)	4 (2)	4 (2)	3 (3)
	6	Was the additional information correct?	4 (2)	5 (1)	2 (4)	3 (3)
Operational benefit	7	Did the system provide new possibilities for your work?	3 (3)	2 (4)	0 (6)	2 (4)
	8	Did the system changed something fundamental in your work routines?	2 (4)	2 (4)	1 (5)	0 (6)

In comparison to the augmentation type "callsigns", "movement detection" was perceived as not reliable. There was no clear opinion regarding the usage of the information, as well as their correctness. There was a clear answer from the executive that this feature did not provide an operational benefit. In comparison, two coordinators saw an operational benefit. No fundamental change in work routines was apparent.

The comments of the free interview regarding the augmentation assistance tools give a more thorough picture: concerns were raised that through augmentation other information is masked. In general, the augmentation of callsigns was rated as more helpful than the highlighting of moving objects (movement detection). The augmentation of callsigns was rated as helpful for parking AC, as well as AC on the final. Both augmentations were rated as helpful to detect far away objects. Some issues with the lower resolution of the video panorama, like detecting far away AC, could be compensated through augmentation. For example, through the motion detection, AC in the traffic circuit are highlighted and thus quickly visible to the controllers.

On the other hand, the danger of over-reliance was reported, especially for the augmentation of the callsigns. The reliability and accuracy of the data was mentioned as a main factor, whether an augmentation solution is accepted or not. If a controller perceives the information augmentation as not reliable, it would be turned off in order to avoid wrong decisions based on faulty information.

Even if controllers did not indicate a fundamental change in work routine, the effect of the augmentation tools on head-down times was controlled by means of the eye-tracking data. The hypothesis was that information augmentation increases the head-up times; thus time spent on the far view should be increased. The comparison of the dwell times on the AOIs for the different information augmentation conditions shows only a significant difference for the use of the radar display between the baseline condition and the two information augmentation conditions. No systematic difference could be found for the dwell times on the far view. The results are depicted in Fig. 7, with (a) the difference for callsigns and (b) movement detection conditions.

Due to the experimental design, each participant worked either in the movement detection (MD) or callsign (CA) condition in the specific role, but all participated in the baseline condition. Therefore, it is impossible to calculate a repeated measure ANOVA (BL, MD, CA). However, paired *t*-tests were calculated for the controller subsample participating in the BL and MD condition and for the subsample participating in the BL and CA condition. First, it was tested whether the dwell times of the two groups differ significantly in the BL condition. The results of the *t*-test ($M_{\text{BL-CA}} = 21.4\,\%$, $M_{\text{BL-MD}} = 20.7\,\%$, $t(20) = 0.21$, $p > 0.05$) show that there is no systematic difference in the baseline condition; thus, the two subsamples are comparable. While in the movement detection condition, significantly more attention is distributed to the radar display ($M_{\text{RC-BL}} = 21\,\%$, $\text{SD}_{\text{RC-BL}} = 10\,\%$, $M_{\text{RC-MD}} = 25\,\%$; $\text{SD}_{\text{RC-MD}} = 14\,\%$, $t(8) = -2.31$, $p < 0.05$) compared to the baseline; in the callsign condition, RC-CA, significantly less attention is distributed to the

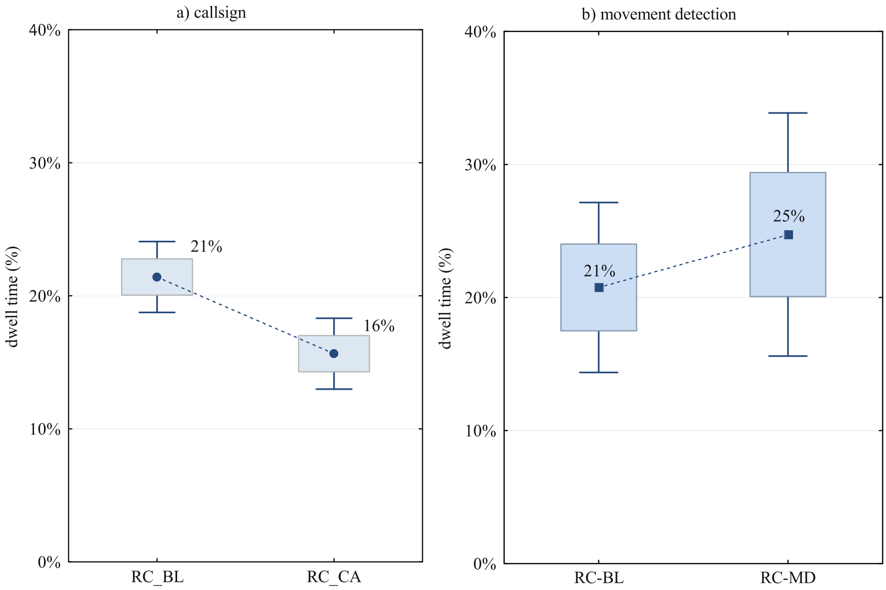

Fig. 7 (**a**) The graph shows the mean percental dwell time on the AOI RADAR for baseline (RC-BL) and callsigns (RC-CA) condition. With callsign augmentation, less visual attention is spent on the RADAR display. (**b**) The graph shows the mean percental dwell time on the AOI RADAR for baseline (RC-BL) and movement detection (RC-MD) condition. With movement detection, more visual attention is spent on the RADAR display. *Boxes* indicate standard error, *bars* 1.96 × standard error

radar display ($M_{\text{RC-BL}} = 21\,\%$, $\text{SD}_{\text{RC-BL}} = 5\,\%$, $M_{\text{RC-CA}} = 16\,\%$; $\text{SD}_{\text{RC-CA}} = 5\,\%$, $t(12) = 4.73$, $p < 0.001$) as compared to the baseline condition.

5 Discussion

5.1 Feasibility, Acceptance, and Usability of the Concept

The results of the questionnaires, used to assess feasibility and usability of the workplace, are promising with regard to the direct comparison of the tower simulator and the new workplace, the RTO-Console. No significant differences were found between those two conditions, regarding trust in automation, mental workload, situation awareness, and usability. One aim for the design of the RTO-CWP was to build it as similar as possible to the conventional tower in order to increase the acceptance for the concept. So, besides enabling remote control, working methods should not be affected by the concept. Therefore, the result indicates the introduced changes not to have a negative influence, compared to a conventional tower simulator.

There are objective differences between these workplaces, like the reduced panorama viewing angle (ca. 125°) that in turn reduces the required head rotation for the 180°-reconstructed far view. The results of the interviews indicate that some of these changes introduced by the RTO-Console could be compensated through training. Nevertheless, there are issues with the new workplace that need further consideration. One aspect is the resolution of the video panorama. Especially, for smaller regional airports with a high percentage of VFR traffic, the visibility of small AC in the traffic circuit is necessary.

In general, the feedback concerning the usability of the workplace was positive. The RTO-Console, the zoom camera, and the tracking functionality are rated as "intuitive to use" and suitable for smaller airports with moderate traffic. The use of high resolution video stream was seen as a "good" approach. Controllers used the video data on the panorama instead of the radar for immediate verification of instructions given to the pilots, like start-up or a new heading, as the update rate of the radar is too low. As regional airports have a higher percentage of VFR traffic and, therefore, a higher chance of unexpected events, this timely update via the video is beneficial.

There are limitations of the results obtained, because in the simulation controllers only had to control air traffic and no ground based traffic was included, e.g. fuelling trucks, follow-me cars, or vehicles for construction work. The coordination with and monitoring of this traffic is a substantial part of the controllers task at a small airport. Furthermore, weather was kept stable over each simulation run. The evaluation of weather situations was indicated by the controllers as potentially difficult, when using the RTO-Console.

Because in this experimental workplace, the reconstructed far view was limited to 180°; procedures to allow safe traffic control for AC flying in the areas without visual information could be applied. This certainly has effects on the capacity and must be seen as a trade-off between technical equipment invested in the remote control of the airport and applicable procedures. In general, the concept for remote control as discussed in the present work applies for smaller airfields that do not have a major issue with capacity. Thus, a reduction of capacity in remote control operations could be a valid approach.

Regarding the two information augmentation solutions, a positive effect of these assistance functions was expected on the scales of the SHAPE-questionnaires; nevertheless, no significant differences to the RTO-Console Baseline could be found. The tower simulator was rated best on the scale for trust in automation when looking at the trends. As there was no automation in this condition, the automation in the other conditions tended to be a source for mistrust in the system. On the other hand, the assistance by augmenting callsigns tended to be less mentally demanding compared to the standard work environment. Seemingly, assistance can diminish mental workload if it is highly reliable. Maybe, no effects of the information augmentation could be found due to the experimental status of the workplace, as well as of the assistance tools. In general, the reliability, the accuracy, and the adjustment to individual preferences of the assistance tools were mentioned as momentous by the controllers. In the RTO-Console, main assistance solutions are based on the video data. Especially, the detection of AC was rated as helpful when they are in such a distance that they have the size of only 1–4 pixels in the video images. This requires the reliable detection of extremely small objects on the basis of video data. If more advanced technical camera and data transmission solutions are available, a higher resolution of the video could resolve these problems. If not, an adjustment of the control procedures is essential.

5.2 Relevance of the Far View and the Visual Information

The eye-tracking data of the present work show that the tower controller directs most visual attention on the video panorama, which replaces the view out of the window. Overall, the percentage was 44 % of the time; these results are consistent with other results in the literature (Pinska 2006; 2007; Oehme and Schulz-Rückert 2010; Lange 2014), as these studies indicate a valid range of 20–54 % of visual attention at the far view. So, whilst working at the simulated remote tower environment, air traffic controllers had comparable working methods regarding their distribution of visual attention as in a conventional tower. In the preliminary study, executive and coordinator had different attention distribution profiles. The coordinator spent less time on the far view than the executive (Möhlenbrink et al. 2010). These results could not be replicated; both roles had remarkably similar profiles. However, compared to the executive, the coordinator spent more visual attention on the flight strips, because he had to document clearances and flight progress on the flight strips. Furthermore, the coordinator had no means to interact with the zoom camera independently, so less attention was spent on this display. The differences in the results of the two studies might be due to the fact that in the main study reported in this chapter, controllers were confronted with an unfamiliar airport, an unknown team member, and a partly new work organisation. It can be assumed that controller teams develop distinguishable profiles of visual attention for their different task sets over time. But the similar visual attention profiles can also be interpreted in terms of redundancy. The coordinator visually follows the traffic in the same manner as the executive does. This behaviour might be an enabler for effective cross-checking and cross-monitoring behaviour, necessary for building up team situation awareness and for adapting continuously within the team (e.g. Dickinson and McIntyre 1997; Paris et al. 2000).

Furthermore, controllers ranked the different information sources they use for tower control. In this ranking, the far view was rated the most influential visual information source followed by radar. But the overall most important information source is radio communication. For remote tower control, solutions for radio communication seem rather straightforward to achieve. Nevertheless, radio communication becomes a research topic if two or more airports are controlled from a remote tower center (Wittbrodt and Thüring 2010; see also chapter “Planning

Remote Multi-Airport Control–Design and Evaluation of a Controller-Friendly Assistance System" on remote multi airport control).

The analysis of critical situations showed that in those situations remembered by the controllers, relevant information was derived most often by the far view, mainly in order to verify information perceived by other information sources. Furthermore, the far view provided information that helped to build up an understanding of the actual traffic situation. This topic is also discussed in detail in chapters "Visual Features Used by Airport Tower Controllers: Some Implications for the Design of Remote or Virtual Towers" and "Detection and Recognition for Remote Tower Operations". In most cases reported by the controllers, the far view was not the only source for relevant information. Triggers for information search were achieved, e.g. via radio communication. The far view was used to timely verify this information. It has to be discussed in how far the video panorama reconstruction of the far view can provide the same quality of information in the sense that it is not potentially distorted by the sensor technology or data transmission.

In order to gain further understanding about the use of information provided by the far view, one approach would be to apply masks with smaller and a higher number of AOIs to the eye-tracking data. In that case, it can be distinguished which functional part of the airport, e.g. runway, final, apron, the controller looked at. Another approach is the application of dynamic AOI (Gross and Friedrich 2010). This approach seems promising for analysing eye data gathered in a simulation in combination with traffic and further process data to understand better the information acquisition process of operators during complex cognitive tasks.

5.3 Benefit of Assistance Tools

One assistance tool investigated in this study was the tracking functionality of the zoom camera. The zoom camera could be attached to the highlighted objects (movement detection or callsign), realising an automatic tracking. Controllers approved this feature as sensible. There are issues with the reliability of this tracking, as well as with the handling. As the study investigated an experimental workplace with advanced functionalities, besides usability problems the operational value of the feature was shown.

Regarding the two types of information augmentation (callsign, movement detection), the callsigns were rated as more reliable and rather correct, compared to the movement detection. Furthermore, controllers claimed the callsigns to be more helpful than the movement detection. In the callsign condition, the controllers were provided with valuable information (the identifier of the AC) directly superimposed on the far view. With this additional information, identification of AC in the approach or on the apron is easier. It is a drawback of the augmentation of callsigns that controllers rely too much on this information, rather than verifying the information derived by radio communication, flight strips, and radar by means of the real time information of the far view. This concern was also raised by the controllers in the study. It might have led to rather conservative ratings with regard to the question if the assistance tools provide new possibilities for the work. Besides these subjective ratings, the results of the eye-tracking data show that, through the augmentation of callsigns in the far view, visual attention was significantly drawn from the radar display. Yet, the augmentation of motion detection results showed the opposite effect. Potentially, in this condition, more attention was drawn to the radar, as AC in the traffic pattern or approach were detected earlier than without augmentation. The radar was then used to identify these AC. Nevertheless, in the callsign condition no direct increase of head-up times (higher dwell times on the far view) could be observed. It might be that controllers distributed their "additional" attention quite individually, so no general pattern could be found.

In order to minimize head-down times as one goal of information augmentation, the callsign of an AC has to be regarded as more relevant than the information provided by motion detection alone. This goal of decreasing head-down times has to be seen in relation to the benefit provided by the regular cross-checking between the different information sources and quality of information they provide. Especially, flight strip data, which resembles planned data or the expected state of the traffic, should not be mixed with the data resembling the actual traffic situation, like radar and the far view so that controllers effectively can monitor and react upon critical differences between expected and actual state of traffic.

6 Conclusion

Overall, within the present investigation, the concept for Remote Control of small low traffic airports showed no significant differences compared to working on a conventional tower simulator as indicated by subjective ratings and usage of information sources. The findings show that the described work environment does not change fundamentally the working procedures of tower controllers, supporting the perspective of a medium-term application. In case, a remote tower solution comparable to the concept under investigation went operational in Sweden in 2015 (LFV 2015).

The design of the RTO-CWP as realised in this high-fidelity simulation enables a controller team to successfully handle the traffic of a regional airport. Reconstructing the out-of-windows view of the tower through a high resolution video panorama proved to fulfil the information needs of the controllers in most cases. There are issues like achievable video resolution and contrast within a reasonable cost frame, which determine the ATC performance under certain conditions and task requirements. It might lead to changed procedures and maybe capacity reduction in remote control operations. This has to be evaluated in the context of the actual traffic demand at small airports.

With regard to low visibility conditions (night, fog), enhancement of the camera technology towards the infrared spectrum could even improve the visual information, compared to the conventional tower view. In general, new assistance tools like information overlay in the video panorama and automatic tracking of the zoom camera were rated as promising, given that high reliability can be provided. For operational use of this work place, future work has to deal with questions of redundancy and safety of the system. Nevertheless, to understand which information the tower controller needs at which time is mandatory prerequisite to design such a safe system. The results of this study demonstrate this need, as not every information augmentation introduced in this study showed the intended effect on reducing head-down times. Obviously, the field of tower air traffic control has received and will receive more attention in the next years. High-fidelity studies are a suitable method to understand the impact of novel concepts on important human factors at a very early stage. The results do not only provide valuable input into the design and further development. High-fidelity studies also proved to be a good method to actively involve the operators into the concept development at an early stage.

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Videopanorama Frame Rate Requirements Derived from Visual Discrimination of Deceleration During Simulated Aircraft Landing

Norbert Fürstenau and Stephen R. Ellis

Abstract In order to determine the required visual frame rate (FR) for minimizing prediction errors with out-the-window video displays at remote/virtual airport towers, 13 active air-traffic controllers viewed high dynamic fidelity simulations of landing aircraft and decided whether aircraft would stop as if to be able to make a turnoff or whether a runway excursion would be expected. The viewing conditions and simulation dynamics replicated visual rates and environments of transport aircraft landing at small commercial airports. The required frame rate was estimated using Bayes inference on prediction errors by linear FR-extrapolation of event probabilities conditional on predictions (stop, no-stop). Furthermore, estimates were obtained from exponential model fits to the parametric and nonparametric perceptual discriminabilities d' and A (average area under ROC curves) as dependent on FR. Decision errors are biased towards preference of overshoot and appear due to illusionary increase in speed at low frame rates. Both Bayes and A-extrapolations yield a frame rate requirement of $35 < \mathrm{FR_{min}} < 40$ Hz. When comparing with published results [Claypool and Claypool (Multimedia Syst 13:3–17, 2007)] on shooter game scores, the model-based d'(FR)-extrapolation exhibits the best agreement and indicates even higher $\mathrm{FR_{min}} > 40$ Hz for minimizing decision errors. Definitive recommendations require further experiments with $\mathrm{FR} > 30$ Hz.

Keywords Remote tower • Videopanorama • Framerate • Visual discrimination • Speed perception • Decision experiment • Aircraft landing • Signal detection theory • Bayes inference

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1 Introduction

This chapter reviews a two-alternative decision experiment with simulated aircraft landing as dependent on video-frame rate (FR) characteristics with the goal of determining the minimum frame rate necessary for minimizing decision errors under Remote Tower working conditions. It collects results partially presented in previous publications (Ellis et al. 2011a, b; Fürstenau et al. 2012).

Recent proposals for decreasing cost of air-traffic control at small low-traffic airports have suggested that technology may remove the need for local control towers. Controllers could visually supervise aircraft from remote locations by videolinks, allowing them to monitor many airports from a central point (Schmidt et al. 2007; Hannon et al. 2008; Fürstenau et al. 2009; SESAR-Ju Project 06.09.03; van Scheijk et al. 2010). While many current towers on A-SMGCS-equipped airports, even some at busy airports like London-Heathrow, can continue to operate totally without controllers ever seeing controlled aircraft under contingency conditions, although with reduced capacity, it is clear from controller interviews that usually numerous out-the-window visual features are used for control purposes (Ellis and Liston 2010; Van Schaik et al. 2010; Ellis and Liston 2011). In fact, these visual features go beyond those required for aircraft detection, recognition, and identification (Watson et al. 2009).

Potentially important additional visual features identified by controllers in interviews involve subtle aircraft motion. These could be degraded by low dynamic quality of remote visual displays of the airport environment. In fact, the dynamic visual requirements for many aerospace and armed forces tasks have been studied, but most attention has been paid to pilot vision [e.g., (Grunwald and Kohn 1994)] and military tactical information transmission [e.g., (Kempster 2000)]. Relatively, little attention was paid to the unique aspects of controller vision which, for example, emphasize relative motion cues. Consequently, there is a need to study some of these visual motion cues to understand how their use may be affected by degraded dynamic fidelity, e.g., low visual frame rates. Such low rates could be due to typically low rates of aircraft surveillance systems, e.g., 1–4 Hz, or to image processing loads arising from the very high resolution, wide field of view video systems needed to support human vision in virtual towers (see chapters “Remote Tower Experimental System with Augmented Vision Videopanorama” and “Remote Tower Prototype System and Automation Perspectives”).

Since preliminary investigation of the role of visual features in tower operations has shown that their principal function is to support anticipated separation by allowing controllers to predict future aircraft positions (Ellis and Liston 2010), we have begun to investigate the effects of frame rates on the deceleration cues used to anticipate whether a landing aircraft will be able to brake on a runway, as if to make a turn off before the runway end.

Our specific hypothesis is that the disturbance due to low frame rate affects the immediate visual memory of image motion within the video frame. Memory processes classically have an exponential decay. Accordingly, one might expect discriminability of the visual motion associated with aircraft deceleration to reflect this feature, degrading only a bit for higher frame rates but more rapidly for the longer period, lower frame rate conditions. A possible descriptive function could be of the form: $1–\exp(-k/T)$. This kind of model captures the likely features that the rate of degradation of motion information increases with greater sample and hold delays T but that there is also an upper asymptote of discriminability corresponding to continuous viewing which is determined by the inherent task difficulty. Significantly, fitting such a model to the drop off in detection performance provides a theoretically based method to estimate that frame rate required to match visual performance out the tower window.

We used two statistical analysis methods for deriving model-based frame rate requirement estimates via discriminability measurement: Bayes inference and signal detection theory (SDT) with parametric (ROC-isosensitivity-curve index d') as well as nonparametric discriminability ($A =$ average area under all proper ROC curves). Bayes inference allows for concluding, e.g. on the probability of an unexpected situation given a certain decision (decision error), from the measured likelihood of that decision (a priori knowledge) conditional on the respective world state (situation) (see Appendix B). Measuring these probabilities with different values of the independent variable (i.e., the frame rate FR) allows for extrapolation to minimum FR for zero error probability. SDT as an alternative method has the advantage of separating the intrinsic subjective preference (tendency for more liberal or conservative (error avoidance) decisions) by simultaneously separating through the measurement of hit and false alarm rates (= probabilities conditional on the alternative experimental situations) from the decision criterion (or subjective decision bias) index c (for d') and b (for A), respectively).

Experimental methods and results are provided in Sects. 2 and 3. In Sect. 4, the two alternative methods (Bayes inference and detection theory) are used for deriving from the measured response matrices the Bayes inference on risk of unexpected world state and estimates of discriminabilities and decision criteria d', c and A, b, respectively. These in turn are used to provide minimum frame rate estimates for maximizing d' and A and minimizing prediction error risk. We finish with a conclusion and outlook in Sect. 5.

2 Methods

2.1 Subjects

Thirteen active German tower controllers were recruited as volunteer subjects for the experiment. The participants' ages ranged from 25 to 59 years and were divided into three experimental groups of 4, 4, and 5. Controllers from small, medium, and large German airports were approximately evenly distributed to the groups.

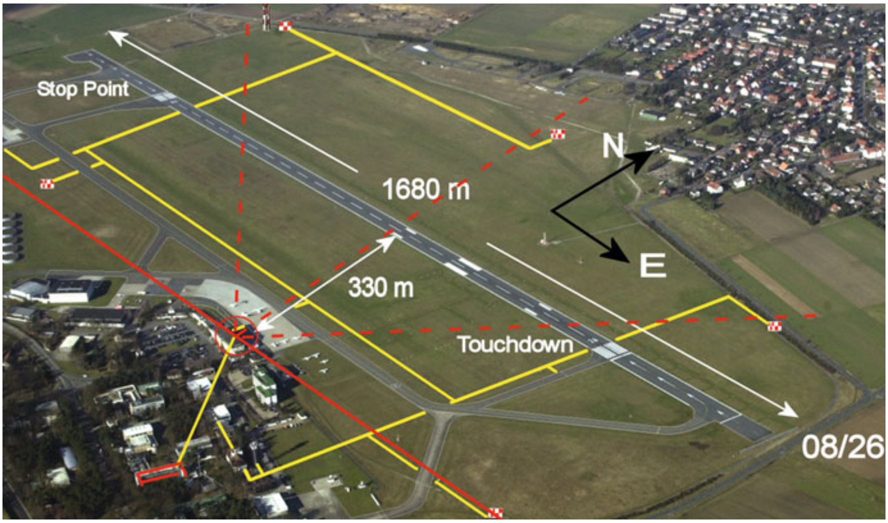

Fig. 1 Aerial view of Braunschweig airport showing the circled location of the simulated (and real) cameras, fields of view of the four cameras (*radial sectors*), and some dimensions and reference points (Ellis et al. 2011a; Fürstenau et al. 2012)

2.2 Apparatus

The experiment was conducted at a Remote Tower (RTO) videopanorama console as part of the DLR Apron-and-Tower Simulator (ATS) of the Braunschweig DLR facility. This simulation system was used to generate 60 landings of a lightly loaded A319 transport at the Braunschweig airport with a 1680 m runway 08/86 (Fig. 1, RWY was extended to 2500 m after this experiment). The simulated aircraft would first appear from E on the right most monitor while in the air at 300 m altitude 32 s before touchdown (Fig. 2). Then it would fly to touchdown seen on the next monitor to the left. Thereafter, it would either roll through to the end of the runway or stop 250 m before the runway end.

The simulator generated 60 1-min landing scenarios with various dynamically realistic deceleration profiles of nominally 1, 2, or 3 m/s^2 maximum (initial) braking and frame rates of either 6, 12, or 24 fps emulating the video signals potentially coming from cameras mounted near the Braunschweig tower. Only the highest deceleration (3 m/s^2) was sufficient to cause the aircraft to stop near the stopping point (Fig. 1) before the end of the runway (leftmost monitor in Fig. 2). The video files were then used in turn as input simulating the actual cameras so the participants could use the video console as if it were connected to actual cameras on the airfield. They present approximately a 180° view as seen from airport tower but compress it to an approximately 120°. Viewing distance between operators and monitors (21″ UXGA: 1600 × 1200 pixels with 4/3 format: 42 × 33 cm, luminosity

Fig. 2 Participant at a simulation console judging the outcome of a landing aircraft just after touchdown (2nd monitor from *left*). Approach on the rightmost monitor, touchdown is on the left side of second monitor from the right. Reconstructed panorama compressing the 180°-tower view to ca. 120° for subjects at the RTO-console (Fürstenau et al. 2012)

sufficient for photopic office environment) was ca. 120 cm. An upper array of tiled monitors for a second airport was present but not used during the testing.

2.3 Experimental Design and Task

The three matched subject groups were used in an independent group, randomized block design in which the three different landing deceleration profiles were used to produce 60 landings to the west on the Braunschweig airport's Runway 26. Each group was assigned to one of the three video frame rate conditions. The approaches were all equivalent nominal approaches for an A319 aircraft but varied in the amount of deceleration after touchdown.

The equation of motion used for the post-processing of logged simulation data assumed that the only braking force (deceleration) after touchdown is given by:

$$\ddot{x} = -b_{\min} - (b_0 - b_{\min})e^{-t/\tau} \tag{1}$$

with $d^2x/dt^2(t = 0) = -b_0$, i.e., braking acceleration is assumed to consist of a constant and an exponentially decreasing part. Of course, this is a strongly simplified model which neglects, e.g., friction and different external forces like braking via reverse thrust. Parameter values as obtained from exponential fits to the logged simulation data are listed in Table 1. Also listed are the stop times $t_{\text{stop}} = t(v = 0)$, $v(t = 0) = v_0 = 70$ m/s and positions x_{Stop} as calculated from the solution to (1). The

Table 1 Deceleration profiles by fitting Eq. (**1**) to logged deceleration data [published in (Fürstenau et al. 2012), with permission]

	Landing braking parameters		
Nominal value (m/s^2)	1.0	2.0	3.0
b_0 (m/s^2)	1.33	1.76	2.39
$b_{\min}$ (m/s^2)	0.45	1.01	1.64
τ (s)	41.3	22.0	12.0
t_{stop} (s)	85.1	54.4	37.4
x_{stop} (m)	2544	1748	1238

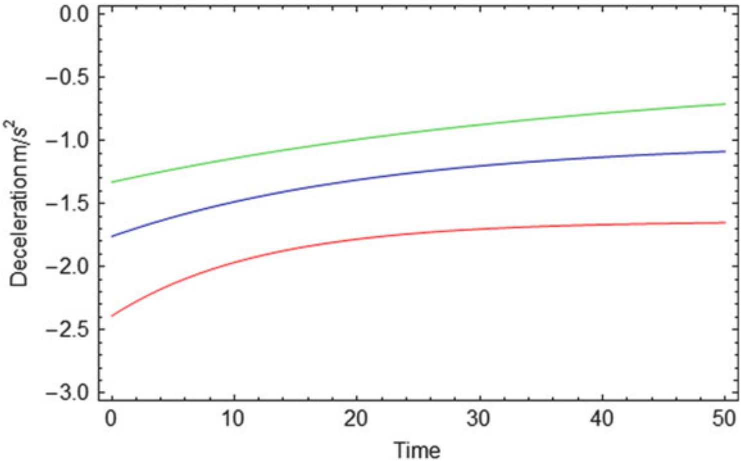

Fig. 3 Deceleration profiles (= decrease of braking acceleration) as obtained by fitting logged simulator data using Eq. (**1**) for the three nominal braking values 1, 2, and 3 m/s^2 [published in (Fürstenau et al. 2012), with permission]

table verifies that only the highest nominal deceleration avoids runway excursion (stop for $x <$ ca. 1500 m).

Braking acceleration profiles (decelerations) according to the equation of motion (1) with parameters in Table 1 are shown in Fig. 3. Calculations refer to runway coordinates with $x \parallel$ RWY, rotated by +4.1° with regard to (E, N, up)-coordinates; $x = 0$ at ARP. Touchdown is at $x = +$ 520 m. Closest distance from observation point to runway is $d_{\text{TWR}} = 330$ m at $x = +245$ m

The participants' task was to report as soon as possible whether the landing aircraft would stop before the end of the runway (stop event S2 (high deceleration), no-stop event S1 (runway excursion due to low deceleration), with response time measured by pressing the space bar. In all cases, they were then allowed to watch the actual outcome and use a certainty level compatible with actual operations. The three different deceleration profiles were randomized to produce a sequence of 30 landings in three blocks of 10. The three blocks were repeated once to provide the 60 landings in the experimental phase used for each of the independent groups. The experimental phase was preceded by a training phase during which the subjects were given familiarity practice with 20 landings similar to those used experimentally. This approach gave participants a chance to learn the task and adapt to a head mounted video-based eye tracker that they wore during the experiment[1]. Including instructions, the experiment required 1.5–2 h per subject.

In addition to the objective data, we recorded participants' subjective certainty regarding each of their decisions on a 0–3 Likert-like scale presented after each landing (0—total guess, 3—total certainty).

3 Results

Errors, reaction times, and estimates of judgment certainty were subjected to planned two-way independent groups ANOVA's based on a mixed design with Subjects nested within Update rate condition but crossed with Repetition which was quantized into 8 Experimental Blocks of 10 landings each, the period of randomization of the deceleration condition. Decision errors appeared to show a learning effect as can be seen in Fig. 4.

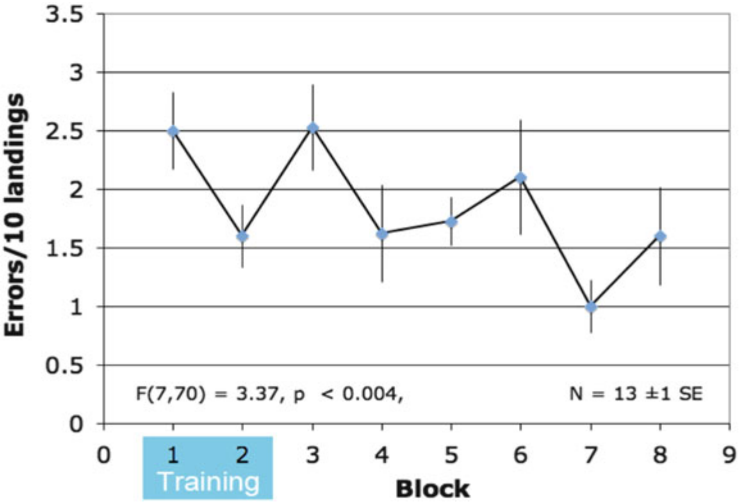

Fig. 4 Error rate as a function of repetition block [(Ellis et al. 2011a), copyright US-government: public domain]

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[1] Eye movements will not be discussed in this chapter. For analysis of eye movements, see chapter "Assessing Operational Validity of Remote Tower Control in High-fidelity Simulation" and references therein.

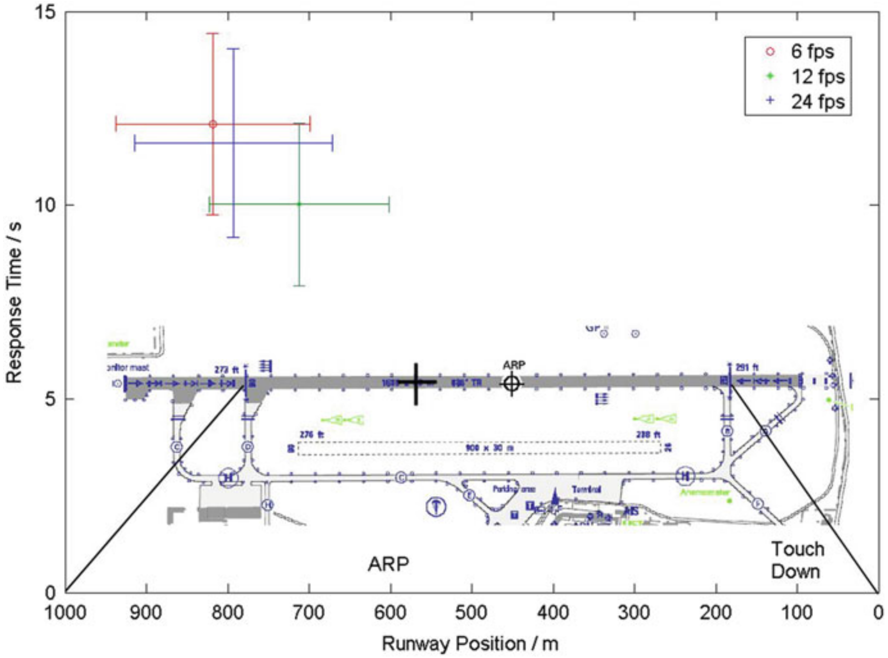

Fig. 5 Airport layout (inset projected to abszissa via *solid black lines*) with response times (ordinate) typically 10–11 s after touchdown, and with A/C typically around 800 m behind threshold (*black cross*), separated for the three frame rates and averaged over all landings (decelerations) and participants. ARP = Airport reference point at 600 m

But once the training blocks were removed and the remaining blocks grouped into two categories, first three (3,4,5) and last three (5,6,7), the statistically significant effect proved unreliable and disappeared ($F(1,10) = 1.52$, ns).

3.1 *Response Times*

Figure 5 shows the measured response times plotted into a graphic of the airport layout, as measured by participants pushing of the keyboard space bar at the operator console (see Fig. 2). The space bar pressing with yes-answer (=stop predicted) or no-answer (= overshoot predicted) occurs typically at RT = 10–11 s after observed touchdown. RT corresponds to *A*/*C* positions between 700 and 900 m behind the threshold.

We achieved the goal of approximately equal response times in the different frame rate conditions ($F(2,8) = 0.864$, ns). Response times after training remained approximately constant across blocks with a statistically significant variation ($F(5,40) = 3.91$, $p < 0.006$) of less than ±2.5 % when the training blocks were excluded.

Table 2 Response matrices (measured H, M; C, FA rates) for the three frame rates (Fürstenau et al. 2012)

Alternative stimuli	Response for 3 video frame rates: probability estimates				
	No-stop predicted			Stop predicted	
Low deceleration No-stop stimulus S1 $n(\text{S1}) = 40$	$p(\text{no}\vert\text{S1}) = C$	6	0.86 (0.02)	$p(\text{yes}\vert\text{S1}) = \text{FA}$	0.14 (0.02)
		12	0.89 (0.03)		0.11 (0.03)
		24	0.94 (0.01)		0.06 (0.01)
High deceleration Stop stimulus S2 $n(\text{S2}) = 20$	$p(\text{no}\vert\text{S2}) = M$	6	0.55 (0.06)	$p(\text{yes}\vert\text{S2}) = H$	0.45 (0.06)
		12	0.45 (0.05)		0.55 (0.05)
		24	0.22 (0.07)		0.78 (0.07)

3.2 Decision Statistics: Response Matrix

The experimental results of this two-alternative decision experiment concerning decision errors as dependent on video frame rate are summarized in the stimulus–response matrices of Table 2. It shows group averages of measured probability estimates, with standard errors of mean (), correct rejection $C = p(\text{no}|\text{S1})$, false alarm $\text{FA} = p(\text{yes}|\text{S1})$, miss $M = p(\text{no}|\text{S2})$, and hit $H = p(\text{yes}|\text{S2})$. S1 = stimulus with runway excursion, S2 = stimulus with stop on the runway, yes = stop predicted (high deceleration perceived), and no = no-stop predicted (low deceleration perceived). Probabilities in horizontal rows (constant stimulus) sum up to 1.

These results may be presented in the form of Venn diagrams as depicted in Fig. 6, which clarifies the character of the measured rates H, M, CR, and FA as conditional probabilities and their base sets with regard to situations (world states) S1 = no-stop and S2 = stop event.

The different areas (width) of the two columns representing situations (or alternatives) S1, S2 reflect different numbers of experimental no-stop (n(S1)) and stop rates (n(S2)), respectively, to be observed by the subjects, and of corresponding a priori probabilities p(S1), p(S2): $n(\text{S1}) + n(\text{S2}) = 60$ with $n(\text{S2})/n(\text{S1}) = ½$ (see also Table 2).

As a preliminary analysis of the results, Fig. 7 does show a significant effect of frame rate on the average error numbers per 10 landings and invites discussion. Extrapolation indicates a minimum frame rate > 30 Hz for minimizing decision errors.

Also it can be seen in Table 2 that like in the averaged error plot of Fig. 7, the measured probability estimates indicate a trend dependent on frame rate (FR): the hit rate $H = p(\text{yes}|\text{S2})$ increases with frame rate, whereas the false alarm rate $\text{FA} = p(\text{yes}|\text{S1})$ decreases. We will show in the following data analysis and discussion section how the measured probabilities in the response matrix can be used for deriving a (Bayes) inference on risk probabilities for safety critical decisions, dependent on the video frame rate as system parameter (risk for a world state different from the predicted event, i.e., risk of surprise situation) by using the a priori knowledge on relative frequencies of the planned experimental situation alternatives S1, S2.

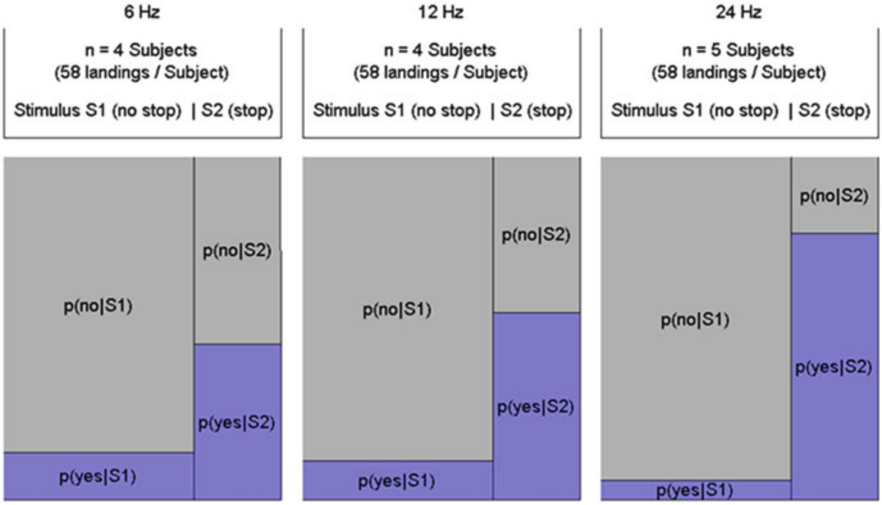

Fig. 6 Venn diagrams representing measured rates of correct ($H = p(\mathrm{y}|\mathrm{S2})$, $\mathrm{CR} = p(\mathrm{no}|\mathrm{S1})$) and false decisions ($M = p(\mathrm{no}|\mathrm{S2})$, $\mathrm{FA} = p(\mathrm{yes}|\mathrm{S1})$) for the two given world states (situations, events) S1 (= no-stop on RWY, insufficient braking, alternative 1 or "noise," in terms of SDT, see below) and S2 (stop on RWY, sufficient braking, alternative 2 or "signal + noise," in terms of SDT)

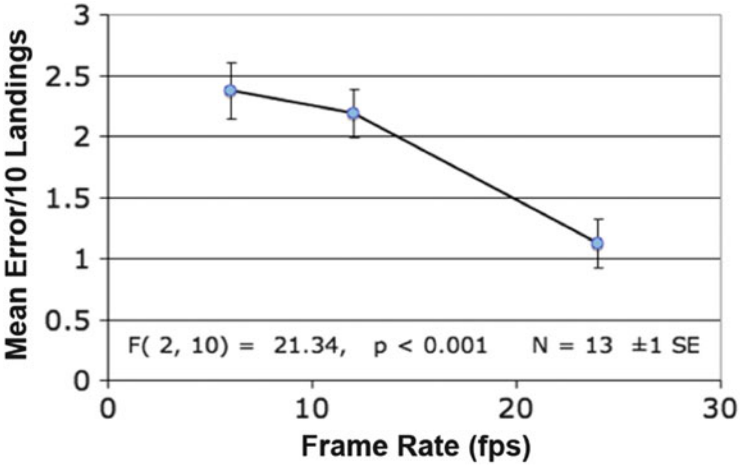

Fig. 7 Mean error rate as a function of frame rate [published in (Ellis et al. 2011a), with permission]

Besides the Bayes inference, the conditional probabilities of the detailed response matrix (Table 2, Fig. 6) will be used to derive a theoretically grounded data analysis for narrowing down the quantitative frame rate requirements. Specifically, the measured estimates of response probabilities conditional on the priori knowledge of experimental conditions (p(S1), p(S2)) suggest the use of signal detection theory (SDT) to derive a quantification of the detection sensitivity (discriminability) as the basis for estimating $\mathrm{FR}_{\mathrm{min}}$. This SDT-discriminability is free of a subjective criterion, i.e., free of a tendency towards more conservative (avoiding false alarms) or more liberal (avoiding misses) decision. For extrapolating towards a minimum required frame rate we will provide an initial hypothesis of a perceptual model to be used for fitting our data. A model-based data analysis would also provide guidelines for future experiments with the potential to generate further evidence supporting the conclusion.

Interestingly, during debriefings after the experiment subjects in the lower two frame rate groups reported that they felt the aircraft were moving "too fast" and that it was this extra apparent speed making discrimination hard. By "too fast" the controllers meant to refer to the apparent ground speed of a transport aircraft compared to what they would expect to see from a tower.

We examined this possibility by looking at a response bias that could arise from aircraft appearing to move "too fast." Such a bias would lead subjects to underestimate whether an aircraft actually coming to a stop would in fact stop, because it would seem to be going too fast. Aircraft in fact not stopping would not be subject to a bias since they would merely seem to be overshooting the end of the runway in any case. Thus, we would expect subjects to be more likely to incorrectly identify a stopping aircraft (S2) as non-stopping versus one that is not stopping (S1) as stopping. Details of this analysis are also presented in the following data analysis and discussion section (Sect. 4)

4 Data Analysis and Discussion

The present analysis will start with the simulation results of the movement/braking dynamics as obtained by integration of Eq. (1) using the parameter values of Table 1 with deceleration profiles of Fig. 3. It provides an impression of the requirements on perceptual discrimination during the experiments. The second subsection provides derivation of the Bayes inference on risk of unexpected world states by using likelihood values and a priori knowledge based on the response matrix of Table 2. The Bayes risks in turn are used for estimating via linear regression the minimum frame rate requirement that minimizes the risk of predicting the false world state. This result will be compared to the frame rate extrapolations of maximum discriminability based on a hypothesized exponential discriminability decrease as obtained from sensitivity index d' and nonparametric discriminability A (= average area under the ROC curves). Also the associated response bias will be discussed in more detail.

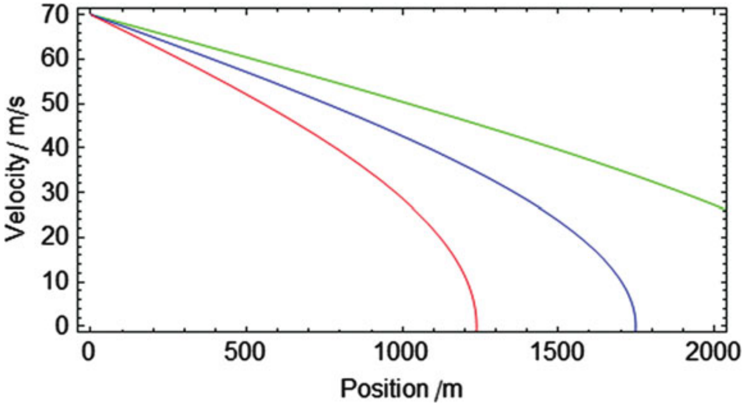

Fig. 8 Phase or state space diagram depicting simulated velocity [integration of equation of movement (1)] versus position

4.1 Simulation of Movement After Touchdown

The integration of the simplified equation of motion (1) for the braking dynamics with accelerations shown in Fig. 3 yields the observed angular movement at the simulated control tower/camera position after transformation into the corresponding reference frame. The result for the velocity dependence on runway position before the transformation is shown in Fig. 8.

This phase- (or state-) space diagram velocity *v* (position *x*) confirms that in fact only the highest deceleration value (red line) leads to a stop at 1200 m before the runway end (at 1650 m). The medium braking results in a slight overshoot, whereas the lowest deceleration leads to a dramatic runway excursion. The following Fig. 9 shows how this result translates into the viewing angle coordinates of an observer at the tower position.

The participants' prediction about stop/no-stop or sufficient/insufficient braking is done some time after passing the 0-angle point at ca. 44–48°, corresponding to the response time $R = 10–11$ s and 700–900 m distance from touchdown. In fact, the decision seems to depend on subtle differences between trajectories in angular state space at decision time considering the fact that the real 180°-panorama view is compressed to ca. 120° in the RTO-CWP panorama reconstruction. It was unclear during the preparation phase of the experiment if these small differences were large enough for discriminating at all between sufficient (stop event) and insufficient braking (no-stop event).

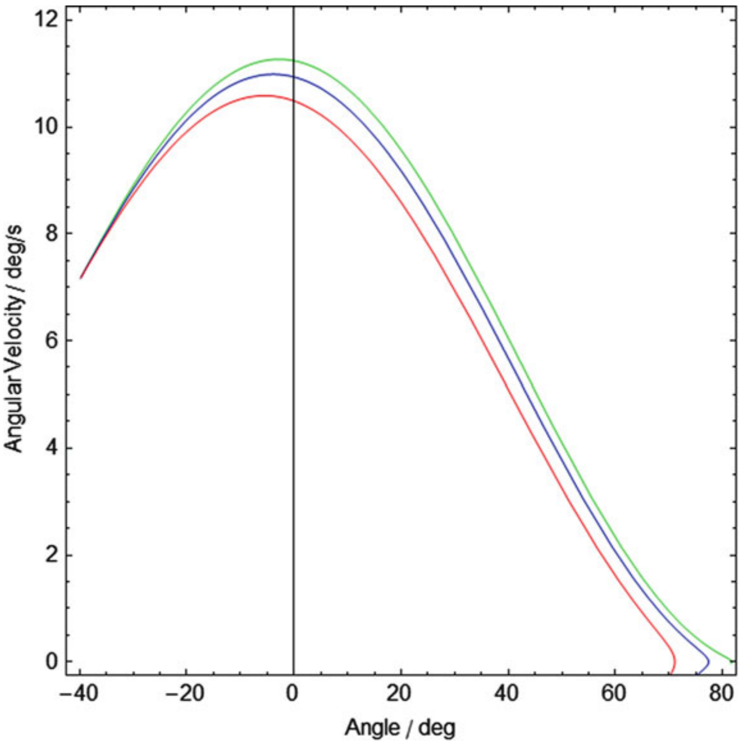

Fig. 9 Simulated angular velocity versus observation angle phase space after transformation of integrated equation of movement into observer coordinates at tower position. Highest angular speed near the normal from TWR to the RWY. $R = 10$–11 s is at 44–48

4.2 Bayes Inference: Risk of Unexpected World State

The Bayes inference probabilities, with standard errors of mean (), about unexpected event S1 (runway excursion with predicted stop) and unexpected situation S2 (stop occurring no-stop predicted) as calculated via Bayes law using the measured likelihoods (yes or no predictions conditional on situations S1 and S2, respectively) are summarized in Table 3. Here, the probabilities (for the same FR) of the columns add to 1.

The runway overshoot probability conditional on stop predicted (Bayes inference on the probability of world state S1 different from prediction "stop" based on perceived evidence) is given by

$$p\left(\mathrm{S1}\middle|\ \mathrm{yes}\right) = p\left(\mathrm{yes}\middle|\mathrm{S1}\right)p(\mathrm{S1})/p(\mathrm{yes}) \tag{2}$$

with a priori knowledge of no-stop stimulus probability $p(\mathrm{S1}) = n(\mathrm{S1})/(n(\mathrm{S1}) + n$ $(\mathrm{S2})$ according to the ratio of the Venn diagram areas and $p(\mathrm{yes}) = p(\mathrm{yes|S1})\ p(\mathrm{S1})$

Table 3 Bayes inference matrix for probabilities of actual world states (situations) conditional on decisions based on perceived evidence [likelihood × a priori knowledge. Published in (Fürstenau et al. 2012), with permission]

	Bayes inference on event probabilities conditional on prediction				
Event alternatives	No-stop predicted (no response)			Stop predicted (yes response)	
Low deceleration No-stop event S1	$p(\mathrm{S1}\mid\mathrm{no})$	6	0.78 (0.02)	$p(\mathrm{S1}\mid\mathrm{yes})$	0.40 (0.03)
		12	0.81 (0.02)		0.30 (0.04)
		24	0.91 (0.02)		0.13 (0.02)
High deceleration Stop event S2	$p(\mathrm{S2}\mid\mathrm{no})$	6	0.22 (0.02)	$p(\mathrm{S2}\mid\mathrm{yes})$	0.60 (0.03)
		12	0.19 (0.02)		0.70 (0.04)
		24	0.09 (0.02)		0.87 (0.02)

$+p(\mathrm{yes}|\mathrm{S2})p(\mathrm{S2})$. Equation (2) quantifies the risk of an overshoot occurring when predicting a stop, i.e., a surprising unexpected world state. It is proportional to the likelihood of missing a planned overrun $p(\mathrm{yes}|\mathrm{S1})/p(\mathrm{yes})$ (for a brief introduction on Bayes inference and references see Appendix B).

Figure 10 depicts the Bayes probability estimates for unexpected (surprise) world states dependent on frame rate, i.e., (a) unexpected runway excursion (S1) conditional on erroneous perception of a high braking deceleration (answer "yes": stop predicted) and (b) the probability $p(\mathrm{S2}|\text{no-stop}) = p(\mathrm{n}|\mathrm{S2})\ p(\mathrm{S2})/p(\mathrm{n})$ that an unexpected stop occurs when predicting no-stop. Both surprise events suggest a linear fit to the three frame rate data as most simple model. As expected, the $p(\mathrm{S1}|\mathrm{yes})$ graph (upper three data points) shows that for decreasing frame rates (FR → 0), the conditional probability for a runway excursion occurring when a stop is predicted rises to chance (0.48 ± 0.01).

Comparing both graphs one immediately recognizes a bias of the lower one, with $p(\mathrm{S2}|\mathrm{no}) \rightarrow 0.27$ for FR → 0 Hz, indicating a significantly reduced number of unexpected stop events conditional on the false "no" response, as would be expected by chance for lim FR → 0. As mentioned above, the S2/S1 imbalance of 1/3 stop events and 2/3 no-stop partly explains this bias: the extrapolation to $\mathrm{FR} = 0$ (no movement information available) yields $p(\mathrm{S2}|n) = 0.27$ and $p(\mathrm{S1}|n) = 0.73$ for the complimentary case so that for low FR with large position jumping $p(\mathrm{S2}|n)/p(\mathrm{S1}|n) \approx 0.4$ reflects the S2/S1 imbalance of 1/2. The decrease of the $p(\mathrm{S2}|n)$ bias and decision bias $p(\mathrm{n}|\mathrm{S2})$ (tendency for false overshoot prediction under S2) with increasing FR goes in parallel with the decreasing overall decision error. So the Bayes analysis confirms the previously reported decision bias (Ellis et al. 2011a, b) as quantified by $M\text{–FA} = p(n|\mathrm{S2})\text{–}p(\mathrm{y}|\mathrm{S1})$ which also decreases with increasing frame rate (see Fig. 11 below). Within the 95 % confidence interval of the linear fit to the data, also $p(\mathrm{S2}|\mathrm{no})$ predicts zero bias and 100 % correct response for frame rates > 35 Hz, which is compatible with the FR limit of zero-error prediction obtained with the "unexpected stop" probability. The linear extrapolation of the Bayes analysis narrows the initial estimate of $\mathrm{FR}_{\mathrm{min}} > 30$ Hz as depicted in Fig. 7 to ca. 30–45 Hz in Fig. 10.

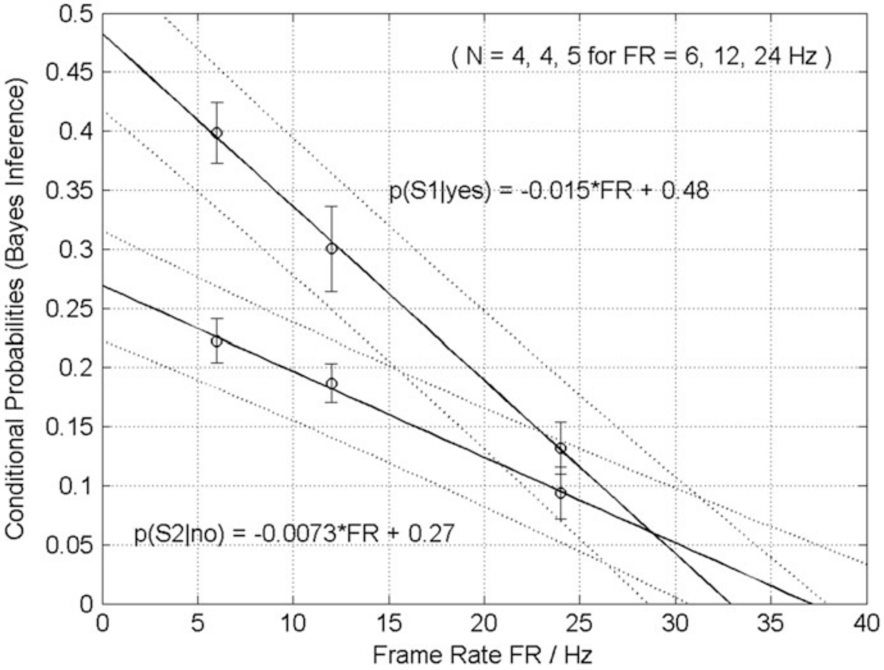

Fig. 10 Bayes inference for the three frame rates (Abscissa) on probability of (a) (upper data points and fit) unexpected situation S1 "a/c will not stop before RWY-end" (braking acceleration $<$ threshold), given the alternative (false) stop-prediction, as calculated from measured likelihoods of subjects predicting "stop on RWY" conditional on S1 (= FA); and (b) (lower data points and fit) of world state S2 "a/c will stop before RWY-end" (braking acceleration $>$ threshold) as calculated from measured probabilities (likelihood) of subjects predicting "overshoot," conditional on S2 (a priori knowledge). Ordinate: mean (with stderr of mean) of probability for (unexpected) situation S_i conditional on prediction/decision d_i, averaged for all subjects within each FR-group. *Straight line* = linear fit with 95 % confidence intervals (*dotted*)

The hypothetical visual memory effect mentioned above would suggest an exponential approach to a minimum error probability with increasing FR instead of a linear behavior. The exponential fit to our data, however, yields a significantly reduced goodness ($F = 140$, $p = 0.054$) as compared to the linear case ($F = 645$, $p = 0.025$), which demonstrates the necessity of experimental data at higher frame rates.

The Bayes analysis also confirms the observation reported before in (Ellis et al. 2011a, b) (see also below, Fig. 11) that the error bias appears exclusively connected with the preference of no-stop decisions, i.e., unexpected stop situations with a lower than chance error probability at FR = 0, because the false-stop prediction errors, as expected, yield a chance Bayes probability $p(\mathrm{S1|yes}) = 0.5$ for FR → 0 (see Fig. 10). The same is true for the complementary case $p(\mathrm{S2|yes})$. The observation of a significant bias of the unexpected-stop event inference (p(S2| no) suggests the need for counter measures, perhaps temporal filtering to smooth

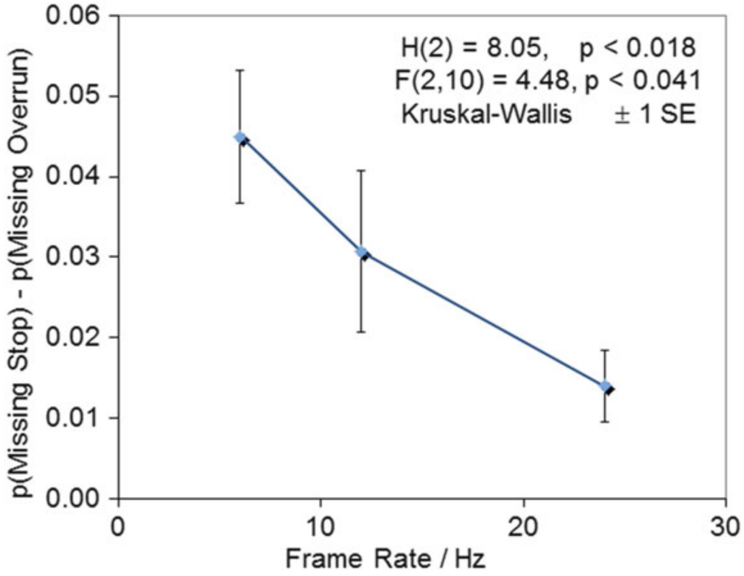

Fig. 11 Error bias (M–FA, normalized for ten landings; $N = 13$, see Figs. 4, 7) towards reporting a runway overrun increases the likelihood of missing a planned stop over missing a planned overrun. Effect decreases with FR [re-drawn from (Ellis et al. 2011a), with permission]

out the discontinuities. Such an approach would undoubtedly benefit from a computational model of speed perception. One starting point for such analysis of the speed perception error could be the spatiotemporal aliasing artifacts that introduce higher temporal frequency information into the moving images.

The measured probabilities of Table 2 used for calculating the Bayes inference are based on error statistics composed of intrinsic discriminability and subjective criteria, i.e., it includes a decision bias or subjective preference for positive or negative decisions. In what follows, parametric and nonparametric variants of signal detection theory (SDT) are used for quantitatively separating both contributions and comparing the resulting FR_{min} estimates with those of the Bayes inference.

4.3 *Response Bias*

A response bias is a well-known effect of low video frame rate on apparent speed of moving objects that is caused by *undercranking*, a movie camera technique of slowing the image frame capture rate compared to the display rate, e.g., for visualizing the growth of plants at an apparently higher speed.

From the results described above, we would expect subjects to be more likely to incorrectly identify a stopping aircraft versus one that is not stopping. Indeed, when we compared the likelihood of erroneously identifying an overshoot versus that of erroneously identifying a stop (Table 2) M–FA $= p(n|\mathrm{S2})–p(\mathrm{y}|\mathrm{S1})$, all 13 subjects showed this bias (sign-test, $p < 0.001$). This general bias towards identifying an aircraft as not stopping, however, is not surprising since approximately twice as many aircraft observed in fact do not stop versus those that do ($p(\mathrm{S1}) = 2\ p(\mathrm{S2})$) and subjects quickly sense this bias during the experiment. What is interesting, however, is that the bias is a decreasing function of the frame rate as depicted in Fig. 11.

The significance of this result, however, needs support based on theoretical considerations and on alternative analysis. The detection bias is clearly reflected by the Bayes analysis as performed above (Fig. 10). Like the error difference, it exhibits a lower than chance probability for $p(\mathrm{S2}|\mathrm{no})$ with lim FR $\rightarrow 0$, yielding $p(\mathrm{S1}|\mathrm{yes})/p(\mathrm{S2}|\mathrm{no}) \approx ½$, that reflects the $p(\mathrm{S1})/p(\mathrm{S2})$ ratio and like the above error difference converges to zero with increasing FR.

Of particular practical interest is the inferred risk of missing a high speed turnoff or of a runway excursion occurring when a stop is predicted, i.e., the conditional probability of overshoot $p(\mathrm{S1}|\mathrm{yes})$ (S1 = no-stop event) due to low or abnormal braking when evidence suggests normal braking (stop prediction).

4.4 SDT Discriminability d′ and Decision Bias c

The principal result of data analysis using signal detection theory (SDT) is shown in Figs. 12 and 13. It confirms the Bayes analysis and suggests that relatively high update rates $\mathrm{FR}_{\mathrm{min}} > 30$ Hz will be required for imagery in virtual or remote towers if controllers working in them are expected to perform the kinds of subtle visual motion discrimination currently made in physical towers. Figure 12 depicts the experimental results of Table 1 in ROC space (receiver operating characteristics) H versus FA. Plotted are the measured hit and false alarm rates for the 13 participants and the three frame rates together with the respective averages (black crosses) and the ROC isosensitivity and isobias curves, parameterized by discriminability d' and criterion value c, respectively. d' and c are calculated according to:

$$d' = 0.5(z(H) - z(\mathrm{FA})) \tag{3}$$

$$c = -(z(H) + z(\mathrm{FA})) \tag{4}$$

with $z = z$-score of cumulative Gaussian densities of the S1-, S2-familiarity distributions (see also Appendix B).

The positive criterion values indicate the controllers' tendency to make conservative decisions, i.e., avoiding false alarms, increasing misses, and trying to be certain about their decisions, according to their work ethics and the written instructions of the experiment. The decrease of this effect is consistent with the decreasing error bias M–FA with increase of FR as reported above.

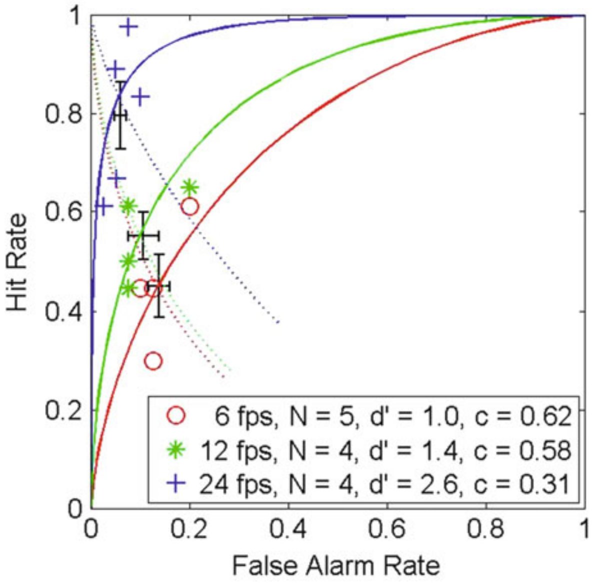

Fig. 12 ROC curve pairs parameterized (d', *solid curves*, c, *dotted curves*) for each of the three frame rates based on Hit and False Alarm rates for each subject. Crosses are the averages for each frame rate subgroup of participants. ROC curves $d'(z(H), z(FA))$, and $c(z(H), z(FA))$ are calculated with the d' and c subgroup averages of the 13 participants. Experimental data and d' parameterized ROC curves correspond to results initially presented in (Ellis et al. 2011a)

In Fig. 13, we have also replotted a result from Claypool and Claypool (2007) examining the effect of change in frame rate on video game shooting score. These overlaid data empirically support our theoretical supposition that the users' performance at higher and higher frame rates may be modeled by an exponentially approached limit. It is certainly interesting that their report of the effect of frame rate on video game score in a first-person-shooter game resembles our results since their task and response measure were so different. In particular, their use of shooting score does not capture the interplay of shooting frequency and hits in a way analogous to that of correct detections and false alarms in our experiment.

Our analysis of d' is in contrast to their count of shots on target, and it is particularly useful since it can be argued to be bias-free, independent of user criteria, and primarily a function of the task requirements and perceptual estimation noise. It can additionally be cross-checked with extrapolation of the error data shown in Fig. 4 and the Bayes inference in Fig. 10, but this extrapolation for errors is harder to justify theoretically without a computational error model. A linear extrapolation which likely underestimates the value, however, suggests that ~40 fps would be needed for a vanishingly small error rate. Based on our exponential memory (sample-and-hold) decay hypothesis, the asymptote of the d' (FR) analysis, like the Claypool and Claypool (2007) data, indicates a higher FR_{min} value, more towards 60 Hz.

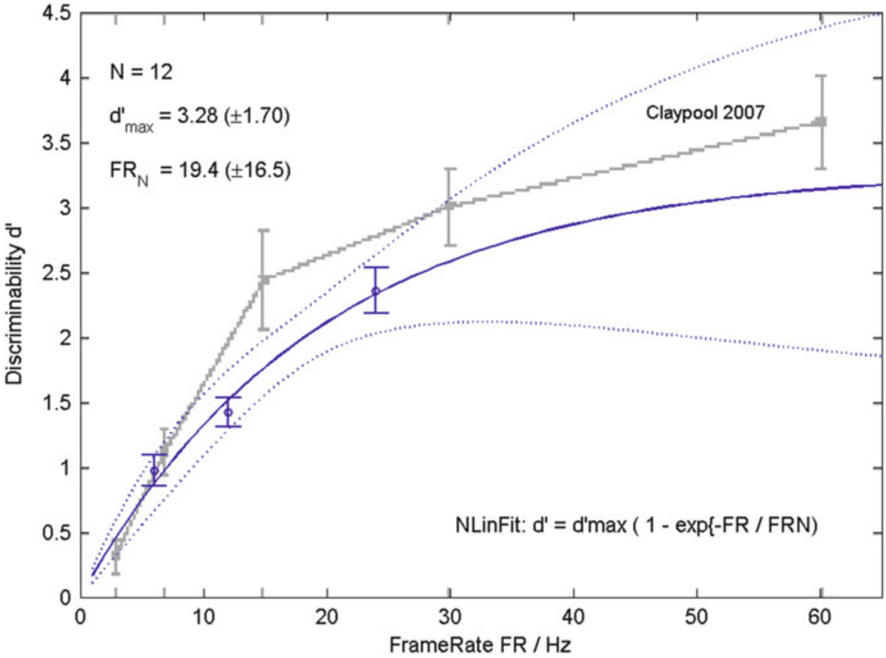

Fig. 13 Group averages ($N = 12$ subjects) of experimental discriminability values d' and exponential regression model (*blue solid trace*) for the stop/no-stop discriminability of landing aircraft. The *lighter gray trace* plots comparative data from Claypool and Claypool (2007). *Dotted lines* show the 95 % regression confidence range. Comparable results for 13 subjects were initially presented in (Ellis et al. 2011a)

4.5 Nonparametric Discriminability A *and Decision Bias* b

Detectability A and likelihood bias parameter b were suggested as improved "nonparametric" alternatives of the conventional discriminability d' and criterion c because it requires fewer statistical assumptions [in its final form it was presented by Zhang and Mueller in 2005 (Zhang and Mueller 2005)]. In (Ellis et al. 2011b), we compared A with d' to estimate user sensitivity of detection that an aircraft will stop. Discriminability A and b are independent of the distributional assumptions required for deriving the conventional d' and c parameters for detectability and bias (see Appendix B). The Zhang and Mueller formulas yield the average area A under all possible proper ROC curves (i.e., all concave curves within the range (0,0)–(1,1)) with nonincreasing slope, obtained from the measured hit (H) and false alarm rates (FA). The constant A-isopleths cut the constant b-isopleths at the group mean (<FA>, <H>) coordinates which are used for calculating the A and b-ROC curves: $A := A_{\text{mean}}(H,\text{FA})$ and $b := b_{\text{mean}}(H,\text{FA})$ for the three different frame rate conditions according to the Zhang and Mueller equations (see Appendix B).

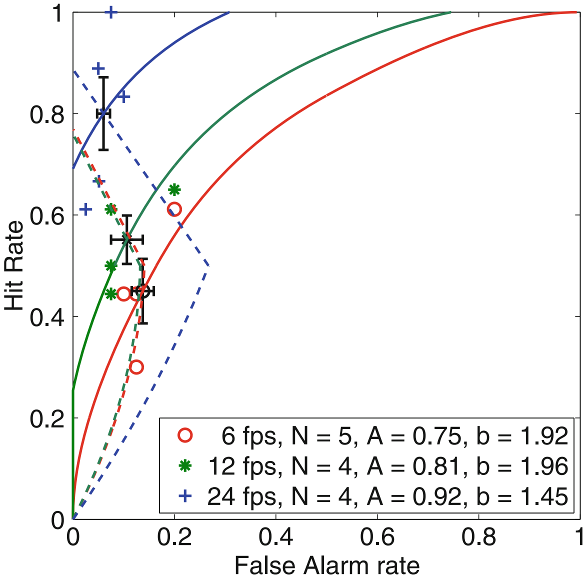

Fig. 14 Measured hit versus false alarm rates (H, FA) for all 13 subjects and the three group averages with standard errors (*crosses*) and with ROC curves for the three frame rates. *Straight lines* = constant sensitivity A-isopleths; *dotted lines* = constant bias (likelihood ratio) b-isopleths [Results published in (Fürstenau et al. 2012), reproduced with permission]

Figure 14 shows the measured hit rates versus false alarm rates for all subjects together with their means (black crosses, as given in Table 1) and isopleths parameterized by constant discriminability A(FR) and constant decision bias b(FR).

Individual hit rates (relative frequencies) are scattered between 0.3 and 1, whereas false alarms rates concentrate in the low probability range < 0.2, indicating conservative decisions, as would be expected for trained air-traffic controllers. Circles, stars, and crosses represent individual measurements (Hit, False Alarm) for FR = 6, 12, and 24 Hz, respectively, as obtained from the 13 subjects with repeated measurements (60 landings per subject). Black crosses with error bars show the group mean values of the individually measured (F,H)-values and the standard errors of means for the three different frame rates. Solid curves represent the isopleths parameterized with the group mean A-values via Eq. (B.15) in Appendix B. The three dotted curves represent the decision bias b, obtained from the parametric representation given in Appendix B. b apparently decreases with sufficiently high frame rate FR towards the neutral criterion value $b = 1$ which confirms the Bayes inference result in Fig. 10 that the overestimation of speed (error bias in favor of misses, decreasing FA) decreases with frame rate: the criterion shifts to more liberal values.

The three (group-average) discriminability parameters A(FR) are depicted in Fig. 15 together with an exponential fit and 95 % confidence intervals (using Matlab “Nlinfit”).

Again, like in the d'(FR) analysis, the exponential model fit to our three data points is based on the hypothesis that low frame rates might disturb the visual short-term memory so that with increasing visual discontinuity the speed estimate or sequential sampling of the speed information up to the decision time becomes

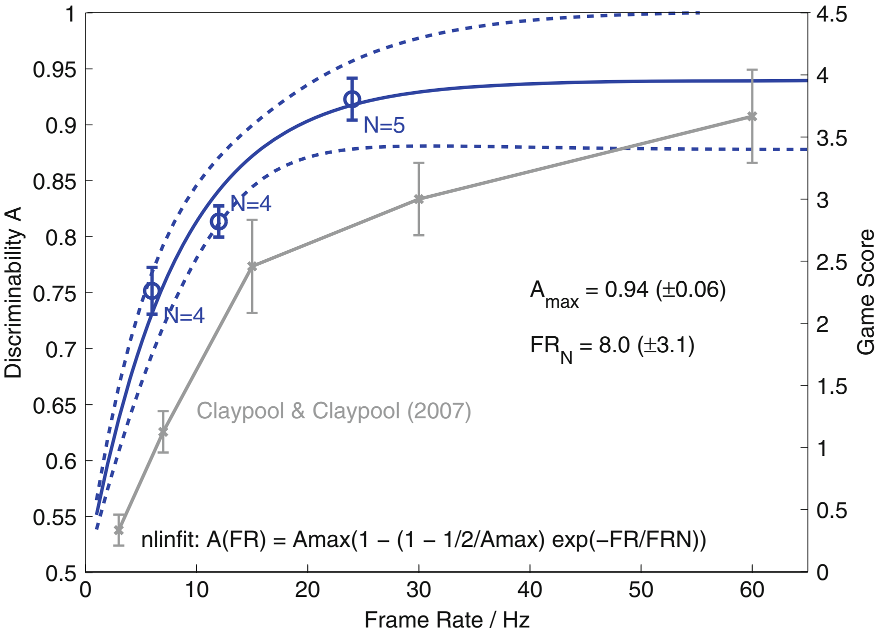

Fig. 15 Group averages (13 subjects) and exponential regression model for A (*darkest solid trace*) of the discriminability of landings with stopping versus non-stopping aircraft. The 95 % regression confidence intervals flanks the model fit. *Lighter gray trace* shows re-drawn comparative data from (Claypool and Claypool 2007) [Result published in Ellis et al. 2011b, Fürstenau et al. 2012, with permission]

biased. Since the *A* parameter unlike the classical d' does not require the usual assumptions of Signal Detection Theory (SDT), e.g., normality of both the signal and noise distributions, it may be considered to provide a better estimate of the frame rate at which participants' performance asymptotes as provided in Ellis et al. (2011a) (see previous section). From Fig. 15, this value seems to be in the range 30–40 fps, a result close to the Bayes analysis with linear model extrapolation (see above), whereas the parametric SDT analysis d'(FR) appears to asymptote at a significantly larger value.

Alternatively and for the sake of parsimony, our three data points, like with the Bayes analysis, may be fitted with a straight line, yielding an extrapolation to ca. 31 Hz for $A = 1$ (maximum discriminability), which lies at the lower end of the Bayes fit confidence intervals.

Like in the d'(FR) analysis, our results are compared with the (re-drawn) published results of Claypool and Claypool (2007). The latter were obtained with subject scores in a shooter game under different frame rates. As mentioned above, they suggest a significantly higher asymptotic FR value for maximizing shooter scores as compared to our extrapolation in Fig. 15, apparently more consistent with our d'(FR)-extrapolation.

Clearly, additional experiments with $FR > 30$ Hz are needed, if possible supported by a well-founded theoretical model, in order to clarify this discrepancy between the different data analysis approaches.

5 Conclusion

It is clear from controller interviews that numerous out-of-windows visual features are used for control purposes (Ellis and Liston 2010; Van Schaik et al. 2010; Ellis and Liston 2011) (see also chapters "Visual Features Used by Airport Tower Controllers: Some Implications for the Design of Remote or Virtual Towers" and "Detection and Recognition for Remote Tower Operations"), which in fact go beyond those required for aircraft detection, recognition, and identification (Watson et al. 2009). In the present work, for analyzing frame rate effects on prediction errors we focused on the landing phase of aircraft because we expected any perceptual degradation to be most pronounced in this highly dynamic situation.

Our preliminary results on the minimum frame rate for minimizing prediction errors ($FR_{min} > 30$ Hz) show that a definitive recommendation of a minimum video frame rate and a confirmation of our initial hypothesis of visual short-term memory effects resulting in the proposed asymptotic characteristic require a further experiment with $FR > 30$ Hz. This high-FR experiment was not possible with the video replays used in the described experiments for technical reasons. Obviously, the presented experimental data are not sufficient to decide in favor of the visual short-term memory hypothesis versus a heuristic decision basis, e.g., sequential sampling or comparison of time dependent aircraft position with landmarks for thresholding. One alternative approach might be some variant of a relative judgement or diffusion model of two-alternative decision making [e.g., (Ashby 1983)].

A formal model for predicting the hypothetical visual memory effects would also be of great help. Recent studies which might be of use for this purpose investigate neural models for image velocity estimation [e.g., (Perrone 2004)] and quantify the temporal dynamics of visual working memory by measuring the recall precision under periodic display presentations between 20 ms and 1 s (Bays et al. 2011; Anderson et al. 2011).

Also more detailed tower controller work analysis would be useful to clarify the operational relevance of increased frame rate for decision error reduction with dynamic events in the airport environment.

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Planning Remote Multi-Airport Control—Design and Evaluation of a Controller-Friendly Assistance System

Rodney Leitner and Astrid Oehme

Abstract A number of research projects aim at air traffic control independent from the controller's location and his outside view. In the context of one of these projects—VICTOR (Virtual Control Tower Research Studies), which was initiated by the German air navigation service provider Deutsche Flugsicherung (DFS), a completely new concept of Aerodrome Remote Control Center (ARCC) was investigated. In contrast to previous approaches, the ARCC concept broadened the monitoring and controlling capabilities of the tower controller towards several airports at the same time. It thereby created new requirements for air traffic control, i.e. an eminent need for planning the air traffic flow of multiple airports. For this additional task, the concept of a planning tool was developed taking into consideration a user-centered approach, the guidelines for usable interfaces and a well perceived user experience. Following these Human Factors standards, our planning tool was developed to be useful and ensure safe handling, but also to look and feel good. For its evaluation, an analytical inspection method, i.e. heuristic evaluation, has been used as well as a questionnaire assessing the aesthetics of the graphical user interface. Eight usability experts assessed the tool, taking notes of any peculiarities and usability problems and carrying out the associated severity rating. With the help of this methodology, 56 issues were identified and corrected. Furthermore, results from additional qualitative statements of the experts for development and optimisation of the user interface were subsequently used for redesign. In terms of looks, the planning tool scored above average in aesthetics ratings. This chapter briefly introduces the tool and its design, and subsequently focuses on our evaluation procedure and results.

Keywords Multiple airport control • Remote control • Air traffic planning • Usability • User experience • UX • Design • Evaluation • Human factors

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1 Introduction

While air traffic has continuously been increasing to 3.3 billion passengers in 2014 and is likely to more than double in the next 15 years (AIRBUS SAS 2013, IATA 2014), a growing fragmentation of the European airspace was identified as a major challenge as early as the late 1990s. Reacting to this obvious trend, the Single European Sky (SES) initiative initiated a reorganisation of the European airspace based on traffic flows instead of national boundaries and proposed additional measures for air traffic management to achieve key objectives: improving and increasing safety, enhancing efficiency and integrating air traffic control services.

At the same time, an intensified liberalisation in Europe had an impact on its air traffic management as well. The air navigation services regulation [the service provision Regulation (EG) 550/2004] opened air navigation services in European states for additional providers. SES regulation as well as SES's focus on efficiency have increased both cost pressure and competition at regional airports and require new, innovative air traffic control (ATC) concepts to tackle multiple challenges. Many air navigation service providers (ANSPs) focus on cost efficiency and have introduced assistance systems and automation to further minimise personnel expenses. In addition to these efforts, several international projects have attempted to realise an ATC workplace independent of location and weather by including a synthetic outside view to increase control capacities at airports.

This chapter reports on the development and first evaluative steps of an assistance system, which serves a novel concept of operations for regional airports. Addressing unique issues of these airports, such as highly inhomogeneous traffic density, the system is conceptualised for a new kind of controller working position. The chapter focuses on the user-centred design process we followed during system realisation and especially dwells on an expert evaluation carried out during prototyping. However, as a start, we give a short introduction on the operational concept the assistance system is designed for and its origination background, before focussing on user requirements towards the system and the evaluation process.

2 Multi-Airport Control

Traffic density at regional airports fluctuates highly and depends on a series of factors like time of the day and weather conditions. Except for the usual peak times in the morning hours and in the late afternoon/early evening, traffic density usually is very low. In particular at smaller airports, this uneven capacity utilisation decreases efficiency. Furthermore, the tasks of an air traffic controller (ATCO) are reduced to tediously surveying the airport ground and the respective control zone. One way to implement a more even distribution of workload, thus, is to bundle the controlling activities of ATCOs in one control centre especially during phases of expected low traffic density. A range of projects follow this approach and work towards an ATC that is independent of outside view. In general, the realisation aims at substituting the outside view. Sensor-based data, which complement video information and provide a clear view on the air traffic area and the nearer surroundings, can overlay the displayed output and support the ATCO with supplemental information.

It is this development of remote tower services that has been supported in the frame of the SES ATM research programme of the public–private partnership SESAR Joint Undertaking and that has helped to realise the first remote tower prototype in Sweden. The project Advanced Remote Tower (ART) established an ATCO working position independent of outside view and location outlined above and was realised with the Saab Remote Tower System (r-TWR). This concept is limited to remote control of one single airport, which is why we proposed an expansion of the control towards several airports applying a so-called Aerodrome Remote Control Centre (ARCC) (Oehme and Schulz-Rückert 2010; Oehme et al. 2013). Obviously, this approach requires an altered, novel operational concept, the development of a new working position and the development of novel controller assistance systems. We will sketch this operational concept that is used, e.g. in VICTOR (Virtual Control Tower Research Studies) in the following paragraphs.

2.1 Concept Behind VICTOR

VICTOR was conducted on behalf of the German air navigation service provider DFS within the German aviation research programme LuFo IV. Its Concept of Operations (ConOps) envisioned two controller working roles: a master controller (MC) and a remote controller (RC) (Oehme et al. 2013; Wittbrodt 2012).

The RC's mode of operation differs from common controllers in one aspect only: the RC has to rely on the video- and sensory-based outside-view substitute provided, because an outside view of the tower is not available. Currently, there is no job position similar to the MC, which is why a detailed operational concept and appropriate assistance systems have to be developed. The new ATCO working position will offer the MC the opportunity to monitor several airports and to actively control one flight movement at a time. Thereby, the concept patently aims at increasing efficiency during low capacity utilisation. In case of rapid traffic increase and the accompanying increase in the MC's workload, one airport will be handed over to a RC. Consequently, the MC only controls the remaining airports, and additional RC working positions will be opened, depending on situation-related demand in case of additional traffic increase. During decreasing traffic, the MC will eventually repossess the responsibility of the airports from the various RCs, and the respective RC positions will be closed.

2.2 Necessity and Elements of a Planning Tool

Since traffic balancing and traffic flow management are demanding tasks, the assistance system used has to assist the ATCO by providing a favourable workload distribution and related attention allocation. Useful and accepted arrival and departure management systems are already available for single airport control (e.g. Bergner et al. 2009).

Compared to the role of current ATCOs, the MC's role contains newly defined role aspects and tasks. In addition to an ATCO's monitoring and control, the MC has to carry out administrative and planning tasks. The planning tasks include sequencing the flight movements, rearranging those movements according to situational demand and organising RC positions by opening them up or closing them again. The MC has to carefully balance the total number of RCs and the respective airport they are responsible for. In this context, both economic and operational factors need to be taken into consideration in order to increase safety and efficiency. For these planning tasks, the MC needs a tool supplying the relevant information and thereby supporting the decision making. It should, e.g. provide an overview of all movements so that the controller can analyse traffic movements and density in order to optimise sequences for controlling the movements one by one in case of overlaps.

Following this ConOps as a first basis, our assistance system supports the MC in these planning tasks. Relating to the novel working position 'MC', it is called MasterMAN (see Fig. 1).

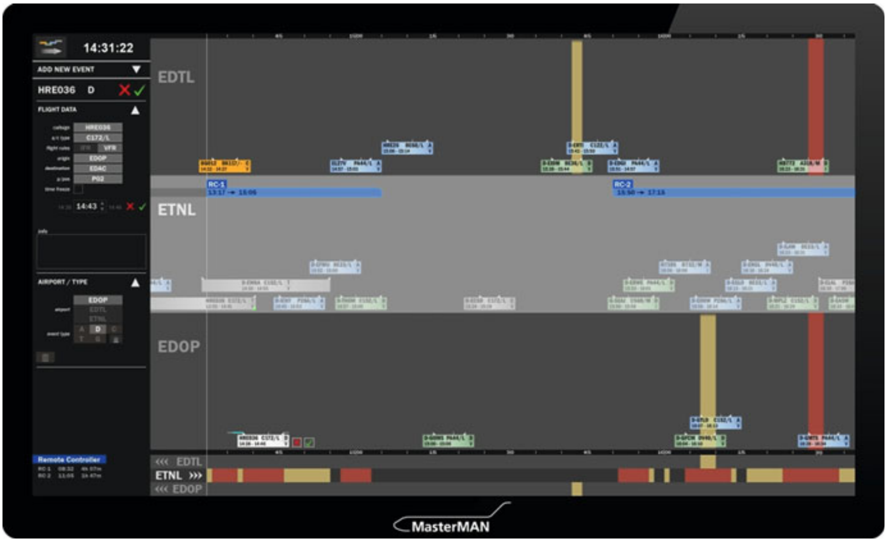


Fig. 1 User interface of MasterMAN

2.3 Requirements for MasterMAN Planning Tool

The success of new systems depends mainly on how well they suit the task they are built for and on the users' acceptance. Consequently, the approach of user-centred design was applied in the development process of the planning tool described here in order to allow for end users to be systematically integrated into the system development process (cp. Moser 2012). Due to their professional expertise, ATCOs can detail best what expectations and requirements they have regarding technical devices for airport control.

Following this approach, we integrated ATCOs in the development process by conducting a focus group with them to identify their specific requirements for such a planning tool and to thus boost their acceptance of the new system. The results were transferred into a requirements matrix of three different fundamental classifications: functional requirements, data requirements and quality requirements.

Data requirements describe the information end users receive from the system and which is essential to their tasks and needs to be readily accessible, e.g. data for a specific call sign, aircraft type or flight. The functional requirements reflect the actions end users want to carry out using this information and result from the interaction of the user with the system. Quality requirements detail how these functional requirements have to be implemented (cp. Leitner and Jürgensohn 2014a) and significantly impact the usability of the system. In total, these user requirements form the basis for the development of the planning tool and are used to develop use cases, stipulate an information and interaction design and develop a graphical user interface. A comprehensive overview of the planning tool is provided in Leitner and Jürgensohn (2014b), while Leitner et al. (2011) report on its related functional, data and quality requirements.

3 Usability/User Experience

3.1 Usability

It is obvious that a system high in usability is easy to use, which is why user friendliness has increasingly gained importance for system development in the last decades. Usability criteria support developing systems with a user-friendly and ergonomic design (Sarodnick and Brau 2011, p. 18).

The international standard *Ergonomics of human-interaction systems* (DIN EN ISO 9241–11:1999–01) describes usability as 'extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use'. The usage context includes the user, the task and the means to fulfil the task within the setting in which a product is used. Effectiveness is described as the accuracy and completeness with which the usage goals can be achieved, whereas efficiency is a measure of effective goal achievement in relation to the resources needed. Usability not only aims at the suitable/appropriate usage of a system but also sets the requirement that the system supports the user in reaching his/her goals in the respective field of application. Usability is a quality feature of products or systems and describes the goal of interface development in incorporating ergonomic findings (Sarodnick and Brau 2011). A systematic assessment of user satisfaction can be carried out by applying a variety of usability evaluation methods (Lehr 2011).

Designing and developing systems with a high usability holds many advantages. These systems are technologically and commercially successful with customers willing to pay more for this quality standard (DIN EN ISO 9241–210:2010–06, p. 8), mainly because usability increases user productivity and thus acceptance and on the provider side reduces expenses for customer support services and training.

Preceding the system development, the usage context has to be defined and subsequently user requirements have to be derived (c.f. Sect. 2.3). These are derived from needs, desires and conditions of the user and describe which goals a user wants to reach with a system.

3.2 User Experience

User experience (UX) is a broad psychological- and human-factors-related construct that maps the perception and response of a person resulting from an actual or expected usage of a product, system or service (ISO 9241–210:2010). According to Hassenzahl and Tractinsky (2006), UX is ‘a consequence of a user's internal state (predispositions, expectations, needs, motivation, mood, etc.), the characteristics of the designed system (e.g. complexity, purpose, usability, functionality, etc.) and the context (or the environment) within which the interaction occurs (e.g. organisational/social setting, meaningfulness of the activity, voluntariness of use, etc.)’. For these authors, a system comprises pragmatic and hedonic qualities with the former concentrating on a product's utility and usability in relation to potential tasks. The latter, however, focuses on the user, i.e. it addresses his/her feeling of so-called ‘be-goals’ (e.g. ‘being competent’, ‘being related to others’, ‘being special’) and general needs (e.g. for novelty and change, personal growth, self-expression and/or relatedness) (Hassenzahl 2008). Hedonic attributes of a product or service thus refer to the user being stimulated (personal development, new impressions), being able to communicate his identity to others (social recognition), and by the products' ability to evoke memories (Hassenzahl 2003). They contribute directly to the core of positive experience, while pragmatic quality does so only indirectly by facilitating its fulfillment. In a similar fashion, the CUE Model (Components of User Experience; Thüring and Mahlke 2007) distinguishes between two qualities: instrumental qualities refer to the experienced amount of support provided by the system and its ease of use (i.e. pragmatic qualities), while non-instrumental qualities address the look and feel of the system. Emotions elicited by the system use are a third component. These three constituents result in the user's overall appraisal of the system and thus influence future decisions and behaviour, e.g. their decisions to use the system regularly, if at all, or their intention to migrate to a different system with potentially similar capabilities.

Despite this obvious major importance, UX is often not considered in the working context. In contrast to other approaches, MasterMAN embraces UX in an aesthetically appealing graphical design in order to facilitate stimulation, user acceptance and ultimately usability.

4 Evaluation of MasterMAN

The development of the system's user interface should hold iterative testing intervals. Preferably, early and regular assessment detects initial shortcomings or even maldevelopments, so those can be remedied quickly and at low costs (Baumann and Lanz 1998, p. 8f). Applicable methods range from formal–analytic methods (analytic task analysis, expert guidelines) through inspection methods (heuristic evaluation and walkthrough methods) to usability tests (inductive or deductive) and surveys using questionnaire (e.g. ISONORM, QUIS or SUMI) (Sarodnick and Brau 2011). We evaluated MasterMAN at an early stage in the form of a *working partial system* prototype (Rosson and Carroll 2002). This was an operative system version which featured the majority of the final system's functionalities in a so-called mixed prototype. While horizontal prototypes provide the entire, but only partially implemented set of functionalities of the human–machine interface, vertical prototypes are limited to fully operating parts of the system (Dumke 2001; Sarodnick and Brau 2011). Integrating the advantages of both kinds of prototypes was used to give early testers the impression of a complete system and to thus suggest its real-life performance in order to be able to include their feedback at later stages of the development process.

4.1 Test Design and Procedure

Besides trying to uncover undetected errors in functionality, the tests were also meant to collect feedback on MasterMAN's quality of experience and UX. As a *working partial system* prototype, it featured all basic functionalities like event adding, editing and deletion, as well as several additional functions such as time/clock setting or selecting airports and aircraft types via adaptive selection lists.

We decided to carry out a heuristic walkthrough (Moser 2012) with human factors experts followed by a pluralistic walkthrough (Karat et al. 1992; Wilson 2014), the latter usually being a group discussion including all system stakeholders, i.e. among other developers, users, usability experts, marketing. This evaluation procedure can quickly identify usability shortcomings, which then can be remedied promptly in the subsequent design process. In the heuristic walkthrough, the expert assessment was conducted one at a time in order to receive independent results. The lack of domain-specific knowledge was compensated by a thorough introduction of the participants to the usage context.

The basic functions of MasterMAN were at the scope of this evaluation phase. In order to make sure that the experts explore and test all functions, four comprehensive scenario tasks were prepared. Participants had to note detected usability issues in systematic categories linked to usability heuristics. These also had to be assessed on a severity scale. VisAWI [visual aesthetics of websites inventory by Thielsch and Moshagen (2011)] was used to access the visual attractiveness of the system to test for hedonic, non-instrumental qualities of UX.

In a final session, a pluralistic walkthrough was conducted, so that the evaluators could openly discuss their impression of the prototype and could propose improvements. As the heuristics used in the first walkthrough were the basis for the subsequent pluralistic walkthroughs and were pivotal in establishing the experts' first impression of MasterMAN, we will discuss their selection.

4.1.1 Selection of Heuristics

The sheer number of usability guidelines and rules is increasingly confusing for both developers and evaluators. For this reason, Nielsen and Molich (1990) have developed heuristics reflecting basic usability principles which can be applied easily during an evaluation. Heuristics support the evaluator with a categorisation of usability issues and indicate problem fields of an application (Nielsen 1994). Besides the detection of usability problems, accumulating individual problems into broader, but considerably fewer categories leads to a comprehensive understanding of a system's shortcomings and helps to prioritise adjustments of interaction and graphical design.

The original list by Nielsen and Molich (1990) encompasses nine heuristics which were later amended by one additional heuristic as a result of numerous revisions and a factor analysis (Nielsen 1994; Sarodnick and Brau 2011). One could have applied these heuristics one by one to evaluate MasterMAN or could alternatively have substituted them with a more appropriate set. Since an extensive comparison of different usability heuristics by Somervell and McCrickard (2005) concluded that there are no significant differences between the various sets of heuristics and because they pointed out that a target-oriented preselection and self-developed heuristics might have a positive impact on the evaluation of an application, we selected an individual set of heuristics.

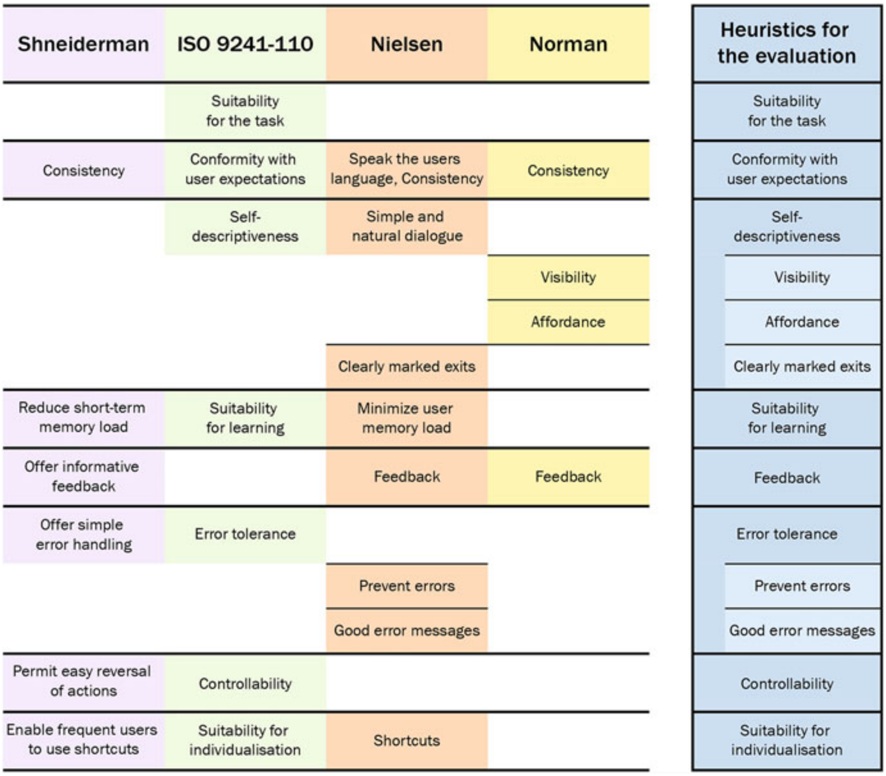
Usability expert Donald A. Norman's focus on man–machine interfaces as well as on everyday objects renders his interaction principles applicable in a larger context. Norman's principles offer a differentiated view on visual attributes of MasterMAN. In addition to Norman's heuristics, we adapted Shneiderman's heuristics (Shneiderman 2002; Shneiderman and Plaisant 2010) and the dialogue principles of the respective standard to avoid user problems (DIN EN ISO

9241–110:2008–09) to our purpose, because the applicability and usefulness of each principle can vary strongly and is context based.

Following a comparison of all stated principles and taking into consideration the specific field of application (ATC), we selected the following heuristics:

- *Suitability for the task*
  The principle is suitable for the task if an implementation of a dialogue enables the user to accomplish his task effectively and efficiently. For this criterion, among others, an emphasis of task-relevant information and a reduction of non-task-relevant information to a minimum would be useful.
- *Conformity with user expectations*
  Compliance to generally acknowledged conventions (DIN EN ISO 9241–110:2008–09) and a certain level of predictability are expected from a well-designed human–machine interaction. This also includes vocabulary the users are acquainted with well. As these expectations differ depending on the user group, establishing a consistent dialogue based on the experiences, expectations and knowledge of the users is of prime importance.
- *Self-descriptiveness*
  To implement this ergonomic principle, a consistent and constant information flow indicating to the user at which stage of the working process she/he currently is has to be established. For example, upcoming working steps could be indicated until dialogue closure.
- *Visibility*
  Following Norman's (1988) definition, visibility describes the visible arrangement of control and other interaction elements. This means that users cannot make use of HMI elements which are not visible to the user, i.e. all context-relevant information have to be placed visibly on the software surface and overlaps or other visual disturbances must not occur.
- *Affordance*
  To prevent usability difficulties, all elements of the user interface should be designed (affordance) implying their respective use at a glance.
- *Clearly marked exits*
  This design principle is essential in order to hand control of any process over to the user. Consequently, it should be possible to exit as many user interface dialogues and interactions as possible. This heuristic encourages the user to independently explore the system, because the user can revoke unintentional actions and processes at any time and can effortlessly return to a former state.
- *Suitability for learning*
  This principle supports and guides the user in learning to use of the system adequately aiming at minimising learning efforts. As it, in general, is much easier for users to recognise visually than to recall the same information from memory (Nielsen 1993), the system should provide dialogue elements and allow the users to choose.

- *Feedback*
  Feedback should be implemented in context-sensitive ways. In most low-persistence situations, users will need feedback only during the process itself, while in other situations with medium persistence a confirmation may be required of the user. Eventually, very important situations require continuous feedback, which hence has to be a substantial part of the user interface. In general, feedback should disappear automatically when it is no longer needed and its extent should be adjusted to the importance and frequency. It should inform the user about what the system is doing or what interactions are necessary especially for comprehensive and complex tasks. The visual presentation of changes can be an adequate feedback as well (Shneiderman and Plaisant 2010).
- *Error tolerance*
  The system has to address two main points. First, user actions must not lead to system crashes or incorrect user inputs. Second, the system should support users in identifying and correcting errors. According to this heuristic, incorrect user inputs should be marked and a constructive feedback to correct the error should be provided.
- *Prevent errors*
  One main strategy of error control is attempting to design a fail-safe system that avoids error-prone situations (Nielsen 1993). Asking users to reconfirm their actions before moving ahead can reduce the frequency of errors especially in situations with grave consequences. One can also adapt the options related to different operations, e.g. by providing radio buttons, shortlists or drop down menus to prevent the risk of spelling mistakes.
- *Good error messages*
  Error messages should support the user in solving critical situations quickly, effortlessly and reliably. To achieve that, the wording of the messages should be brief, clear and comprehensible. However, the user should have facile access to a detailed explanation of the problem in the form of ‘multiple-level messages.’ Instead of overloading user’s cognition by putting all potentially useful pieces of information in one message, a combination of a short first message that upon user demand is replaced by a more elaborate message will allow for both quick reactions and detailed comprehension of the problem when necessary.
- *Controllability*
  A well-controllable system allows the user to influence the progress of a task process regarding direction and speed (DIN EN ISO 9241–110:2008–09). Each intervention should be available independently at all times and offer options to correct preceding interactions.
- *Suitability for individualisation*
  Users should be allowed to adapt the interface design to agree with their personal preferences, needs, tasks, working conditions and skills. For common users, this in particular means individually defined shortcuts in order to reduce the number of interactions with the system and to increase speed. Experienced users often profit from using abbreviations, shortcuts and hidden macros.



Shneiderman	ISO 9241-110	Nielsen	Norman	Heuristics for the evaluation
	Suitability for the task			Suitability for the task
Consistency	Conformity with user expectations	Speak the users language, Consistency	Consistency	Conformity with user expectations
	Self-descriptiveness	Simple and natural dialogue		Self-descriptiveness
			Visibility	Visibility
			Affordance	Affordance
		Clearly marked exits		Clearly marked exits
Reduce short-term memory load	Suitability for learning	Minimize user memory load		Suitability for learning
Offer informative feedback		Feedback	Feedback	Feedback
Offer simple error handling	Error tolerance			Error tolerance
		Prevent errors		Prevent errors
		Good error messages		Good error messages
Permit easy reversal of actions	Controllability			Controllability
Enable frequent users to use shortcuts	Suitability for individualisation	Shortcuts		Suitability for individualisation

Fig. 2 Comparison of usability principles and overview of the heuristics used

The heuristics *visibility*, *affordance* and *clearly marked exits* can be subsumed under the heuristic *self-descriptiveness* (DIN EN ISO 9241–110:2008–09). However, the granularity of this heuristic should be increased which is why these three have explicitly been set out during the evaluation. The same holds true for the heuristics *prevent errors* and *good error messages* in the field of *error tolerance*. Figure 2 provides a summary and comparison of the usability heuristics described above.

4.1.2 Severity Rating

The heuristics described above constitute categories of design recommendations/principles. Within these categories, problems are likely to be created during user interface development, e.g. a system may lack comprehensive and meaningful error messages. This is why human factors experts are asked to assess during system exploration whether the recommendations are met. Instances where principles are reneged on highlight usability problems. Within our study, all problems were recorded on specifically designed documentation sheets. The evaluators were encouraged to think aloud during system exploration, and their output was recorded and reviewed by a trained examiner.

Usually, it is not feasible to eliminate all detected usability problems during the subsequent system development phases. Therefore, problems were not only categorised by topic but also prioritised, i.e. the evaluators also provided a severity rating for each detected problem (Nielsen 1993). The severity rating took various criteria into account, such as in how far the problem would impair task completion, how frequently the problem occurred or in how far it impacted the further working process.

The severity rating for any problem discovered in this process is a subjective assessment by the respective evaluator and is not necessarily reliable. Nielsen (1993), therefore, recommends to not rely on the ratings of a single evaluator. Following this approach, we ensured that each evaluator assessed the system independently, and we subsequently aggregated these individual assessments in order to increase the validity of the evaluation.

4.2 Test Preparation

4.2.1 Sample Description

Carefully selecting test participants is crucial to obtaining relevant, objective results (Tullis and Albert 2008). Interestingly enough, the number of evaluators needed for a study also influences the quality of the results. While basically a single evaluator should suffice, various investigations have concluded that this setting cannot identify most usability problems and fails to detect between 70 % (Tullis and Albert 2008, p. 119) and 65 % (Nielsen 1993, p. 156) of heuristics violations. Woolrych and Cockton (2001) identified intrapersonal and external factors to influence the evaluator's detection rate to a large extent. Put plainly, different evaluators uncover different problems, which render aggregating several evaluators' assessments worthwhile. Especially, complex evaluation objects require several evaluators (Tullis and Albert 2008, p. 118 f.). Tan et al. (2009) reported an asymptotic trend of detected problems with approximately seven to eight evaluators, i.e. the amount of usability problems detected increases digressively with the number of evaluators, resulting in the rule of thumb that five evaluators (magic number 5) are sufficient in order to uncover more than 80 % of problems (Nielsen and Landauer 1993; Tullis and Albert 2008; Virzi 1992).

In addition to the number of evaluators, their expertise plays an important role in problem detection (Karat 1994, p. 224). Nielsen (1992) investigated three groups at different levels of expertise in the usability domain: novices, regular (usability) evaluators and double experts. The latter additionally held domain expertise, i.e. they were not only experienced in usability but also in the respective field of application the user interface was to be used in. The novice evaluators unsurprisingly held the lowest detection rate for usability problems with an average of 22 %, followed by the regular experts at 41 % and the double experts at 60 %. Taking into consideration that sometimes there simply are no double experts for a combination of domains and that double experts usually are scarce and expensive, regular usability and human factors experts are the commonly used, reasonable and most suitable alternative (Karat et al. 1992).

For the heuristic evaluation described here, we recruited eight evaluators (five males), who had an average professional experience in human factors of 10.1 years (range: 2–25 years). For this sample size, Nielsen and Landauer (1993) estimate a detection rate for usability problems of 85–99 %, which we deemed highly suitable for our purposes. The youngest participant was 27 and the oldest 59 years old (∅ 40.6 years). Half of the sample had a professional background in psychology and the other half in engineering. One participant was an aviation engineer and held a private pilot licence; he thus accounted for a double expert.

The evaluators' affinity for technology was assessed using TA-EG by Karrer et al. (2009). The questionnaire consists of 19 items with a 5-level Likert scale (1 = 'strongly disagree' to 5 = 'strongly agree'). Overall, the evaluators stated a high competency and a slightly positive attitude towards technology (see Fig. 3).

4.2.2 Development of Traffic Simulation

Screen Displays

A proper heuristic evaluation of MasterMAN required a traffic simulation, supporting the basic functions necessary for carrying out ATCO planning tasks. In order to reach a substantial level of reality, a simulation unit of a working position was developed. It included the planning tool itself and additional screens

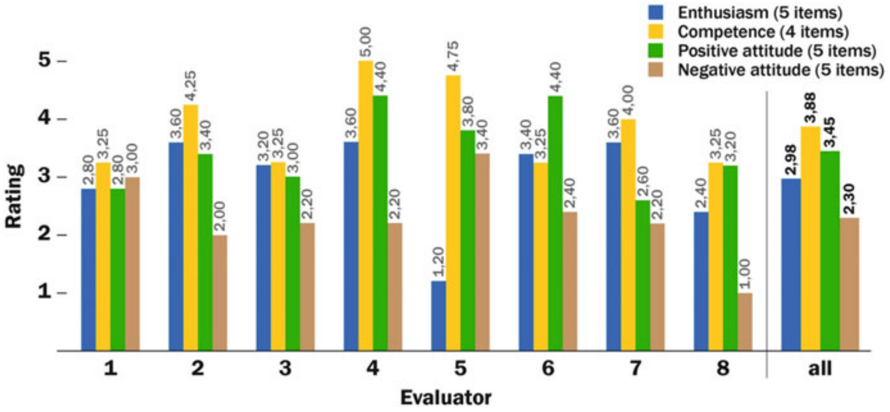


Fig. 3 Evaluators' affinity for technology

on which aircraft movements at an airport and its immediate airspace were visualised.

The flight movements were based on the flight plans of three regional airports, thus realistically simulating real-life situations. They included Schwerin-Parchim (EDOP), Rostock-Laage (ETNL) and Black Forest Airport Lahr (EDTL). For displaying the movements, several views have to be provided to the ATCO, which closely resembles a working position in an Aerodrome Remote Control Center. Since the simulated working position is independent of location and tower view, the view outside the tower window (e.g. on the taxiway) does not have to be emulated; however, the controller has to be enabled to observe and control movements on the taxiway. The overview of the airport and its operational airfield was realised via planar top view display (planport depiction) in a schematic way. The views of all three airports were scaled to include the runway(s) and landing strip(s), all taxiways, the apron as well as the immediate vicinity of the airport. The views displayed on the monitor used for evaluation comprised a width of about 12 km in reality.

Besides the planport views of the three airports, the respective radar views were required. A radar display already is a fundamental component of an ATCO's working position, both for tower and centre controllers. It will remain being fundamental in remote control. In our test set-up, the radar displayed a width of about 80 km and provided the whole area of responsibility (control zone CTR) of the 'controller'. Further areas covered were the broader periphery of the airport with prominent points for orientation such as beacons, villages, motorways, lakes and rivers, which are required for small aircraft navigating via visual flight rules.

Flight Routes and Taxi Movements

In order to be able to simulate and display flight movements on radar and planport view, movement paths were required and accordingly realised. Since the main focus was on evaluating MasterMAN's planning tool, simplified approach and departure paths were generated for the radar display. The radar movement paths extended the runway view beyond the immediate control zone of the respective airport and followed one of three different directions up to the simulated border of the generated radar display. In addition to these general paths, three crossing movement paths were prepared for the radar screen to simulate crossing traffic in the respective scenarios.

For the planport view, further movement paths were needed in order to display landing and departing aircraft, but also aircraft taxiing on the airfield. Three different movement paths were generated, each of which simulated an aircraft land and finally taxi to one of three predefined, real-life parking positions. Additionally, three take-off paths were prepared, which started at one of the parking positions each and went via taxiways to the take-off position, where they initiated the take-off. Finally, we also included movement paths for traffic circuits, which are operated frequently at smaller airports.

For all airports, a total of 54 movement paths were defined to simulate realistic aircraft movements on the two displays. Landing aircraft received an approach, landing and taxiing path each and departing aircraft correspondingly received a taxiing, take-off and departure path. The paths could be combined randomly in order to simulate numerous varying flight movements. A change in the runway's operational direction was not necessary for our test purposes and was fixed at the beginning of the test.

Task Scenarios

The tests comprised of the two test procedures, heuristic walkthrough and (sample wise) reduced pluralistic walkthrough. Evaluation tasks for a total of four scenarios were defined for the heuristic walkthrough. For each of these evaluation tasks, the action steps necessary to fulfil the task effectively and efficiently were carefully defined, so that a deviation from the action steps provides clear indication of usability issues.

The evaluation tasks were, furthermore, classified according to their difficulty. Tasks low in difficulty mostly comprised of a small number of action steps, while a considerably larger number of action steps were usually attached to difficult tasks. Because the system was novel to the evaluators, we arranged the tasks in the scenarios so that the complexity of the tasks continuously increased during the evaluation session (cp. Table 1). Since the tasks were consecutive, each completed scenario resulted in learning effects thereby enabling evaluators to realise even complex tasks consisting of several steps. Additionally, some task types were repeated in the follow-up scenarios (tasks marked in light grey in Table 2) to further deepen these learning effects.

Materials

Each of the evaluators received the following material:

- Task instructions for the four scenarios
- Note pads for each of the 10 heuristics for writing down usability problems discovered
- A questionnaire on demographic data
- A questionnaire on visual aesthetics
- A questionnaire on affinity for technology

Table 1 Categories of severity rating adapted from Nielsen (1993)

Severity rating (SR)	Description	Meaning
1	*Cosmetic problem*	Solving the problem if additional resources are available
	There is no interference of the functionality	
2	*Minor problem*	Solving the problem if it is often mentioned
	Problem is avoidable	
3	*Medium problem*	Solving the problem should be implemented
	User notes the problem and gets used to it	
4	*Major problem*	Solving the problem is urgently necessary
	User has big problems with accomplishment of the task	
5	*Disastrous problem*	Solving the problem is compulsory
	User cannot accomplish the task	

Table 2 Tasks for the evaluation

Scenario 1	• Postponement of an event and confirmation • Cancellation of an event • Undo of postponements • Immediate handover of one airport to a remote controller • Immediate takeover of one airport of a remote controller
Scenario 2	• Independent solving of time conflicts • Creation of a new event • Modification of a data set of an event and confirmation • Cancellation of an event • Creation of a new event
Scenario 3	• Creation of a non-relocatable event • Planning of an handover of one airport at a specific time • Runway closure with immediate effect • Cancellation of an event • Creation of a new event • Independent solving of time conflicts
Scenario 4	• Planning of a runway closure at a specific time and independent solving of conflicts by postponing events • Performing a manual optimisation by postponing events and handover of one airport if necessary • Modification of a data set of an event and confirmation • Cancellation of an event • Creation of a new event

4.3 Conduction

In preparation of the evaluation, a basis for a common understanding of the usage context of MasterMAN's planning tool and of the evaluation goal was established by giving the evaluators a short overview of VICTOR as well as detailed information on multi-airport control and working procedures of a MC. Additionally, a detailed introduction was given on the graphical user interface and the functionalities of the planning tool as well as the available controller assistance monitors (e.g. the planport). The evaluators were encouraged to ask comprehension questions before the evaluation started.

The predefined tasks for the first evaluation step (heuristic walkthrough) included working instructions, which were designed to consecutively lead evaluators through the system functions. Thus, evaluators learned about the planning tool in a stepwise manner and used each function at least once. The tasks did not have a time limit, so evaluators were completely self-paced and able to note all conspicuousness using the defined heuristics.

An examiner attended the evaluation and documented the evaluators' task-based usage paths whenever evaluators departed from a predefined ideal path. After experiencing the planning tool based on the tasks and scenarios, evaluators had the opportunity to investigate and assess parts of the system in detail. No time limit was set and evaluations took 70–120 min. Finally, data on demography, visual aesthetics and affinity to technology were gathered.

The second evaluation step (pluralistic walkthrough) was planned as a group discussion amongst evaluators and developers in order to scrutinise discovered usability problems. The issues were categorised into 'unique problems' and 'shared problems', where the latter were usability problems discovered by at least two evaluators. The group discussion started with these shared problems regardless of how their severity had been rated. MasterMAN was used live to reproduce each problem and to display it on the spot, which allowed for collecting severity ratings even from evaluators who had previously not experienced the said problem. In addition to all shared problems, all unique problems with severity ratings of four and above were assessed and discussed. In the discussion, first attempts for solutions were established.

4.4 Results and Analysis

The eight evaluators found a total of 58 usability issues, 15 of which were shared problems. In Fig. 4, those shared problems are marked with a black square with the difficulty of detecting a problem increasing from left to right and the evaluators' ability to detect usability problems increasing from top to bottom. Figure 4 provides an overview of the number of unique and shared problems, as well as the evaluators' mean severity ratings. The evaluators discovered between 6 and 14 problems. Their average severity rating ranges from 2.17 to 3.79 (Fig. 5).

Figure 6 depicts the 13 heuristics used for evaluation as well as the number of problems discovered by the evaluators. Evaluators identified no issues in the heuristics *good error messages* and *suitability for individualisation* and just one issue, respectively, in the heuristics *clearly marked exits* and *suitability for learning*. Most of the issues were found in the categories *conformity with user*

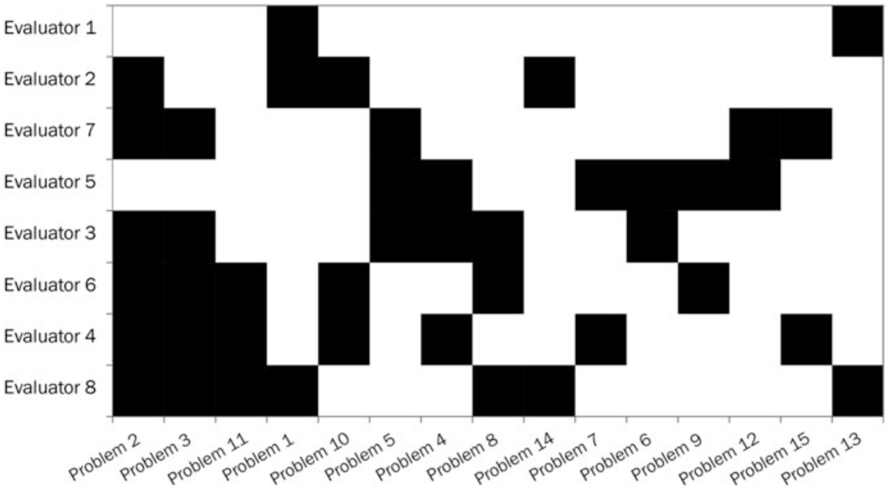


Fig. 4 Distribution of shared problems. Ability to detect usability problems is plotted for individual evaluators versus difficulty of problem detection. *Black squares* depict detected shared usability issues

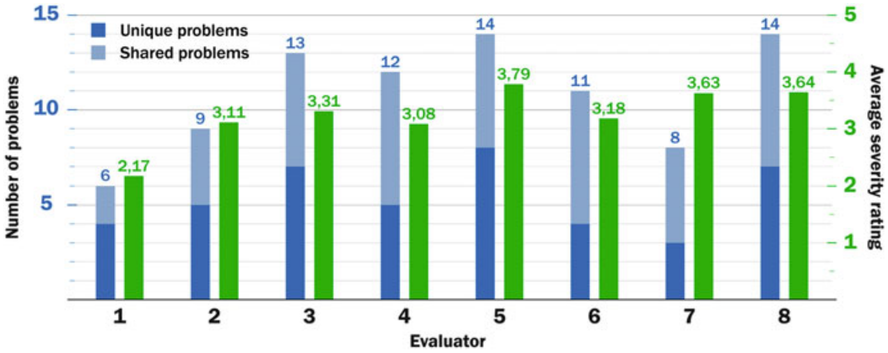


Fig. 5 Number of *unique* and *shared problems (left ordinate; left one of column pair)* and mean severity rating (*right ordinate; right one of column pair*)

expectations, *suitability for the task* and *feedback*. Especially, considering the problems detected in these categories, a subsequent redesign of the user interface is mandatory. Additionally, all problems with high severity ratings, i.e. of four and above, will have to be reviewed in detail. Solution approaches for these problems, which already have been developed during group discussion have to be substantiated further and will be implemented in the user interface accordingly.

Aesthetics is a central element of UX and influences, amongst others, usability (Moshagen et al. 2009) as well as user satisfaction (Lindgaard and Dudek 2003). We assessed layout aesthetics via VisAWI questionnaire on the subscales *simplicity* (clearliness and structuredness), *diversity* (inventiveness and dynamics),

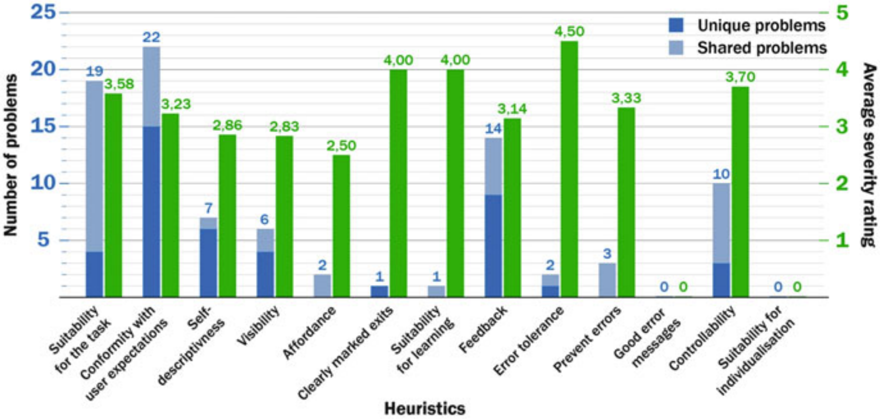


Fig. 6 Number of *unique* and *shared* problems (*left ordinate; left one of column pair*), as well as average severity rating of the heuristics (*right ordinate; right one of column pair*)

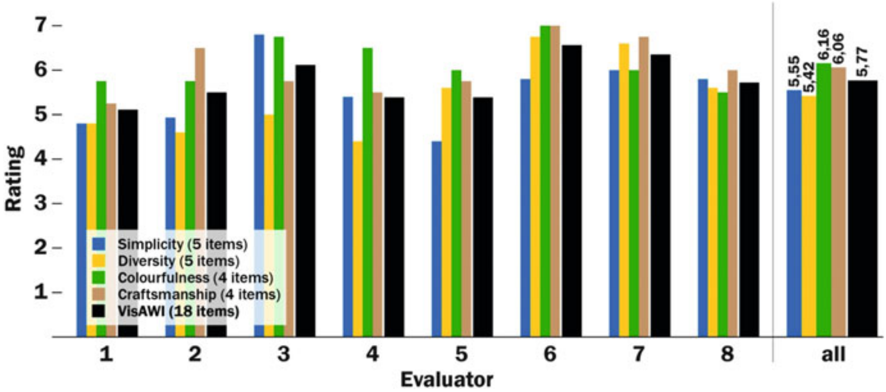


Fig. 7 Mean values of the four VisAWI subscales and mean overall rating of all evaluators (subscale list from top to bottom corresponds to columns per evaluator from left to right)

colourfulness (colour composition, choice and combination) and *craftsmanship* (topicality, sophistication and professionalism of design) as well as the overall layout impression the assistance system makes.

Figure 7 provides the mean values for the four subscales and the overall rating. In each case, two of the subscales consist of four or, respectively, five items. According to VisAWI threshold analysis (Hirschfeld and Thielsch 2015), a user interface is perceived positively with an average overall rating of 4.5. For the planning tool, evaluators assigned ratings of 5.11–6.56 (Ø 5.77) (cp. black bars in Fig. 7), which is well above the established threshold. Thus, we assume there is no demand for action regarding the aesthetics of the assistance system's user interface.

5 Summary and Outlook

A user-centred development process demands an integration of user needs as well as further stakeholder and expert assessments in order to finally achieve high user acceptance, usefulness and usability. In following this approach, we collected user requirements in a first step, which built the basis for the system and interface design of MasterMAN's planning tool. After implementing the respective graphical user interface and basic functions, the usability evaluation reported here was carried out in order to discover user–system interaction problems. For our purposes, heuristic evaluation once again proved to provide valuable and nuanced input for mandatory as well as optional redesign. Complemented with UX-related system assessment, we concluded a number of redesign approaches from this first step of evaluations. In this process, MasterMAN already scored well in providing good error messages and clearly marked exits as well as being suitable for learning and individualisation. The overall aesthetic appearance was rated well above the set threshold and thus presumably supports a positive user experience.

In a next step, redesign measures will be implemented in a timely manner. Valuable input for this step was provided in the group discussion. Additional to the human-factors expert evaluation, user input from ATCOs will be collected in a simulator study. In this study, ATCOs will work on different scenarios, which represent common situations occurring during a day shift in an ARCC. The results of this study will likewise facilitate the development of the planning tool. In case the users deem comprehensive changes on the tool necessary, further redesign and evaluation steps will be initiated in order to develop a most useful and effortlessly usable system for a MC.

The work of ATCOs, especially at small and regional airports will change fundamentally within the next decade. With MasterMAN they will have the opportunity to control traffic flows of several airports in an integrated way and actively anticipate and plan a whole day of air traffic. A further step to planning and optimisation of air traffic is a precise personnel planning assistance, which includes deployment availabilities of ATCOs. The combination of these very different tasks is to date not provided by any assistance system. In terms of MasterMAN functionalities, this will be our next developmental step.

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Part III
RTO Engineering and Field Testing

Remote Tower Experimental System with Augmented Vision Videopanorama

Norbert Fürstenau and Markus Schmidt

Abstract The goal of the research described in this chapter was the development and setup of an initial experimental version of the "virtual tower" with focus on replacement of the direct view out-of-windows. Specifically, the intermediate step of a remote tower operation (RTO) work environment for remote surveillance and control of small airports is described which served for verifying the main functionalities. A structured work and task analysis detailed the requirements on the new human-machine interface (HMI) and emphasized the "far view" out of the tower windows as important information source. Consequently, a digital high-resolution videopanorama system was implemented as central HMI component to replace the airport tower out-of-window view. Field tests using this reconstructed panorama indicated the effective visual resolution for object detection to show reasonable agreement with theoretical predictions under ideal conditions. As addition to the panorama, an integrated zoom function provided an enlarged narrow-angle "foveal" component by means of a remotely controlled pan-tilt-zoom camera with tracking functionality. The digital reconstruction of the far view allowed for integration of "video see-through" augmented vision features by integration and superposition of, e.g., weather and electronic surveillance data, and it allowed for video replay of stored surveillance information.

Keywords Remote airport traffic control • Human-machine interface • Work analysis • Video panorama • Augmented vision • Requirements • Performance • Field test • Simulation

1 Introduction

This chapter provides results of the initial phase of Remote Tower research at the German Aerospace Center (DLR), starting with the "Visionary Projects" study "Virtual Tower" (ViTo, 2002–2004), with focus on the project RApTOR (Remote

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Airport Traffic Operation Research, 2004–2008). The chapter is based on a number of previous publications (Fürstenau 2004; Schmidt et al. 2006, 2007; Fürstenau et al. 2008b, 2011) and on the initial concept outlined in the virtual tower patent (Fürstenau et al. 2008a).

The growth of air traffic, the increasing use of small airports by low-cost carriers, and the requirement for cost reduction of air traffic control have pushed the search for new solutions to increase efficiency of air traffic control. For traffic control on the airport movement areas and within the control zone, the virtual tower idea was put forward by DLR since more than ten years, based on earlier suggestions by Kraiss and Kuhlen (1996) and Ellis [see the Foreword and references therein and fundamental considerations in (Ellis 1991)]. Specifically, for small airports, remote tower operation (RTO) with a new type of remote tower center (RTC) provides the potential for multiple airport control from a single control room. Corresponding RTO/RTC prototypes have been developed since about 2004 and are presently being tested under operational conditions.

RTO/RTC is considered as intermediate step toward the virtual tower for larger hubs, as a new kind of airport traffic control center without the need for an expensive tower building. In contrast to the small low-traffic airports, large hubs usually rely on electronic surveillance (surface movement radar, SMR) and so-called (advanced) surface movement guidance and control systems (A-SMGCS) which support and partly replace the visual surveillance. Corresponding RTO and virtual tower projects were started in Europe (Germany, DLR/DFS; Sweden, Saab/LFV), Canada (Nav Canada and Searidge Technologies), and the USA (Vogel 2009; Hannon et al. 2008) (see also chapters “Detection and Recognition for Remote Tower Operations,” “The Advanced Remote Tower System and Its Validation,” and “Remote Tower Research in the United States”).

A number of tower work and task analyses performed during recent years (Pinska 2006; Tavanti 2006; Werther and Uhlmann 2005) partly accompanied by model-based simulations of controller’s decision processes [e.g., (Werther and Schnieder 2005; Werther et al. 2007)] determined the importance of visual surveillance for creating the controller situational awareness. In the tower work environment of large airports, the permanent shifting of attention between far view and displays contributes to workload and generates head-down time problems (Pinska 2006). Both may be reduced by augmented vision systems such as transparent head mounted or head-up displays which superimpose traffic or weather data on the out-of-windows view (Fürstenau et al. 2004; Schmidt et al. 2006; Peterson and Pinska 2006). Consequently, it was concluded that the digital reconstruction of the far view of the control tower by means of a high-resolution videopanorama with a kind of video see-through augmented vision element (Barfield and Caudell 2001) will be an important component of the human-system interface in a future towerless work environment, and it will support the acceptance of the controller operating remote towers. The concept of a high-resolution videopanorama as potentially low-cost human-machine interface (HMI) for replacement of the direct view out of the tower windows is supported also by the fact that small airfields usually lack any advanced electronic surveillance.

A corresponding first experimental system was realized at the Braunschweig Research Airport (BWE) within the RApTOR project around 2004–2005, based on a 180° live video reconstruction of the tower out-of-windows view (Schmidt et al. 2007). Video see-through augmented vision features were realized by integrating information from real-time moving object detection and from Mode-S multilateration via feeding transponder data into the reconstructed far view.

Initial verification of the basic RTO design features was performed under realistic conditions using a DLR test aircraft for field testing (Fürstenau et al. 2008b; Schmidt et al. 2009). This kind of testing is a costly undertaking and easily exceeds a project budget. That is why a number of questions regarding the requirements, performance, and acceptability of the new RTO controller working position (CWP) were investigated in a specific remote tower simulation environment as extension of DLR's conventional tower simulator [see Sect. 5, Part II of this book, and (Papenfuß et al. 2010)]. Naturally, many questions regarding the performance and acceptability of the video-based panorama reconstruction including zoom functions usually can rely on field tests only because no simulation is able to reproduce the reality in full detail. Nevertheless, some useful predictions and estimates can be derived also from appropriate theoretical considerations presented in Sect. 3.1 of the present chapter and in chapters "Detection and Recognition for Remote Tower Operations," "Remote Tower Prototype System and Automation Perspectives," and Appendix A for the technical design.

Section 2 reviews results of a structured work analysis, followed in Sect. 3 by a detailed description of the design and technical description of the augmented vision videopanorama system realized within DLR's first RTO project RApTOR as basic experimental environment for field testing. Results of the initial field trials for verifying relevant performance parameters are reported in Sect. 4. In Sect. 5 a brief overview of the simulation environment is presented, while details and simulation results are described in Part II of the book. Section 6 provides a conclusion and outlook.

2 Work Analysis

In this section we will briefly review the initial work analysis which accompanied the basic RTO design and development as described in Sect. 3. A cognitive work and task analysis (CWA) was performed by means of structured interviews of domain experts (controllers) from medium-sized airports (Werther and Uhlmann 2005) which followed a method described by Vicente (Vicente 1999). He separates the analysis into five levels, i.e., analysis of (1) work domain, (2) control task, (3) strategy, (4) social organization and cooperation, and (5) operator competency. The latter was not considered in this context because controllers due to the rigid selection process, highly specific training, and formalized detailed work procedures may be considered a very homogenously qualified group of operators.

The formalized results provided the input data for a formal airport control model (FAirControl), developed for the computer simulation of the controller decision-making processes at the tower work positions which supported the interviews (Werther and Uhlmann 2005; Werther et al. 2007). In Werther (2006a, b) and Werther and Schnieder (2005), it was shown how the results of a CWA can be transferred into an executable human-machine model, based on colored Petri nets (CPN) for simulating the controller work processes in relation to the airport processes. The formal model allowed for evaluation of different variants of work organization and supported the design of the new work environment and the monitoring of psychological parameters, e.g., uncovering of reduced situational awareness.

The model was separated into submodels for the human agent (controller), interaction, and traffic processes. The interaction model defines the controller-process interactions and includes subnetworks for description of information resources, such as radio communication and visual perception of the traffic situation. The executable model with graphical representation of the controlled traffic process was useful in identifying the controllers' strategies in task organization and pursuance of goals. It supported the communication between domain experts and system developers by simulating different traffic situations to establish a basis for the structured interviews. Details can be found in previous publications, e.g., Werther et al. (2007)

One major focus of the repeated and model-supported interviews of two tower supervisors concerned the visual information from the outside view. The following list summarizes the most important visual information ordered by area/distance (rating = 5 from a scale of 1 (= not important) to 5):

1. Approach/departure range (2–3 km, max. 5 km)
    - Recognition of A/C, direction of movement
2. All airfield areas (taxi, apron, stand)
    - Recognition of all active objects (A/C, vehicles, humans, animals)
    - Classification of A/C
    - Recognize smoke at A/C (e.g., turbine fire)
3. Runway range (800–1500 m, max. 2 km)
    - Observe runway state, detect aircraft parts
4. Taxi area (500–900 m, max. 2 km)
    - Recognition and position of passive objects (A/C and parts, vehicles, obstacles)
5. Apron area (200 m)
    - Recognize aircraft damage

6. Stand area
   - Recognize aircraft damage
   - Recognition and position of passive objects (luggage, vehicles)
7. RWY/taxiway lights
   - Monitor intensity
   - Monitor function

Based on the CWA framework, the information sources, work constraints, control tasks, and decisions of two controller working positions (CWP) at a medium-sized airport tower [tower and ground executive controllers (TEC, responsible for landing and starting aircraft; GEC, responsible for ground traffic/taxiing)] were analyzed. The contribution of information gathered through direct view out of the tower window (visual information) was of special interest. The information gained for three visibility conditions (normal vision, night vision, limited vision < 2 km) were identified and rated according to their relevance. All decision tasks of the TEC- and GEC-CWP's were analyzed. A total of 60 decisions ($N_{\mathrm{GEC}} = 29$; $N_{\mathrm{TEC}} = 31$) were modeled following this template (Papenfuß and Möhlenbrink 2009).

Four main issues were found in this analysis: (1) Small regional airports usually got no expensive electronic surveillance, leaving visual observation as the main information source on the live (traffic) situation on the airport surface. (2) Safety relevant information like foreign objects on the runways or bird swarms can only be sensed—if not through direct visual surveillance—by expensive sensor infrastructure that is unlikely for small airports. (3) The controllers' acceptance for a remote working place is expected to be higher if the working procedures and the look and feel remain as similar as possible to the known working procedures. (4) The reconstruction of the far view via digital video enables the augmentation of the videopanorama via information superimposition, e.g., to reduce head-down times.

The frequency (F) of use of different information sources over the whole spectrum of possible control task decisions derived from the CWA for the GEC and TEC controller working positions quantify their information requirements (Werther and Uhlmann 2005; Schmidt et al. 2009). Oral communication via radio ($F = 97\,\%$) is the most often used information source, followed by weather information ($F = 35\,\%$), telephone ($F = 33\,\%$), and direct view out of the window ($F = 21\,\%$). The latter number may be compared with values reported in the literature which vary between 20 and 50 %, depending on airport class and CWP [for an overview and further reference, e.g., Tavanti (2007)].

In order to select possible information for video augmentation, a further analysis of the detailed control tasks was conducted. The use of information sources was furthermore analyzed according to the working positions (TEC, GEC) and the kind of traffic that is controlled (VFR versus IFR). The availability of assistance systems, like departure coordination (DEPCOS) or extra monitors, depends on available information (e.g., surface movement radar, usually only on large airports) and is very specific for every single airport (size, traffic amount). Compared to the GEC, the TEC uses more different information sources over all tasks ($N_{\mathrm{GEC}} = 12$; $N_{\mathrm{TEC}} = 16$) and more information sources in single tasks [mean values $\mu_{\mathrm{GEC}} = 3.4$; (std. dev. = ±1.0); $\mu_{\mathrm{TEC}} = 4.6$, (std. dev. = ±1.6)]. TEC combines more information sources to achieve an integrated picture of the traffic. The analysis also revealed typical information source access profiles: while GEC mostly uses communicative items like radio ($F_{\mathrm{GECradio}} = 97\,\%$) and telephone ($F_{\mathrm{GECtelephone}} = 55\,\%$), the TEC, after the radio connection ($F_{\mathrm{TECradio}} = 97\,\%$) to the pilot, most often uses the radar ($F_{\mathrm{TECradar}} = 55\,\%$), control strips and flight plan information ($F_{\mathrm{TECplan}} = 35\,\%$), and weather information ($F_{\mathrm{TECweather}} = 45\,\%$).

The quantitative analysis of information source usage showed that different information needs depending on working position and character of traffic can be identified. In particular, the percentage of VFR traffic is significantly higher on regional airports as compared to international ones. The analysis showed that decisions for VFR traffic compared to IFR traffic required more often weather information ($F_{\mathrm{VFRweather}} = 45\,\%$, $F_{\mathrm{IFRweather}} = 25\,\%$) and control strip information ($F_{\mathrm{VFRstrips}} = 31\,\%$, $F_{\mathrm{IFRstrips}} = 11\,\%$).

One advantage of using a digital videopanorama as core of the RTO HMI is the possibility of augmenting the far view with additional information. For the control of small regional airports with a lot of VFR traffic, the augmentation of weather information can help to reduce head-down times of the controller. Furthermore, information normally saved on flight strips can be attached to the aircraft position on the video display. Through analyzing the information needs of controllers in different situations, a framework for the design of a work environment that reduces workload by integrating information and by adding automation can be achieved. Carefully added automation, such as an assistance system to reliably detect and signal moving objects for monitoring tasks, can support the controller and allow for the simultaneous control of several airports from a remote tower center (RTC, see chapter "Planning Remote Multi-Airport Control–Design and Evaluation of a Controller-Friendly Assistance System").

The work analysis outlined above with regard to visual surveillance may be compared with the comprehensive overview and discussion of cues presented in chapters "Visual Features Used by Airport Tower Controllers: Some Implications for the Design of Remote or Virtual Towers" and "Detection and Recognition for Remote Tower Operations" of this book.

3 Experimental Remote Tower System

In this section the development of the initial experimental RTO system at Braunschweig Research Airport is described. Motivated by the important role which visual information plays for the tower work processes according to the work analysis, in particular at smaller airports, a high-resolution digital videopanorama system with augmented vision functionality was developed as outlined in DLR's basic virtual tower patent (Fürstenau et al. 2008a, b). It served as experimental environment for investigation of different aspects of the remote tower operation and RT center concept and for development of a prototype demonstrator described in the following chapter "Remote Tower Prototype System and Automation Perspectives." This initial experimental system was used for verifying by field testing basic design features as realized within the DLR project RApTOR (2004–2007).

3.1 Optical Design and Expected Performance

The design of the experimental videopanorama system described in the following Sect. 3.2 was based on the assumption that a digital video reconstruction with a visual resolution comparable to the real view out of the tower windows in combination with a PTZ camera for providing a binocular function should be sufficient to fulfill the requirements as derived from the work analysis reviewed in Sect. 2.

Performance predictions of the visual system were based on the assumption that signal delay (small latency effects), optical resolution, contrast, and dynamic range are the most important parameters characterizing system quality, i.e., detectability of (moving) objects and discriminability of relevant operational situations. The effective resolution is largely determined by visual contrast which is discussed in more detail in Appendix A. With regard to aircraft detection and recognition, basic work was published by Watson et al. (2009). Here we provide an (optimistic) estimate of the ideal resolution corresponding to the Nyquist limit of the modulation transfer function (MTF, see Appendix A). The MTF quantifies the contrast-dependent resolution as dependent on the spatial frequency, i.e., the frequency of periodic black-white line pairs. The Nyquist limit is that spatial frequency value represented by the lowest discriminable light-dark spatial object wavelength transmitted to the observer by the camera-monitor system. Of course this is an ideal value which is given by the pixel size and distance, i.e., the pixel resolution. In fact, not surprisingly the validation of the prototype panorama system (see the following chapters "Remote Tower Prototype System and Automation Perspectives" and "Which Metrics Provide the Insight Needed? A Selection of Remote Tower Evaluation Metrics to Support a Remote Tower Operation Concept Validation") showed that under realistic environmental conditions, this ideal resolution limit quite often will not be achieved.

The optical resolution and signal-to-noise ratio depends on the technology and parameters of the image sensor (CCD or CMOS technology, sensor size, and number of pixels), the focal width, and the quality of the selected camera objectives, which also determine the achievable contrast (through the MTF, see Appendix A). For the panorama system, a compromise between achievable resolution and number of cameras, i.e., cost, was made. Concerning size (= diagonal) of image sensor (horizontal/vertical width H/V) and focal width f, the design criteria may be derived from the curves in Fig. 1 which are based on the fundamental (thin lens)

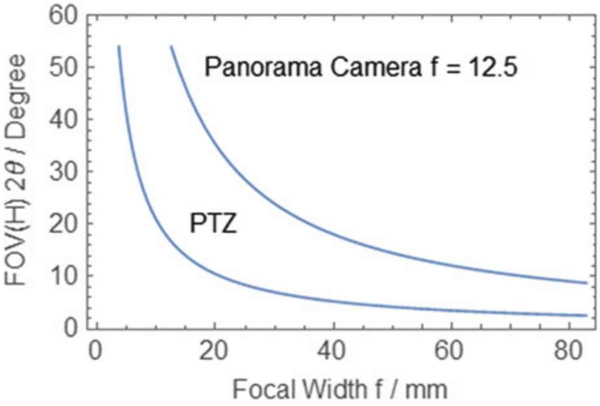

Fig. 1 Horizontal field of view (FOV) as function of focal width f of the objective for panorama camera with 1″ image sensor, $f = 12.5$ mm (left endpoint of the curve), and PTZ camera with $f = 3.6$–82.8 mm and ¼″ image sensor

approximation between field of view ($\mathrm{FOV} = 2\theta$) and f (valid for large distances, where the image is close to the focal point at f:

$$\theta = \arctan\left(\frac{H}{2f}\right) \tag{1}$$

with half angle θ of FOV on the vertical axis.

For a 200° panorama, four cameras require per camera FOV ≈ 50°. With 1″ image sensors (sensor size $H \times V = 12.8 \times 9.9$ mm), this determines the required focal width of the wide-angle objective $f = 13.7$ mm. The graphic depicts the actually used commercially available objective with $f \approx 12.5$ mm (FOV = 54°), the left end of the upper curve. The PTZ camera specifications were 1/4″ image sensor, $H \times V = 3.2 \times 2.4$ mm, and with zoom objective $f = 3.6$–82.8 mm. The corresponding FOV range as depicted in the graphics varies between 53° and 2.2°.

From (1) the angular pixel resolution of the panorama may be estimated within the paraxial approximation (for details see also Appendix A; $\Delta H = p << f$) as $2\theta = \alpha \approx 2$ arcmin = 0.033°, with $\Delta H =$ pixel size $p = 7.5$ µm (+0.5 µm gap). This may be compared with the diffraction-limited value of the human eye [≈ 1 arcmin, e.g., (Bass 1995), see also Appendix A]. Toward the edge of the image sensor, the pixel FOV decreases which reduces the received light power per pixel accordingly. This in turn would reduce the contrast toward the edges of the image and add to a number of other image-degrading effects that are corrected more or less with high-quality lens systems (for some additional details, see Appendix A).

In other words, by using the fundamental relationship $G/B = (g/f–1) \approx g/f$ derived from Newton's (thin) lens equation as a paraxial estimate, with $g =$ object distance, $G =$ object size, and $B =$ image size $\approx p$, the minimum vertical object size at $g = 1$ km distance corresponding to 1 camera pixel p is $G/p = 0.6$ m/1 pixel or again ca. 2 arcmin angular resolution. With the given vertical camera position, we get 1 m/1 pixel along the line of sight. This optimistic estimate is idealized and does not include limitations due to contrast of cameras and display and possible image distortions and diffraction effects with small lens aperture stop. It represents the Nyquist limit of the modulation transfer function (MTF) which states that as minimum condition for resolution at least two pixels of the image sensor have to cover the distance (spatial wavelength λ_{min}) of an alternating pattern of (ideally) black and white lines (i.e., 2 measurements = pixel distance = λ_{min}). For some more details, see Appendix A.

Moreover, the observable resolution at the videopanorama HMI is reduced due to imperfect optics of the camera and the limited dynamic (illumination dependent) image compression and influenced by the resolution of the display system (ideally the same as the camera) and gamma adjustment of camera and display (see Appendix A). The estimated resolution value of about $2'$ (about two times the diffraction-limited value of the human eye) may be approached with decreasing camera aperture D (increasing depth of focus, reducing lens imaging errors), which is of course possible only under good light conditions and sufficient object–background contrast. Furthermore, under bright illumination (bright sunlight), the automatic aperture control of the lens decreases aperture (increases aperture f-number $f\# = f/D$, see Appendix A) which may start decreasing resolution if $f\# >$ ca. 6. This decrease is due to diffraction effects originating from the wave nature of light leading to blurring of the idealized point focus. The aperture is focused into a light disk diameter corresponding to the so-called Airy radius $q_1 \approx f\#/\mu\mathrm{m}$ (for wavelength $\lambda = 0.6$ μm (green), see Appendix A) of the point spread function that exceeds pixel size $p \approx 8$ μm with decreasing aperture diameter (increasing $f\#$).

For realization of the panorama, only 1424 × 1066 pixels of each camera (50° horizontal viewing angle) are actually used in order to match the 180° panorama angle. For improving the pixel resolution to match the human eye, the focal width would have to be doubled, resulting in a fourfold number of cameras (for covering roughly the same horizontal and vertical FOV). This of course would also mean a multiplication of the system cost (including data processing and HMI) by a comparable factor.

From the above discussion, it becomes evident that RTO controllers require a zoom camera (with reduced FOV, however increased pixel resolution) not only as equivalent for the binocular but also to compensate for the limited videopanorama resolution. The theoretical (idealized, paraxial) angular pixel resolution of the PTZ camera used for the experiments below is given by $\alpha_Z \approx p_{\mathrm{H}}/Z f_0$, yielding $\alpha_Z = 1$ arcmin ($Z = 4$, viewing angle $2\theta = 15°$) and $\alpha_Z = 0.2$ arcmin ($Z = 23$, viewing angle $2\theta = 2.5°$), with p_{H} = horizontal pixel size = 4.4 μm, f_0 ($Z = 1$) = 3.6 mm, and f_{max} ($Z_{\mathrm{max}} = 23$) = 82.8 mm. With larger Z of course also a conventional binocular function is obtained (although limited by the individual MTF and gamma adjustment of the individual camera-display systems, see Appendix A).

3.2 Digital Reconstruction of the Out-of-Windows View

A block diagram of the initial augmented vision videopanorama system is shown in Fig. 2. The basic sensor component in the initial design consisted of four high-resolution (1600 × 1200 pixels) high-dynamic range (14 bit/pixel CCD cameras ($P_{1,\ 2,\ 3,\ 4}$)) covering the Braunschweig airport runway area within 180° viewing angle, complemented by a remotely controlled pan-tilt-zoom camera (P_5: PTZ).

The cameras (upper photo in Fig. 2) are positioned 18 m above the airport surface, horizontally aligned on top of a building at the southern boundary of the airport, ca. 100 m east of Braunschweig tower, and 340 m south of the main runway 08/26 (1670 m, until extension to 2500 m after 2008). The vertical aperture angle of about ±20° (with respect to the horizontal line of sight) allowed for a closest surveillance distance of about 60 m and about 365 m observation height at 1 km distance or ca. 125 m above the runway. The latter value was criticized later on by domain experts during a more detailed requirement analysis as being too low. This resulted in a redesign for the validation experiments described in the following chapter “Remote Tower Prototype System and Automation Perspectives.” Upon request of several domain experts, the visual system was extended by (stereo) microphones at the camera site and a digital connection to loudspeakers at the controller console.

For each camera (frame rate = 25 frames/s), the signals are split into two outputs, according to Fürstenau et al. (2008a, b). One feeds the data compression and encryption (AES256) for transmission to the RTO HMI, while the other drives the simultaneous real-time image processing for movement detection. The five recording PCs with the compression software near the camera position allow for storing panorama and zoom data (roughly 500 GByte of data per day) and provide the possibility of complete panorama replay. Figure 3 shows an aerial view of the Braunschweig Research Airport from southeast direction indicating camera position and camera viewing sectors.

A GBit ethernet switch feeds the images from the five sensors into a single-mode fiber optic data link which transfers the typically 100 MBit/s data (night + day average) of the panorama system and PTZ over a distance of 450 m to the visualization system. A second GBit ethernet switch splits the incoming data into five output channels for decompression, with one PC per camera in the initial setups. The PCs also synchronize the displays of the four segments. Each camera is remotely controlled with respect to aperture and γ-correction (see Appendix A). The PTZ camera is controlled with respect to azimuth, vertical angle, and zoom ($Z = 1$–23-fold, focal width 3.6 mm–82.8 mm, corresponding to 54°–2.5° visual angle).

The augmented vision videopanorama (AVP) HMI for a single operator/single airport surveillance in an early version is depicted in Fig. 4 (Fürstenau et al. 2007). It was based on four 21″ LCD monitors (UXGA, 1600 × 1200 pixels) for displaying the reconstructed panorama and a separate one for display of the remotely controlled PTZ camera.

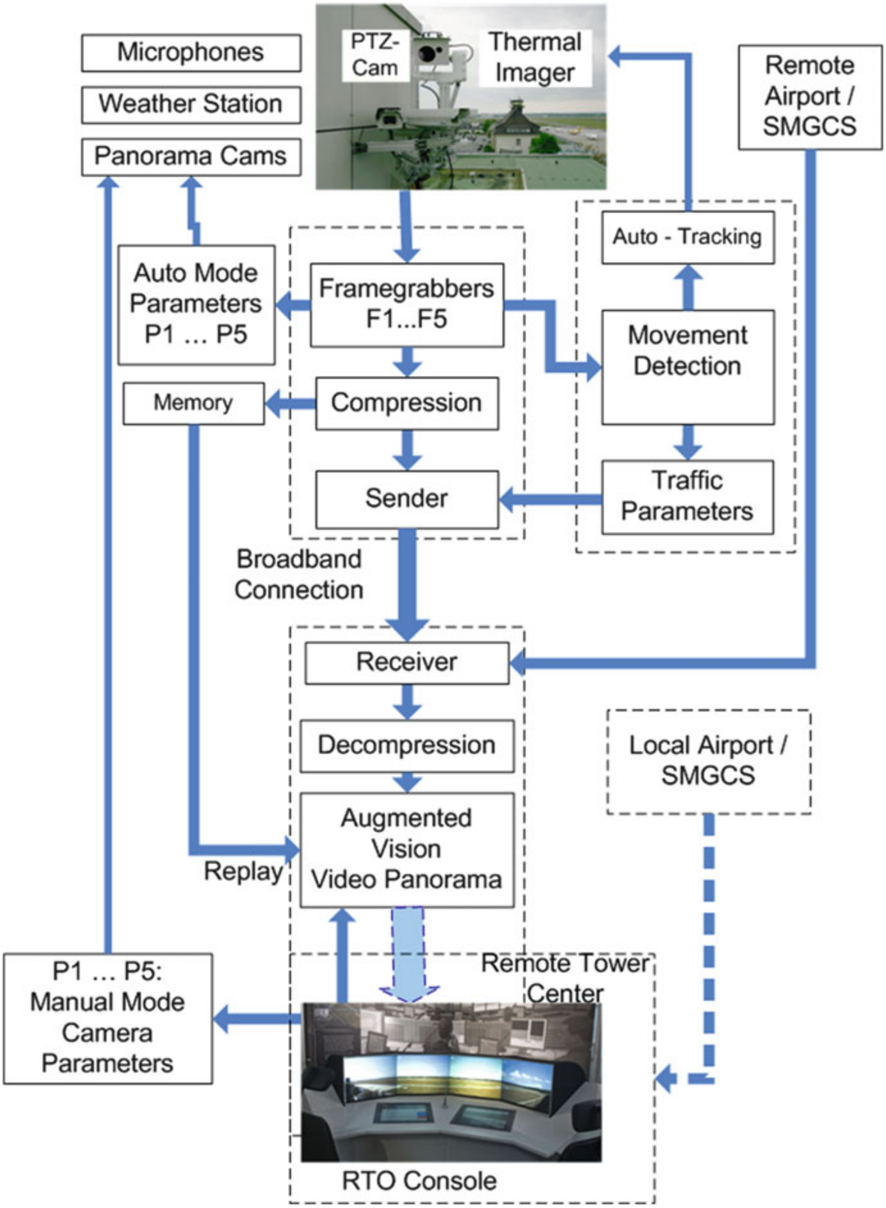

Fig. 2 Schematic block diagram of augmented vision videopanorama system as set up in 2005 (initially without IR camera), reprinted from Fürstenau et al. (2011) with permission. *Arrows* indicate flow of information with GBit fiber optic data link between sender and receiver. Wide light-*blue arrow* indicates visual information for the controller. 180° FOV RTO videopanorama shown in the *bottom photo*: panorama version with backprojection displays (see Fig. 5). Compressed angular arrangement (ca. 125°) for cameras no. 1–4, PTZ display, and touch-input interaction display integrated in the controller console

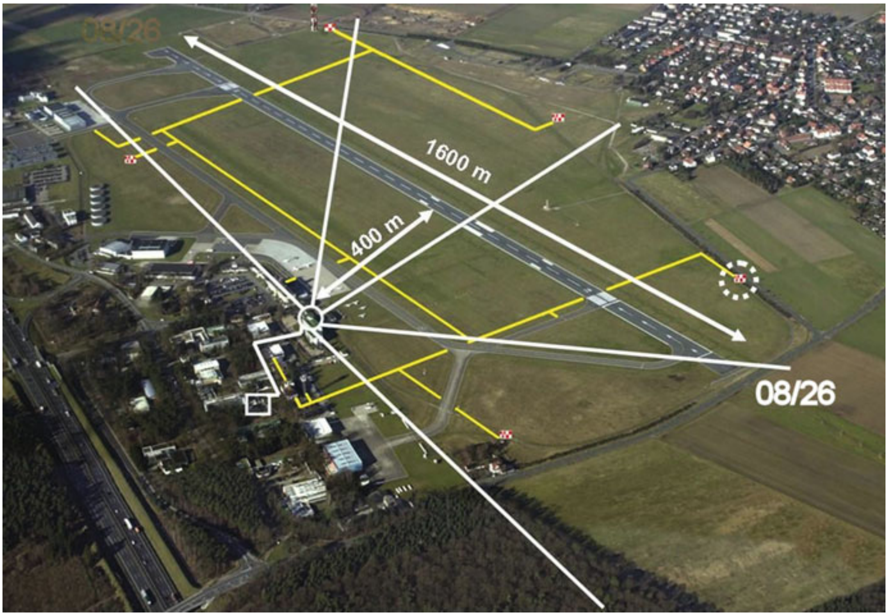

Fig. 3 Braunschweig Research Airport BWE (2005, runway extended to 2.5 km after 2008) with 1.67 km runway 08/26 extending E–W, fiber optic data link (*thin yellow lines*) connecting sensor containers (enlarged, one with *broken circle*) used for measuring static resolution. Circle with radiating lines indicates panorama camera position and field of view, respectively. Reprinted from Fürstenau et al. (2011), with permission

The monitor frames may be considered a disadvantage of this realization of the videopanorama, although the resulting discontinuities were not seen as a major negative aspect by the domain experts during the system validation in human-in-the-loop simulations and field tests. An alternative videopanorama setup is shown in Fig. 5 (Schmidt et al. 2009). It allowed for seamless stitching of the single-camera images without disturbing display frames. This backprojection system used a custom-made compact construction with video projectors generating images on 31″ screens, with 1400 × 1050 pixels, 3500 ANSI lm, and contrast of 3000:1.

This version [initially published in Schmidt et al. (2009)] was used as an initial RTO extension of the DLR tower simulator (see Sect. 5 of this chapter and chapter “Remote Tower Simulation Environment” of this book). Besides displaying the live videopanorama, the interface could accept video and simulator output signals. This allowed for using the videopanorama display system without changes for performing human-in-the-loop experiments with domain experts.

Fig. 4 Early version of 180° videopanorama (1600 × 1200 pixel) with pan-tilt-zoom camera display on top, demonstrating augmented vision function: superimposed transponder label tracking the landing aircraft using automatic movement detection (see Sect. 3.4, Fig. 7). Two pen touch-input displays integrated in the console display additional information required by the controller: the one on the right was used for electronic flight strips (flight data) and control of the camera parameters, PTZ, weather information, and tracking. Initially published in Fürstenau et al. (2007)

3.3 Videopanorama Interaction and Control Display

Interaction of the operator with the panorama system (panorama cameras, PTZ, weather station, microphones) was performed via a pen touch-input display which can be seen integrated in the consoles of Figs. 4 and 5. Figure 6 shows details of the display.

In order to obtain a compact RTO operator HMI which, e.g., should fit into a typical tower environment of a medium-sized airport, the pen touch-input display is designed to incorporate videopanorama control features as well as traffic information, e.g., electronic flight strips. A mini-panorama at the top is updated with 5 Hz and serves for commanding the PTZ camera orientation via pointing of the touch pen. The display also contains buttons for optical PTZ parameters and activation of automatic object tracking via movement detection, a virtual joystick as an additional option for commanding PTZ orientation, and weather data.

For PTZ positioning, the target can be defined manually or by automatic movement detection. A yellow square is positioned at the respective location of

Fig. 5 Experimental RTO videopanorama (180°) backprojection system. It was installed in the RTO simulator environment (see Sect. 5) and could display simulated as well as live traffic (the latter shown in the photo). PTZ display is integrated in the console (*right side*) beside the interaction and camera control display on the left (Sect. 3.3). Reprinted from Schmidt et al. (2009), IEEE, with permission

B738	M	TVS401	A1404	1902	FMS	LKPR	ESSA	009	29
B735	M	CSA617	A5640		FMS	OKBK	LKPR	008	29
B738	M	TVS821	A1403	1808	FMS	LKPR	LHBP	007	29
B762	M	ELY523	A5612		FMS	LLBG	LKPR	006	29
A310	M	CSA109	A4321		FMS	CYUL	LKPR	005	29
B752	M	BCS918	A1410	1807	FMS	LKPR	EDDF	004	29
B752	M	BAW854	A2541		FMS	EGLL	LKPR	003	29
A321	M	DLH3265	A1405	1804	FMS	LKPR	EDDF	002	29

Fig. 6 Initial design of pen touch-input interaction display [reprinted from Schmidt et al. (2009), IEEE, with permission]. Minipanorama on top as option for PTZ positioning via touch (actual position visualized by *yellow square*). Center, electronic flight strips; right, from top, PTZ control buttons, virtual joystick as another option for PTZ positioning, weather data with wind direction (from weather sensors); left, optional buttons, e.g., for preset PTZ position

the panorama, defining the target area to be zoomed in. With the tracking mode turned on, the square moves coherently with the corresponding object, after touching it on the display. An algorithm for real-time movement detection is running on a separate parallel processor of the image compression PCs of each camera (see next Sect. 3.4).

3.4 Augmented Tower Vision and Movement Detection

One of the design goals was the minimization of the number of additional interaction systems and displays and for improving low visibility conditions by integration of additional sensor data (e.g., from IR and multilateration) and relevant traffic information into the videopanorama by using augmented vision techniques.

Augmented vision as defined for 3D virtual reality systems discriminates between so-called “optical see-through” and “video see-through” systems (Barfield and Caudell 2001). With optical see-through information displayed, e.g., in a transparent head-mounted or head-up display is superimposed on real-world objects, whereas with video see-through the real world is displayed as a digital video image with relevant data digitally superimposed. The advantage of the latter option is zero latency time between environment and superimposed information, whereas fast image processing with object and head tracking and minimization of latency effects by predictive filtering is required for appropriate superposition in optical see-through systems.

Within the videopanorama, real-time aircraft position information is integrated as obtained from the (radar-based) multilateration system at the Braunschweig airport via the aircraft (A/C) transponder. An example is shown in the inset of Fig. 7 with an enlarged section of display no. 4 (looking east) depicting a yellow transponder code with multilateration position attached to the landing aircraft. It indicates A/C position on the approach glide path. Under reduced visibility, this augmented tower vision (ATV) feature allows for localizing the A/C near the correct position because the transponder code, A/C label, and numerical information are integrated near the nominal object image location in real time.

Another example of augmented vision data is the integration of GPS-ADS-B position information transmitted via transponder. An example is shown in Fig. 7 where D-GPS data measured during flight testing (see Sect. 4) are superimposed (off-line) on the video in the form of flight trajectories (red) that, after geo-referencing, are transformed from geographical into display coordinates.

Contours of the movement areas and the 3° glide path are superimposed on the videopanorama for guiding the operator attention during low visibility or nighttime to those areas where moving vehicles are expected. Movement areas are also the preferred targets of a high-resolution (640 × 512) infrared camera system with PTZ function operating in the mid-IR range (2–5 μm) which was integrated into the experimental system in a later phase for investigating improved night vision and

Fig. 7 Part of the initial version of the panorama display with PTZ display on top. Inset: screenshot of camera #4 (= east) display showing augmentation during landing [reprinted from Schmidt et al. (2009), IEEE, with permission]. Superimposed glide path (*violet*, added for replay), GPS trajectories (*red*), live multilateration position (*yellow*, from transponder), and automatic movement detection (*red square* with object number)

visibility under CAT I conditions (see chapter "Remote Tower Prototype System and Automation Perspectives" of this book).

For image processing, two different strategies were followed, with the initial goal of automatic object tracking with the PTZ camera via movement detection: (a) hardware implementation of algorithms on FPGAs and (b) software processing with a second processor of the video-compression PC (at the sensor system location).

An initial version of automatic moving object tracking with the PTZ camera was realized by method (b) with a simple video-frame difference method for object-movement detection (for more sophisticated approach, see chapter "Remote Tower Prototype System and Automation Perspectives," Sect. 4). In practice an update rate of 5 Hz was used although theoretically 20 Hz was estimated to be achievable. The basic performance of the software-based movement detection algorithms could be verified with automatic PTZ tracking activated on the interaction display. It demonstrated the practical usefulness of this feature, however, with limited reliability due to relatively simple algorithms based on image subtraction and texture analysis of detected clusters. An example is depicted in Fig. 7 (inset) with the numbered frame surrounding the approaching aircraft.

An advanced approach (using strategy (a), see chapter "Remote Tower Prototype System and Automation Perspectives," Sect. 4) for automatic object detection

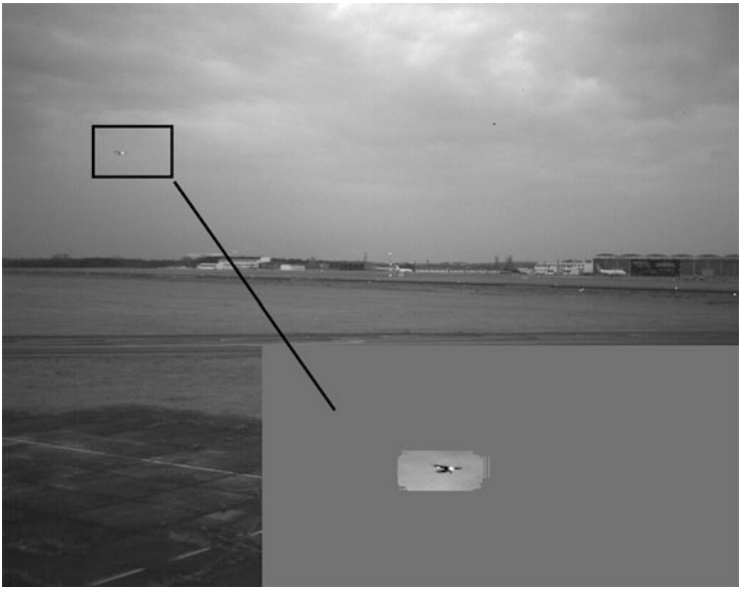

Fig. 8 Object detection (aircraft in cloudy sky) using automatic background subtraction (contributed by DLR Unit Optical Information systems, W. Halle)

and discrimination, e.g., between cars and aircraft on the movement areas or between aircraft and birds in the sky, was described already in the virtual tower patent (Fürstenau et al. 2008a, b). The challenge in the present context for achieving a reliable performance lies in the fact that different algorithms have to be implemented for flying objects in the air with a dynamic background (moving clouds) and for moving objects on the ground with a more stable background. An example based on automatic background subtraction is shown in Fig. 8. Detection relies on the combination of different criteria: (1) speed (A/C faster than clouds) and (2) A/C texture different from clouds.

3.5 Triangulation

In order to determine the position of aircraft on small airports without electronic surveillance, a stereophotogrammetry method (triangulation) was investigated for analyzing the high-resolution videos. An additional camera was positioned at a distant position, and it was used for observing the same field of view of one of the fixed panorama cameras (realizing a stereo system). In order to achieve the required spatial resolution, it is necessary to choose the appropriate base length between both cameras. The analysis and initial tests showed that for a sufficient position resolution, the second camera of this stereo system has to be placed at the opposite side of the airport. With a baseline of 450 m (ca. position of nearest multilateration system container in Fig. 2), theoretically, the position of an aircraft at a distance of three kilometers can be obtained with an accuracy of 12 m (1.5 m at 1 km distance, based on pixel resolution). In the present case, only the preliminary field test was performed with a reduced camera baseline of ca. 20 m so that the additional stereo camera could be placed on the roof of the same building as the videopanorama sensor system that provided the first camera of the pair of stereo pair.

A video processing framework was realized for this purpose in order to unify and simplify the design and development of the video processing loops. Based on this framework, a heterogeneous object tracker for various image sections and object types detected the different objects. The tracker worked on each stereo camera separately. For triangulation of the object position, corresponding object pairs in both images have to be identified automatically. In order to retrieve the desired accuracy, the cameras were time synchronized and calibrated with regard to interior and exterior orientation. This requirement was fulfilled already for the panorama camera system with augmented vision function which was based on the transformation from geographical into display coordinates. However, this experimental triangulation system allowed only for initial proof of concept. The tests showed that for a larger measurement campaign allowing for reasonable quantification of performance in the approach and departure direction, the viewing angle between runway and line of sight (and in particular the angle difference between cameras) would have to be increased significantly by extended baseline which was not within the scope of the initial RTO project.

4 Field Testing for Verification of System Performance

In this section we present results obtained by field tests, in particular flight testing with the DLR DO-228 test aircraft for verifying the theoretically expected system performance. The main question to be answered refers to the comparability of the videopanorama with the real view out of the tower windows. For this purpose, different experiments and measurements were performed for determining signal latency and visual resolution under realistic environmental conditions. The results allowed for an initial experimental estimate of the effective (subjectively experienced) visual resolution of the reconstructed far view.

4.1 Latency

In order to react quickly to critical situations, domain experts require a low delay (<0.5 s) between real-world events and video reconstruction in the RTO HMI. The video-system delay basically consists of computing time contributions from the color image construction at the camera site using an implementation of the Bayer algorithm and the image compression-decompression (CoDec). A special laser arrangement with beam shutter was used to determine this time interval. The 450 m single-mode fiber optic data link allowed for feeding the laser beam via a beam splitter into one of the fibers of the installed cable at the panorama site and use the output at the camera site for illuminating one of the cameras. The returned camera signal could be compared with the non-delayed beam from the beam splitter. An overall latency time between image acquisition and panorama visualization of 230 ms–270 ms was measured. Of course, compared with this value, the delay due to camera-monitor separation is neglectable for distances up to some 100 km, given the speed of light = 300 km/ms.

In realistic long-distance connections between remote airports, however, due to additional (opto-) electronic equipment with potential additional sources of delay, the actual latencies should be verified for each individual situation (see chapter "Remote Tower Prototype System and Automation Perspectives," Sect. 5).

4.2 Optical Resolution: Static Measurements

With the known size and distances of static objects on the airfield, it is possible to evaluate the practically achieved effective videopanorama resolution as compared to the theoretical (optimistic) estimate of ca. 2 arcmin. For verification we used the red-white (1 m squares) multilateration sensor containers at the end points of the fiber optic A-SMGCS data network as reference objects (see Fig. 2, height and width $G = 2$ m). The nearest containers as captured by the NE- and E-looking camera $P_{3,4}$ are located at distances $g_{\mathrm{E}} = 400.8$ m (Ref. Obj. 1) and $g_{\mathrm{NE}} = 588$ m (Ref. Obj. 2, broken white circle), respectively.

With the abovementioned lens equation, we obtain 7.8 and 5.3 pixels, respectively, of the camera chip covered by the container images in the vertical direction. These values correspond to a measured resolution of $\alpha_{\mathrm{v}}{}^{\mathrm{exp}} = 1.7$ arcmin for Ref. Obj. 1 and $\alpha_{\mathrm{v}}{}^{\mathrm{exp}} = 1.4$ arcmin for Ref. Obj. 2, which appears reasonably close to the theoretical estimate.

4.3 Performance Verification: Flight Tests

In what follows we review previously published results (Fürstenau et al. 2008b; Schmidt et al. 2009) which were obtained by measuring the detectability of repeated simple flight situations for determining the subjectively experienced visual resolution of the reconstructed far view. For generating statistically relevant performance data of the videopanorama system including the zoom function, a flight test plan was set up for the D-CODE to observe with controllers and nonexperts repeatable scenarios for object and maneuver detection under real-view and videopanorama conditions. Here we report on two experiments under VFR conditions performed on 2 days in May 2007, one with clear sky and one under reduced visibility (<10 km), with one pretest in December 2006.

4.3.1 Experimental Design

Flight tests of two-hour duration each, with the DLR DO-228 (D-CODE) test aircraft, were performed with successive approaches, touch and go (or low approach) and takeoffs. Five subjects [2 controllers of the Braunschweig Tower (S_1, S_2) and 3 nonexperts (S_3, S_4, S_5, members of the human factor department)] observed the flyby from a position near the panorama camera system and monitored times of 11 characteristic events e_1–e_{11}: out of sight, low/steep departure angle, takeoff, touchdown, approach main/grass runway, landing gear down/up, steep approach, and first sighting. The measurements were performed with notebook (touch-input) computers used by each participant, using a specially developed data input software (GUI). Pilots received the flight plan for up to 16 approaches. For the trials, a WLAN with time-synchronized camera and data acquisition was used. One of the GPS trajectories recorded for each flight with the onboard Omnistar satellite navigation system is shown in Fig. 9, including event observation positions $x(e_i)$ of the corresponding observation times $t(e_i)$. For the present task of determining the perceived video resolution, only the six well-defined events with the lowest event time variances were used (see Table 1).

The distance between the airport reference point ARP and the departure and approach turning points was ca. 4 km and 14 km, respectively. Each flyby was characterized by six parameters, with parameter values statistically mixed:

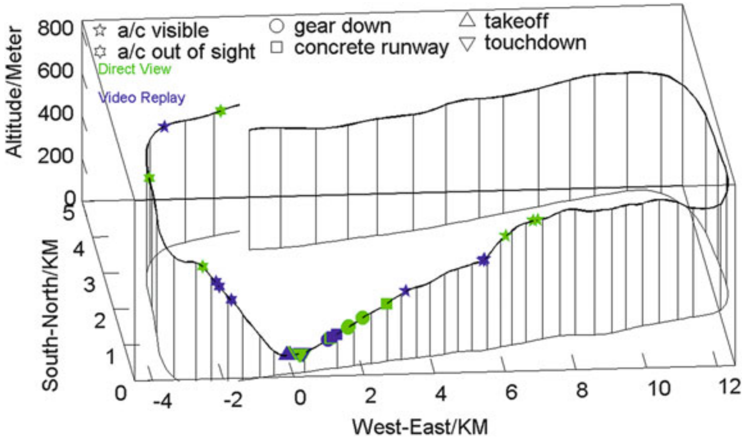

Fig. 9 GPS trajectory no. 4 out of 11 test flights during the pre-experiment on December 13, 2006 (clockwise direction). *Green*/*blue* symbols represent event observations under real-view (*green*)/ videopanorama replay conditions (*blue*). Approach direction 260° at RWY 08/26 with touchdown near ARP at 0 km (52°19′09″N, 10°33′22″E). *Vertical lines* = 10 s intervals on flight trajectory. Final speed ca. 100 kn

Table 1 Trial #2(May 21, 2007, clear view, > 10 km) and #3(May 22, 2007, cloudy, < 10 km). Mean, standard deviation, and std. error of event observation time difference $\Delta t = t$(real view)–t(replay). Reprinted from Schmidt et al. (2009), IEEE, with permission

	N	Mean (Δt/s)	SD (s)	SE (s)
Trial #2 (clear) *Event e_i*				
e_{11}: A/C visible	54	−85.1	77.9	10.7
e_8: Gear visible	42	−13.0	12.9	2.0
e_6: Main RWY	28	−34.3	49.5	9.5
e_7: Grass RWY	22	−29.4	45.5	9.9
e_5: Touchdown	22	+1.8	1.0	0.2
e_4: Takeoff	17	+2.3	2.5	0.6
Trial #3 (cloudy) *Event e_i*				
e_{11}: A/C visible	54	−26.5	18.3	2.5
e_8: Gear visible	44	−13.2	7.6	1.2
e_6: Main RWY	28	−15.7	16.0	3.1
e_7: Grass RWY	20	−25.8	24.5	5.6
e_5: Touchdown	25	+2.0	1.0	0.2
e_4: Takeoff	23	+2.0	1.4	0.3

1. Approaching main (concrete) or grass runway
2. Approach angle normal or high
3. Landing gear out: early, normal, and late
4. Low-level crossing of airport or touch and go
5. Touchdown point early or late
6. Departure angle normal, low angle, and steep angle

While pilots had a detailed plan to follow for the sequence of approaches with different parameter values, the participants only knew about the different possibilities within the approaches. They had to activate the corresponding field of their input display of the tablet PC and set a time mark at the time of their observation of one out of the 11 possible events during each of the D-CODE approaches and flybys, respectively. Also, all approaches of additional (non-D-CODE) A/C were monitored. Experts and nonexperts were briefed separately before the first experiment, with both groups filling separate questionnaires. For each trial raw data from all subjects and for all approaches under real-view conditions were collected into a single data file.

During test #1 significant time drifts between the individual computers were observed which were corrected for by comparing with the P_1 camera time as reference before and after the 2-h experiment for generating correction factors. For trials 2 and 3, a WLAN with time-synchronized camera and data acquisition touch-input laptops was used.

On December 13, 2006, the first out of three 2-h trials was performed (as a pretrial for testing and improving the procedures) with lower cloud boundary at 600 m. Two more experiments were performed in 2007 on May 21 with clear sky and May 22 with reduced visibility (<10 km). The latter results are listed in Table 1.

4.3.2 Experimental Results and Discussion

Videopanorama

For each trial, raw data from all subjects and for all approaches under real-view conditions were collected into a single data file. Evaluation of the different approach, touch and go, and departure conditions (in trial #1, 14 approaches with 11 D-CODE and 3 other aircraft) yielded the intersubject event time measurement scattering with mean and standard deviation (stdev) of the sample and standard errors (sterr) of mean for the $n = 5$ subjects.

In pretrial #1, typical unbiased estimates of sample stdev for event e_{11} (first sighting during approach) were between 2 and 25 s (sterr = 1–15 s). Comparing approach detection time with low stdev with the GPS track yielded first sighting (e_{11}) of A/C (headlight) at distance 9 km. The minimum sterr of, e.g., 1 s for e_{11} and 0.2 s for e_5 (touchdown) presumably represented the optimum observation conditions for all subjects (i.e., all $n = 5$ attending first sighting direction during expected appearance time).

Quantitative data on the difference in event-detection times between real view and videopanorama were obtained by repeating the experiments with the videopanorama replay after a week or more in order for the subjects to no longer remember the different flight conditions. It was expected that due to lower resolution of the videopanorama as compared to the real view, distant events of approaching/departing A/C (like first/last sighting of A/C) should receive an earlier/later mark under real view as compared to video observation. Correspondingly, within-subject evaluations of the direct viewing and videopanorama replay observations yield time differences $t(\text{real view}, e_i)–t(\text{video}, e_i) < 0$ and > 0 for approaching (app) and departing (dpt) A/C, respectively.

Results of the initial pretrial #1 were reported in Schmidt et al. (2007) and Fürstenau et al. (2007), showing experimental visual resolution between 1.3 and 2 arcmin in reasonable agreement with the theoretical prediction and with the static verification measurements (Sect. 4.2). In Table 1 the results for six of the 11 possible observation types are listed for the trials #2 and #3 (May 21, sunny day, and May 22, cloudy day), averaged overall participants and all flights with pairs of observation (time marks) of real-view video, with number of observation pairs N, mean time difference Δt(real-view video), standard deviation SD, and std. error of mean.

All displayed events exhibit reproducible and significant pos.(dpt.) and neg. (app.) delays between videopanorama and real-view conditions. For example, the significant negative delay measured as overall mean for e_8 (landing gear visible, -13.0 ± 2.0 s and -13.2 ± 1.2 s, respectively) shows this event to be observable with video only 0.7 km closer to the airport (A/C speed ca. 100 kn = 185 km/h), as compared to the real-view conditions [e.g., e_{11}(real view): A/C (lights) recognized at ca. 8 km]. If we assume that detection time difference is determined by the difference of optical resolution between real view (resolution of the human eye ca. $\alpha_E \approx 1$ arcmin = 1/60°) and videopanorama system, the measured time difference Δt(real-view video) $= t_E – t_V$ from Table 1 can be used for calculating the effective resolution α_V of the optical system. The extremely large observation time difference and SD of e_{11} in trial #2 was due to real-view event registration under clear view conditions (mostly expert subjects S1, S2) long before the A/C turned toward approach at the ILS turning point. For the video observation only after passing this point and entering the glide path, the A/C became visible.

For suitable events with known object size G, the single Δt-values allow for calculation of α_V via

$$\alpha_V = \alpha_E(1 + \alpha_E v_E \Delta t / G)^{+1} \tag{2}$$

where the resolution angle α is given by $\alpha_{E,V} = G/x_{E,V}$ measured in rad, with event observation distance $x_{E,V}$ under real-view (E) and video replay (V) conditions. G is the object size, e.g., aircraft cross section for e_{11} or landing gear wheel size for e_8. For e_8 we obtain in this way $\alpha_V = 1.4\ \alpha_E$ (with G(main wheel) $= 0.65$ m, $v_E = 100$ kn). For e_{11} (using G(cabin) $= 1.8$ m) trial #3 yields 1.3 α_E. Both values are in agreement within the experimental uncertainty, although smaller (i.e., even better) than the theoretical (optimistic) estimate.

In order to obtain a statistically relevant and model-based mean value, a linear regression procedure is employed for those events where the visual resolution (more or less modified by image contrast) may be assumed to play the dominant role for event timing. Because e_1 was unreliable due to observability problems (the aircraft quite often vanished from the P1-camera observation angle before e_1 was observable), only e_4, e_5, e_8, and e_{11} were used for this evaluation.

For applying a regression procedure, the independent variable "event e_i" has to be replaced by a quantifiable variable. A linear model is obtained when considering the observation distance x as obtained from the GPS reference trajectory instead of the observation time, yielding the Δx(E–V) $= v_E(t)\ \Delta t$ versus x_E (= distance from event position x_E to airport reference point ARP). The plot of the four data points ($[x_E, \Delta x = v_E \Delta t]$, for e_4, e_5, e_8, e_{11}) in Fig. 10 for trial #3 (cloudy day) is obtained by averaging real-view video observation delays for all flights and all subjects and correlating the measured time values with the corresponding time-synchronized GPS position data $x_E(t)$.

The corresponding linear model with video and real-view resolutions α_V and α_E, respectively, was derived as (see Appendix A)

$$\Delta x(\text{eye} - \text{video}) = (1 - \alpha_E/\alpha_V)x_E \tag{3}$$

$$\alpha_V = \alpha_E(1 - \beta_1)^{-1} \tag{4}$$

With the slope $\beta_1 = \Delta x / x_E = 0.429$ (± 0.02 std.err.), 95 % confidence interval of parameter estimate $ci(95\,\%) = 0.1$, $R^2 = 0.99$, and significance level $F = 321$ (at $p = 0.003$), a corresponding α_V estimate of 1.75 arcmin (±0.08) is obtained, again exhibiting surprisingly good agreement between the detection threshold of

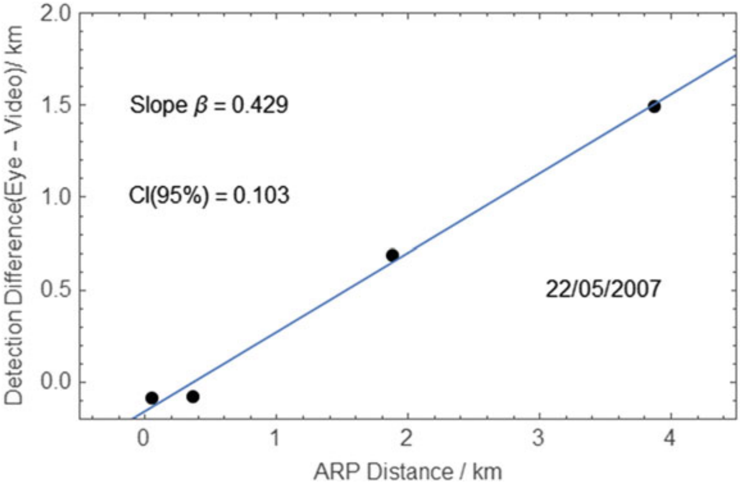

Fig. 10 Experiment #3 (reduced visibility): Mean event observation position differences Δx (real view-video replay) for e_4, e_5, e_8, and e_{11}, between real out-of-windows view and video replay conditions versus mean GPS position estimate of x_E for trial #3 including linear regression

perceived events with the theoretical predictions and also the experimental visual resolution data from field observations of known static objects.

Although, in contrast to the above described results from the #3 test under reduced visibility, the #2 test results were obtained under good visibility conditions; they exhibit a decreased detectability as shown in the following Fig. 11. In this case, the slope $\beta_1 = \Delta x / x_E = 0.730$ ($\pm$ 0.04 std.err.) with 95 % confidence interval of parameter estimate $ci(95\,\%) = 0.2$, $R^2 = 0.99$, significance level $F = 268$ at $p = 0.004$), a correspondingly higher α_V estimate of 3.7 arcmin (±0.6) is obtained, although with a reduced confidence.

The reason for this apparently low detectability and corresponding resolution value despite sunshine and clear weather was already discussed above with respect to the large real-view video detection time and scattering of event e_{11} (initial detection during approach). Under real view, observers quite often detected the A/C already before turning into final approach on the glide path, resulting in a wrong (too short) distance. A too early detection (too short distance of e_{11}) in fact results in an overestimation of slope. Because this systematic error did not occur during all observations, also the large scattering can be explained in this way.

As suggested already by the reduced confidence (large uncertainty range) of the #2 experiment results, we may conclude that the #3 experiment provides the more reliable resolution value that moreover agrees with the time-based analysis, relying on aircraft speed instead of satellite position data, with the static measurements in Sect. 4.2 and with the theoretical estimate in Sect. 3.1.

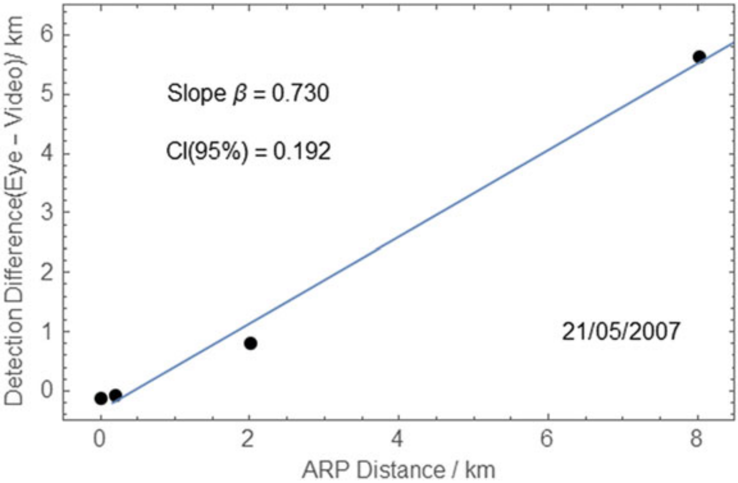

Fig. 11 Experiment #2 (good visibility): Mean event observation position differences Δx (real view-video replay) for e4, e5, e8, and e11, between real out-of-windows view and video replay conditions versus mean GPS position estimate of x_E for trial #3 including linear regression

Zoom Function

In order to decrease the duration of the replay experiments for evaluating observations with the PTZ camera (e_{11}, e_8), only the approach sections of the videos until touchdown (event e_5) were used. Because due to this procedure time synchronization with real-view experiments was lost, PTZ experiments were related to panorama replay with touchdown time as common reference. For data evaluation Eq. (4) with substitution of a_V through α_{PTZ} and α_E through a_V was used, yielding

$$\alpha_{PTZ} = \alpha_V (1 + \alpha_V v \Delta t / G)^{+1} \tag{5}$$

The experimental results for the effective zoom camera (PTZ) resolution are presented in Table 2.

The experimental data are reasonably close to the theoretical value $\alpha_{PTZ} \approx 1' = \alpha_E$ as obtained under the hypothesis of resolution-limited object detection times (see Sect. 3.1). These data were obtained with 20 participants observing those three rounds around the airport of each of the two days, which included a touchdown (e_5) to be used as common PTZ videopanorama reference with Δt (panorama -PTZ) $\approx$ 0 s.

Table 2 PTZ experiment for determining effective resolution

Trial #2 and 3	α_{PTZ}/arcmin for (Δt/s)	
Zoom factor Z (2θ)	e_{11}: First sighting	e_8: Gear down
3.6 (16.2°)	1.07 (52)	1.35 (10)
4.0 (14.5°)	1.30 (32)	1.23 (14)
Mean	1.2 (42)	1.3 (12)

Δt = measured event observation time difference t(panorama)–t(PTZ)

$Z = 3.6$, day 1, clear; $Z = 4$, day 2, cloudy

2θ = field of view

5 Simulation Environment

Detailed descriptions of the (advanced) RTO simulation environment and human-in-the-loop experiments using this system are presented in separate chapters of this book (chapters “Remote Tower Simulation Environment,” “Assessing Operational Validity of Remote Tower Control in High-Fidelity Simulation,” and “Videopanorama Frame Rate Requirements Derived from Visual Discrimination of Deceleration during Simulated Aircraft Landing”). Here only a brief overview of the initial RTO simulator is given.

For investigating possible RTO/RTC work system alternatives with different traffic scenarios and determining RTO system specifications under reproducible experimental conditions, DLR’s apron and tower simulator (ATS, depicted in Fig. 12) was extended by a remote tower operator (RTO) console as shown in Fig. 5.

Besides the possibility of displaying the live stream of the panorama camera system, it was the main purpose of the ATS-RTO console to provide a simulated real-time panorama as derived from an image generator (IG) with simulated airport traffic generated by the ATS simulation engine. The simulation included PTZ camera, displayed on the touch-input display integrated into the console. Position data, flight plan data, weather information, and airfield lighting were provided by the simulation. This allows simulation of the advanced augmented vision capabilities of the RTO controller work position (CWP) via integration into the simulated far view for trials within the validation setup with professional controllers as test subjects. For simulation trials, an eye-tracking measurement system could be added to the system with optical head tracker for obtaining quantitative fixation and dwell-time data of the areas of interest attended by the operators.

There are several reasons for validating the RTO/RTC concept, besides field tests also by means of integration into a real-time simulation environment. First of all, it ensures control and reproducibility over experimental conditions and constraints. Variation of traffic mix and load, environmental conditions, and the creation of possibly conflicting situations allow the evaluation of human factors and safety-related issues. Furthermore, the ability to vary between different CWP configurations and operational procedures in the simulator enables a more comprehensive analysis of related organizational and operational constraints for the

Fig. 12 RTC simulator environment used for remote tower experiments [reprinted from Fürstenau et al. (2011), IFAC, with permission]. Photo depicts the previous 200° vision system of the DLR tower simulator (ATS), extended by the 180° RTO backprojection console (*left*). The latter could alternatively display RTO simulations or the live panorama

implementation of the new remote tower center (RTC) concept. The simulation setup supports also the analysis of HMI and RTC work system design. Special real-time simulation capabilities were prepared for validating RTO working positions located within a RTC for two small airports as depicted in Fig. 13.

The real-time simulator experiments were an integral part of the (iterated) concept development and validation process. Due to its characteristics, the experiments carried out within the simulator focused on certain specific issues. The experimental design covered the analysis of operational procedures, the dedicated work environment, and the evaluation of its influences on controller workload and situational awareness. Additionally, the developed work share within the combined RTC environment was observed and analyzed as well as attention- and perception-related factors. Within the experiments, variation of different visual conditions, including reduced visibility conditions (fog), and a variation of available light situations (day- and nighttime conditions) were examined.

Another important issue was the specification of technical system parameters like video-frame rate (see chapter “Videopanorama Frame Rate Requirements Derived from Visual Discrimination of Deceleration During Simulated Aircraft Landing”). These parameters were varied systematically in order to investigate the limitations of the reconstructed far view, search for alternative solutions, and derive specifications for operational use.

Fig. 13 RTC simulator setup for human-in-the-loop simulation with simultaneous surveillance of two remote airports using two augmented vision videopanorama systems

Results of RTO/RTC simulation experiments including structured interviews with professional controllers are published in Möhlenbrink et al. (2010) and Papenfuß et al. (2010) and in chapter "Assessing Operational Validity of Remote Tower Control in High-fidelity Simulation" of this book.

6 Conclusion and Outlook

Basic elements of DLR's initial experimental remote tower operation (RTO) system at the Braunschweig Research Airport are described, and the theoretically expected performance of the RTO videopanorama including zoom function as core of the new controller working position is estimated. The RTO human-machine interface was developed under the guideline of human-centered automation, and basic results of structured cognitive work analysis are briefly reviewed. Initial field test results are reported which were evaluated by assuming the visual (pixel) resolution to play the dominant role for event detection. Quantitative evaluation of field trials by comparing real-view and videopanorama detectability of different events confirmed the theoretically predicted videopanorama resolution of ca. 2 arcmin. Resolution of the pan-tilt-zoom (PTZ) camera was near the predicted value of ca. 1 arcmin with zoom factor $Z = 4$ and exceeded it with increasing Z. Advanced features like PTZ object tracking based on real-time image processing for movement detection and augmented vision by superimposed flight data such as multilateration position transmitted by mode-S transponder were demonstrated. Separately investigated extensions for improving low visibility conditions include a high-resolution thermal imager that is a component of the improved prototype RTO videopanorama system (see chapter “Remote Tower Prototype System and Automation Perspectives”) developed for the shadow mode validation experiments (see chapter “Which Metrics Provide the Insight Needed? A Selection of Remote Tower Evaluation Metrics to Support a Remote Tower Operation Concept Validation”).

Besides the experimental system for field testing, a first version of RTO simulator environment was realized for high-fidelity human-in-the-loop (HitL) RTO simulation experiments (see chapter “Remote Tower Simulation Environment”). It included an eye-tracking measurement system for obtaining quantitative data on the areas of interest attended by the operators during simulation trials. High-fidelity HitL experiments complement field trials due to the improved possibility for experiments under reproducible and more laboratory-like controlled conditions.

Acknowledgment We are indebted to several colleagues who contributed to this research. First of all, we acknowledge the contributions of Michael Rudolph who designed and wrote the software for the diverse RTO components like image compression/decompression, stitching of the panorama elements, and augmenting the raw image. We have to thank Christoph Möhlenbrink who helped with the design, setup, and analysis of the field tests. We acknowledge contributions by Monika Mittendorf for the help with preparation and analysis of the flight test data. Many thanks are due also to the DLR flight experiment department for excellent cooperation.

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Remote Tower Prototype System and Automation Perspectives

Markus Schmidt, Michael Rudolph, and Norbert Fürstenau

Abstract In this chapter, we describe the development of the videopanorama-based Remote Tower prototype system as the main goal of the second DLR-RTO project (RAiCe, Remote Airport traffic Control Center). One focus was on the implementation of an advanced RTO environment at a second airport (besides a comparable system at the Research airport Braunschweig). It was used for the worldwide first RTO-validation experiments with controlled flight scenarios for directly comparing RTO versus tower conditions using a DLR test aircraft (see separate chapters “Which Metrics Provide the Insight Needed? A Selection of Remote Tower Evaluation Metrics to Support a Remote Tower Operation Concept Validation,” “Model Based Analysis of Two-Alternative Decision Errors in a Videopanorama-Based Remote Tower Work Position”). The advanced RTO system served for analyzing the performance of the near prototype level of hard and software solutions and for preparing and executing passive shadow mode field test with participation of domain experts for providing more realistic operational conditions. We describe the design and setup of this RTO system which was realized in cooperation with the German air navigation service provider DFS. A detailed work analysis with DFS domain experts during workshops and RTO simulations provided a breakdown of the specific requirement specifications. The analysis showed that it would be impossible to consider all of these requirements in an RTO design within a reasonable cost frame. This concerned the selection of type, numbers, and focal width of cameras, their visual resolution, contrast, dynamic range and field of view, zoom functions and the corresponding number, and type of displays or projection systems for the reconstructed panoramic view. The vertical FOV turned out as a crucial factor for the visual surveillance up to an altitude of 1000 ft. above the runway in the panoramic view as one of the basic design conditions. We describe hard- and software aspects of the system design, its setup, initial tests, and verification as precondition for the RTO-validation experiments. Furthermore, we include some details and results addressing the automation potential using image processing. The requirement for automation of functions such as pan–tilt–zoom camera–based object tracking, e.g. via movement detection was

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derived from the results of validation experiments described in chapters "Which Metrics Provide the Insight Needed? A Selection of Remote Tower Evaluation Metrics to Support a Remote Tower Operation Concept Validation," "Model Based Analysis of Two-Alternative Decision Errors in a Videopanorama-Based Remote Tower Work Position," and "The Advanced Remote Tower System and Its Validation." Results of functional tests and performance verification complement the initial flight test results of chapter "Remote Tower Experimental System with Augmented Vision Videopanorama".

Keywords Work analysis • Human-machine interaction • RTO requirements • RTO design • Augmented vision • Visual resolution • Visual contrast • Contrast enhancement • Image optimization • Thermal imaging • Electromagnetic compatibility • Automation • Movement detection • Object tracking

1 Introduction

One of the basic goals of the DLR project Remote Airport Traffic Control Center (RAiCe, 2008–2012) as follow-up of the initial experimental system development within the project Remote Airport Traffic Operation Research (RApTOr, 2005–2007, chapter "Remote Tower Experimental System with Augmented Vision Videopanorama") was the setup and test of an improved RTO system at a second airport. It served for demonstrating and analyzing the next (near prototype) level of hard and software solutions, for designing and testing long distance real-time video data transmission, and for preparing and executing RTO-passive shadow mode test at this airport. These goals were achieved within a cooperation with the German air navigation service provider (ANSP) DFS (project RAiCon, Remote Airport Cooperation, 2011–2012).

In what follows, we will briefly review in Sect. 2 the results of in-depth work and task analysis addressing the specific design requirements for Remote Tower Operation at low traffic airports selected for the prototype verification and validation experiments. In Sect. 3, the concrete design and setup of the advanced prototype systems at airports Braunschweig and Erfurt is described, including RTO-specific software development, the controller working position (CWP), and the long distance wide area network (WAN) connection between the remote airport and the DLR tower lab in Braunschweig. Section 4 addresses RTO-specific aspects and perspectives of advanced image processing and thermal imaging. In Sect. 5, verification with functional tests for quantification of relevant RTO-system features is addressed. We finish this chapter with a conclusion and outlook in Sect. 6.

2 Work and Task Analysis for Requirement Specifications and Prototype Design

The major characteristics of the type of airport under consideration are given by a few points only:

1. Low ratio of IFR versus VFR traffic. Only the former requires controlled airspace. On low-traffic airports quite often only a handful of regularly operating flights (IFR, usually commercial international flights) has to be controlled.
2. VFR traffic (usually general aviation) is highly weather dependent and often generates unexpected events due to heterogeneous pilot skills and experience.
3. Low-traffic and regional airports usually have only a low level electronic sensor infrastructure (e.g., no surface movement radar SME).
4. The tower provides 1–2 working positions, with often a single operator during low traffic hours.

The specific low-traffic airport requirement specifications for the prototype RTO system design built upon the initial results obtained within the initial DLR remote tower projects (ViTo, RApTOR, 2002–2007, see previous chapters). Increased cooperation with the German ANSP DFS and several RTO-simulation campaigns with voluntarily participating (and paid) controllers increased significantly the number of experts (tower controllers and supervisors) contributing their domain knowledge, provided a more detailed requirement breakdown through discussions, and formalized interviews and design workshops. The comparison of the updated requirement specifications with achievable technical parameters showed that in particular for the reconstruction of the visual information (the “far view”), it was hardly possible to consider all of these requirements for a realizable design under reasonable cost constraints. This concerned the numbers of cameras and the corresponding number of displays for the panoramic view, the visual resolution, dynamic view, contrast, and the field of view in vertical and horizontal direction.

Of course there exist ICAO and DFS requirements for tower construction concerning direct visual observability conditions which may be used as guidelines for the reconstructed far view. These are more or less specific, e.g.,:

- The tower should have an appropriate distance from the landing threshold
- The vertical FOV should be at least 1000 ft. above the RWY, i.e., at least ca. 40° rel. to the horizon at a distance of 400 m between tower and runway (ICAO 2013), (DFS: BA-FVD343)
- Good 360° panoramic view (implicitly assuming visual resolution of the human eye), including airport circles, approach sectors, runway, movement areas
- At least one CWP with places for 2 persons for training purpose, including consoles equipped with different VHF/UHF stations, control strips, telephone communication

The following graph (Fig. 1) depicts the percentage of use of different information sources for all identified controllers tasks, separated for the ground (PG) and

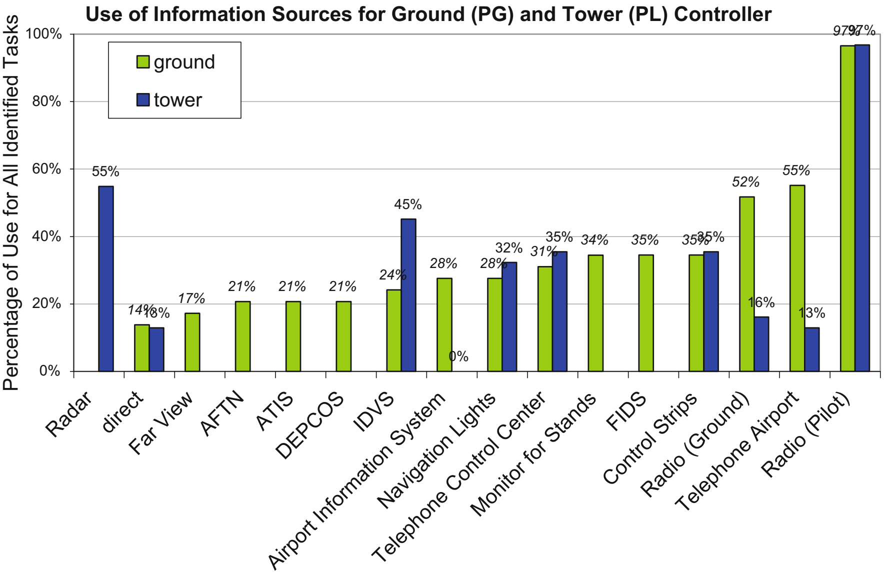

Fig. 1 Use of information sources of tower and ground controller for decision and support tasks. Average of 29 PG-tasks and 31 PL tasks (clearances, communications, etc.)

tower (PL) controller obtained from controller interviews (Papenfuß and Möhlenbrink 2009).

The graphic is based on structured interviews with two supervisors and relates to medium-sized airports. It provides an indication that PL and PG make quite different use of the different available information sources. Out-of-windows view appears to be used mainly by the PG whereas exclusively the PL uses the (approach) radar. Radio communication with pilots, control strips (flight plan information), telephone communication with approach control and airport, and weather information display IDVS are other important communication/information channels. Clearly, the distribution of work will differ at small- and low-traffic airports from medium and large ones (the latter ones generally have separate apron controllers which usually are airport operator employees) so that the PL–PG work distribution may be different at different airports and of course vanishes for the single operator situation (see also chapters "Assessing Operational Validity of Remote Tower Control in High-Fidelity Simulation," "Remote Tower Experimental System with Augmented Vision Videopanorama").

During prototyping of the advanced RTO system, the DLR team together with DFS domain experts discussed the concept and the design of the improved RTO-controller working position (RTO-CWP). Within two specific design workshops, the participants derived the framework for an operational design based on the requirement specifications and other conditions. From a complete requirement list (separated for day and night operation), we will extract here only some aspects of interest for the far view reconstruction, the core HMI component of the RTO-CWP.

- 360° panoramic view is considered necessary for observability of all movements of aircraft in the airport vicinity (including airport circling within the control zone) and of cars and persons on the movement areas. The direction opposite of the RWY shall be visualized at least on demand within 3 s.
- Recognition of traffic situations/movements (before reaching of clearance boundaries) and emergencies without delay for timely control actions
- Discriminability of weather conditions (wind, cloud parameters) and recognition of weather changes
- Recognition of aircraft and vehicle positions, operating states, and movement state (direction, acceleration, braking)
- Recognition of fixed and mobile obstacles
- Object detectability: size 0.3 m/1 km distance (=1 arcmin visual resolution)
- Zoom function (=binocular function): continuous, $Z_{\max}$ within 2 s, preset and hot spot viewing positions (pan–tilt–zoom, PTZ)
- Manual and automatic tracking of 0.3 m objects in 1 km distance
- All requirements are valid for day and night operation

It seems worthwhile to remind the experimental results of the field tests reported in the previous chapter "Remote Tower Experimental System with Augmented Vision Videopanorama": the initial experimental videopanorama system at Braunschweig research airport showed an optimistic visual resolution of about 2 arcmin (0.6 m/km, about half as good as the human eye, not considering contrast effects; see also Appendix chapter A) which was obtained with the best high-resolution CCD cameras available at that time [ca. 2006: (Fürstenau et al. 2008b, 2007; Schmidt et al. 2007)]. Meanwhile, technology changed to HD format as standard, even quad-HD available, and cost for high-resolution cameras decreased from >10 k€ to <5 k€.

3 The RTO System Setup and Human–System Interface

3.1 Videopanorama Camera System

The crucial aspects for the selection of the most important system design requirements with regard to the reconstruction of the tower out-of-windows view (the "far view") derived from the task analysis are the visual resolution and the vertical FOV, according to the requirement for object detectability in the videopanorama up to an altitude of 1000 ft. (300 m) above the runway (ICAO 2013).

Table 1 shows the theoretically available options used for comparing the different configurations, as dependent on number of cameras and focal width. The pixel

Table 1 Different design options for RTO-videopanorama camera system (1 arcmin = 1/60° = 0.3 mrad)

	Option 1	Option 2	Option 3
Number of HD cameras/ displays	5	7	10
Vertical/horizontal FOV	68°/190°	46°/182°	34°/190°
Resolution/arc minute per pixel	Ca. 2	Ca. 1.44	Ca. 1
Main focus	High FOV	Medium FOV and resolution	High resolution
Conclusions	Medium effort Medium resolution	Affordable but realistic	High effort Huge required space for the R-CWP

resolution of the cameras for all options is determined by HD format, i.e., 1920 × 1080 pixels.

Because the FOV by most experts was considered more important than the maximum achievable resolution (within the given cost frame for the system components and complexity), the RTO-system setup was defined following option 1, with the following characteristics:

- 5 industrial HD cameras, 2/3″ CCD technology, with $f = 8$ mm lenses
- Single camera housings with heating and air blaster cleaned front window
- Pan–Tilt–Zoom (PTZ) camera with VGA resolution, continuously horizontally rotatable with tilt angle from −30° to 90° rel. to the horizon.

Figure 2 shows the panorama camera system with pan–tilt–zoom (PTZ) camera on top after adjustment (viewing direction north, 360° horizontal FOV, with electronic box beyond). In addition to the power supply and optoelectronic components for data transfer, it contains an air blast system for remotely controlled cleaning of the camera housing windows.

The cameras originally included infrared filters which served for optimizing the RGB color definition. These were removed in order to increase the overall sensitivity at the cost of color reproduction fidelity. The effective dynamical range of the cameras (including video image (color)) preprocessing was 8 bit (=255 intensity steps) for each of the three RGB color channels. The video frame rate typically was set to the maximum possible value of 30 Hz (see chapter “Videopanorama Frame Rate Requirements Derived from Visual Discrimination of Deceleration During Simulated Aircraft Landing”).

Fig. 2 Panorama camera and PTZ setup at the Airport Braunschweig/Wolfsburg

3.2 RTO-Controller Working Position

Based on the experience gained within the first DLR RTO project (see chapter "Remote Tower Experimental System with Augmented Vision Videopanorama") and a close cooperation with DFS domain experts, including two specific design workshops (see Sect. 2), an improved design of the new RTO-controller working position (RTO-CWP) was realized. A corresponding version although somewhat extended for experimental purposes with 360° panorama was set up in the DLR Tower Lab at the Inst. of Flight Guidance. It replaced the initial version shown in chapter "Remote Tower Experimental System with Augmented Vision Videopanorama" and served for testing the long distance WAN connection between Braunschweig and Erfurt.

Figure 3 depicts the extended RTO-CWP showing the 360° panorama of Braunschweig airport: six portrait orientation displays with 68° vertical and 228° horizontal FOV are complemented by two horizontal displays attached to the left and right side covering the southern direction. The PTZ display with camera interaction controls is integrated in the tilted touch-input display at the operator console which in addition contains a second touch-input display with electronic flight strips.

Fig. 3 Prototype RTO-Videopanorama with basic controller console in the DLR Tower-Lab (2013) reproducing the out-of-windows view at Braunscheig airport. 360° horizontal FOV with 6 vertical displays for the 228° view towards the runway in northern direction. Two horizontal displays covering the southern 136° viewing sector with the same resolution

This experimental RTO-CWP at the DLR Tower Lab (see chapter "Remote Tower Simulation Environment") was used as development environment. It demonstrated the excellent data transmission performance of the WAN connection between Braunschweig and Erfurt, i.e., the flawless transmission of the video streams over several hundred kilometers (see Sect. 3.3). The experience gained with the experimental system combined with the results from the design workshops yielded an operational RTO-CWP prototype design derived from the latest DFS controller console with three levels of information or surveillance and control input, respectively, as depicted in Fig. 4.

The realization based on this design and the installation of the RTO-CWP in a control room adjacent to the Erfurt airport tower building was realized by DFS engineers. This final version as depicted in Fig. 3 was used for the validation experiments described in the following chapters "Which Metrics Provide the Insight Needed? A Selection of Remote Tower Evaluation Metrics to Support a Remote Tower Operation Concept Validation" and "Model-Based Analysis of Two-Alternative Decision Errors in a Videopanorama-Based Remote Tower Work Position." In addition to the videopanorama and the touch-input control and PTZ display integrated in the operator console (for details see Sect. 3.4), the work position also includes the standard displays for the essential operational ATM

Fig. 4 Implementation of the R-CWP at Erfurt tower control room without direct airport view. Three levels of information with the videopanorama in the back, the row of four flight information displays, operator console with two large touch-input displays, and a small one at the right side for radio communication are clearly structured (for details see text)

data (from left to right): IDVS (weather data; see also chapter "Introduction and Overview," Fig. 2), (approach) radar, flight data (electronic flight strips). The latter could be moved to the large touch-input display on the right side of the operator's console.

The described camera system together with the RTO-CWP in Erfurt was the technical basis for the validation tests described in the following chapters. This initial quasi-operational validation by means of the so-called passive shadow mode tests (no communication between RTO controllers and pilots) serves as the basis of larger scale-validation exercises within the European ATM-research context (SESAR Work Package 6.8.4).

3.3 High Bandwidth Wide Area Network

One goal of the second DLR Remote Tower project was the concept development, implementation, and the verification of a high bandwidth long distance connection between the RTO-CWP in the DLR Tower Lab (see chapter "Remote Tower

Simulation Environment") and a remote airport for testing the performance of the data transfer of the video streams from the advanced prototype sensor system. This long-distance connection over several hundred kilometers was realized with the advanced videopanorama system described above, between the camera system on the Erfurt tower and the experimental RTO-CWP at the DLR Tower Lab. The live videopanorama could be displayed simultaneously at the latter CWP and at the operational RTO-CWP at the ground level of the Erfurt tower building for the validation experiments without direct far view. For testing the live transmission and verifying its performance (see Sect. 5), a specific secure high bandwidth WAN connection was set up. A peer-to-peer fiber-optic connection between the RTO-CWP and Erfurt tower was realized by an external provider with a minimum bandwidth of 50 Mbit/s (optionally to be increased up to 100 Mbit/s) and the router/switching devices at both endpoints. The network was decoupled from the DLR domain as well as from the internal DFS network so that data security at both sides of the connection was established.

3.4 RTO Software and Human–Machine Interaction

The advanced RTO software for the prototype RTO system to be used for the shadow mode-validation experiment (see chapters "Which Metrics Provide the Insight Needed? A Selection of Remote Tower Evaluation Metrics to Support a Remote Tower Operation Concept Validation" and "Model Based Analysis of Two-Alternative Decision Errors in a Videopanorama-Based Remote Tower Work Position") was based on the initial experimental RTO system at Braunschweig research airport (DLR project RapTOr, see chapter "Remote Tower Experimental System with Augmented Vision Videopanorama"). Besides improved image processing and quality [data compression (CoDec)], and Bayer color format interpolation, see below), it provided more flexibility for integration into other hard and software environments.

The general data path of a video stream in the remote tower software is shown in Fig. 5.

The stream of the captured raw images is transferred to the grabber who converts it to RGB images. According to the basic concept (Fürstenau et al. 2008a, b) in the following step the output of the grabber is split into two paths. The first one feeds the uncompressed data into the movement and object detection for achieving minimum delay and maximum image processing quality. The second stream passes an image compression stage and is recorded for playback and transmitted to the remote location. For the initial experimental system (see previous chapter "Remote Tower Experimental System with Augmented Vision Videopanorama"), an MJPEG encoder was used because of limited computational power and the unlimited bandwidth in the local (GBit-Ethernet) network. For the functional verification of the prototype system with long-distance transmission, in contrast, a H.264 encoder was employed to transfer the high definition video stream to a remote

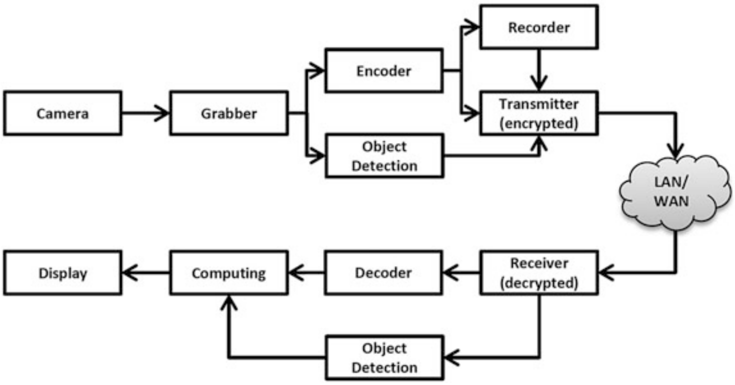

Fig. 5 Data path of the video stream

location with a limited network bandwidth of 50 Mbit/s. To ensure data security, the stream was AES-256 encrypted by the transmitter. After decryption, the receiver forwards the stream to the video decoder which in turn forwards the decoded video to the display.

The initial experimental system provided the possibility to use any kind of grabber that delivers Microsoft DirectShow drivers and industrial CameraLink grabbers. For the prototype, this support was extended to industrial GigE Vision grabbers and GigE Vision cameras connected with a standard network interface card. This ensured integration of a wide range of GigE Vision cameras. Furthermore, a software grabber allowed for integration of simulated cameras of the DLR tower simulator. In this way, the same RTO software could be used for the real world live stream and for the synthetic DLR simulation environment. The possibility to use network interface cards instead of special grabber cards resulted in a significant cost reduction.

For the majority of high quality industry cameras, the captured images are provided in the Bayer color format. The grabber has to interpolate a RGB color image from the raw picture with an adequate algorithm to provide the best quality possible with preferably low delay. The demosaicing process usually is done onboard in hardware if industrial products are used. In the case of standard network interface cards, however, the raw Bayer images are provided and the images have to be converted with custom made algorithms. For the RTO prototype, an adaptive homogeneity-directed demosaicing algorithm was implemented because it delivers high quality images in a reasonable time. The interpolation was done in OpenCL on a high end graphics card resulting in a very low computation time. The maximum video frame rate (see chapter “Videopanorama Frame Rate Requirements Derived from Visual Discrimination of Deceleration during Simulated Aircraft Landing”) was limited to ca. 33 Hz by the GigE Vision IP-based camera interface standard.

For manual control of the pan–tilt–zoom (PTZ) camera, a specific display was developed that offers several possibilities to navigate the camera based on pen-touch input functionality. Figure 6 depicts a photo of this advanced HMI

Fig. 6 Pan–tilt–zoom camera control pen-touch input display with viewing direction indicator (virtual joystick, bottom right) including zoom factor selection ($Z = 2, 4, 8, 16$) and mini-panorama. For details see text

version which represented an advanced version derived from the initial experimental one described in chapter "Remote Tower Experimental System with Augmented Vision Videopanorama."

On the top right side, a number of preset buttons and buttons for static commands like move, zoom, or (window) clean are located. Below, a kind of wind rose can be seen. The inner circle serves as "virtual joystick" where a seamless movement of the camera in a specified (tilt) direction is possible with specified speed. The outer ring serves for commanding the desired horizontal (pan) position. The actual position and field of view of the camera is highlighted there with yellow color. On the left side of the ring, a corresponding vertical scale is integrated for setting the tilt position. Outside of the ring are the fields to control predefined zoom factors, $Z = 2, 4, 8, 16$. At the bottom left, a reduced version of the video panorama can be seen. A click inside this sector moves the camera viewing direction to the corresponding pan–tilt angles. The position of the camera is shown in the video panorama by a yellow frame. Usability trials with operators showed that this feature supports the orientation when users manually control the camera.

Structured interviews of controllers during design workshops and RTO-simulator experiments (see Sect. 2 of the present chapter and chapter "Assessing Operational Validity of Remote Tower Control in High-Fidelity

Simulation”) as well as during the shadow mode-validation experiments (chapters “Which Metrics Provide the Insight Needed? A Selection of Remote Tower Evaluation Metrics to Support a Remote Tower Operation Concept Validation” and “The Advanced Remote Tower System and Its validation”) showed that automated tracking of the pan–tilt–zoom camera would be very helpful. The remote tower software offers the automatic tracking of aircraft by multilateration data via Mode-S transponder and by using vehicle positions from automatic movement detection (see Sect. 4). This functionality was already demonstrated in the first RTO project RApTOR with a more basic approach (see previous chapter “Remote Tower Experimental System with Augmented Vision Videopanorama”). It was not intended to activate the automatic movement detection and tracking functions within the validation experiments due to limited reliability that was not sufficient for operational testing. The results of the validation experiment however show that automation features of this kind are probably required in order to rise the RTO-system performance and usability to the operational level (see chapters “Which Metrics Provide the Insight Needed? A Selection of Remote Tower Evaluation Metrics to Support a Remote Tower Operation Concept Validation” and “Model Based Analysis of Two-Alternative Decision Errors in a Videopanorama-Based Remote Tower Work Position”).

4 Perspectives of Automatic Movement and Object Detection

The basic automatic movement detection and PTZ tracking functions were demonstrated already with the initial experimental RTO system of the DLR project RApTOR, together with augmented vision features. This concerned in particular dynamic Mode-S transponder information overlay (A/C identification and altitude, see previous chapter “Remote Tower Experimental System with Augmented Vision Videopanorama”). The importance of a certain degree of automation by using data fusion of, e.g., Mode-S transponder information and/or movement detection with PTZ object tracking was derived from the performance deficits of the basic prototype systems as quantified in the initial validation experiments (see chapters “Which Metrics Provide the Insight Needed? A Selection of Remote Tower Evaluation Metrics to Support a Remote Tower Operation Concept Validation,” “Model Based Analysis of Two-Alternative Decision Errors in a Videopanorama-Based Remote Tower Work Position,” “The Advanced Remote Tower System and Its Validation”).

Here, we present some additional research, mainly done by experts at the DLR unit “Optical Information Systems”/Berlin-Adlershof (a cooperation partner within the DLR-RTO projects). They were presented at the RaiCe Final Workshop (Remote Airport Traffic Control Center (RAiCe), 2013). Although these developments were not implemented for the validation experiments due to limited operational stability, they indicate promising directions for future RTO automation which will be particularly useful for the reduction of operator's workload and increase of usability under multiple airport control within a Remote Tower Center (RTC, see chapter "Planning Remote Multi-Airport Control—Design and Evaluation of a Controller-Friendly Assistance System"). For example, a selective marker in the images of the real time view as augmented vision element (see chapters "Introduction and Overview," "Remote Tower Experimental System with Augmented Vision Videopanorama," "The Advanced Remote Tower System and Its Validation") could help the (remote) tower operator to focus the attention to moving objects and potentially critical situations.

For this purpose, an experimental version of automatic scene analysis by means of image processing in combination with an object tracker was investigated. In the system, two different image processing approaches were realized in order to investigate the specific advantages and drawbacks. The algorithms were running in parallel and on the one hand employed optical flow analysis and on the other hand region tracking with background estimation. The combination of both was visualized as superimposed information within the videopanorama (augmented vision). These approaches are suitable for moving object detection and are briefly described in Sects. 4.1, 4.2, 4.3.

A specific problem of movement and object detection in the RTO environment in contrast to exclusive ground traffic that has to be solved by all of these approaches is moving objects like birds and clouds, without relevance for the RTO tasks. It turned out that this can be solved only by using different algorithms for the image sections below and above the horizon.

4.1 Movement Detection via Optical Flow Analysis

Optical flow analysis is comparable to the human peripheral vision. It detects objects due to their motion in a series of subsequent images. Following Shi and Tomasi (1994) in a first step, the corners in the image are selected as features. In a second step, these features are tracked with the KLT-Tracker (Tomasi and Kanade 1991) through a block of eight subsequent images. Because both feature detector and tracker have to be very sensitive in order to support the detection of small (and distant) objects as well, the majority of the tracked features will be wrong ones. Two techniques are used in order to disclose and erase wrongly tracked features.

First, the features are redundantly tracked back from the last image of a block back to the first image (Wohlfeil and Börner 2010). Erroneously tracked features can be determined by comparing the initial and final position of a tracked feature. Figure 7 depicts an example of optical flow analysis with a scene of the east-viewing camera on the tower of Erfurt airport.

Features moving less than a pixel during the block of eight images are regarded as features of static objects and ignored (red dots in the figure). All remaining features are displayed in the figure as red crosses with a red line showing their

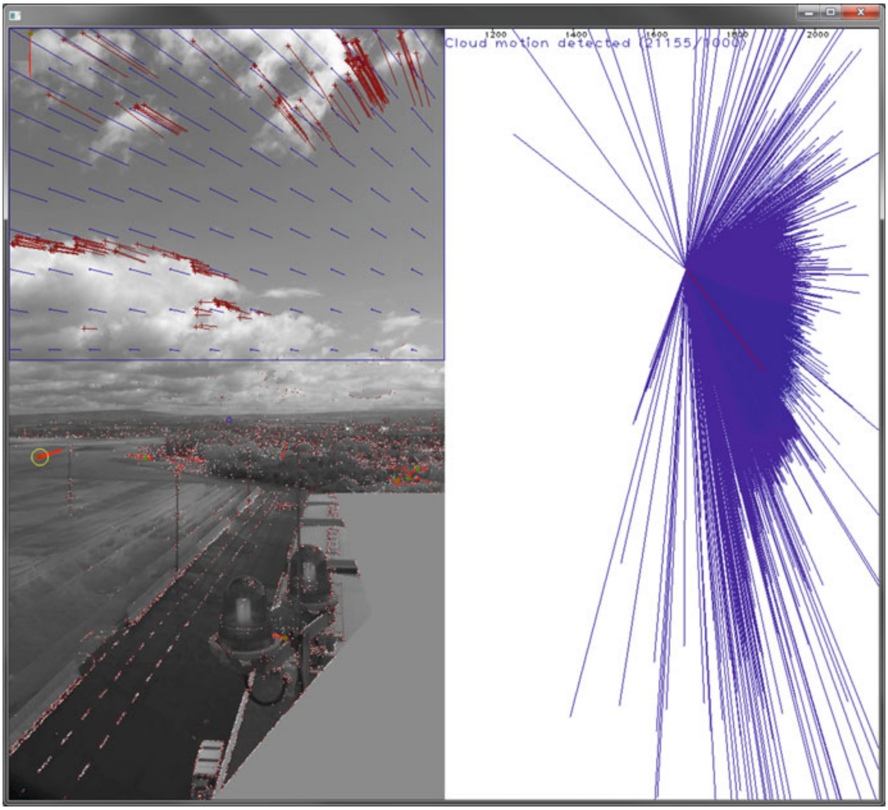

Fig. 7 Example of object tracking with the optical flow method (scene from Erfurt airport tower). Filtering out of static objects (*red dots*) and clouds (*dark red* and *blue lines* indicating average movement direction), with remaining real (traffic) object recognition (*yellow circle with bright red line*). For details see text

current motion. In a second step, additional irrelevant features are erased by assuming that relevant objects move almost linearly within the short periods of eight frames.

Another problem is the motion of the clouds and their shadows. They move linearly, and without a human understanding of the scene they have all attributes of real moving objects in the sky or on the ground, respectively. Anyway, by means of the tracked features in the sky, the mean cloud motion in object space can be determined by assuming that all clouds are in a height of 1000 m and move in almost the same direction during several minutes. By knowing the mean cloud motion in object space, the mean cloud motion in image space is calculated (blue lines in the upper part of Fig. 7). Features in the sky, which move in the same way as the clouds, are regarded as features of clouds (dark red in the figure). Features which move in a different direction or with different speed are features of objects.

Finally, the remaining features are clustered to objects (yellow circles in the figure) and tracked through multiple blocks of images, assuming almost linear motion of the objects also during longer periods of time.

4.2 Region Tracking Algorithm Based on Background Estimation

Static background subtraction was successfully used for detection of moving cars and other objects in general ground traffic. With the present application, however, many false positive candidates especially for moving clouds in the sky were generated. On the other hand, the implemented feature tracking algorithm based on optical flow as described above also exhibits deficits. For example, it does not provide a size or shape estimation for the object candidates. That is why experiments were performed with both algorithms used in parallel. An example result is depicted in Fig. 8.

In the first step, sufficiently reliable candidate objects are detected with both approaches which are then fused on the object level. Only candidates detected and tracked with both approaches in a series of subsequent images are sent to the server as detected objects.

4.3 Object Classification

The previous two algorithms were specifically optimized for combined detection of moving aircraft. Especially, the optical flow algorithm will lose sight of the detected moving object immediately upon stop of movement. Also the object detection with the background estimation is not able to detect the tracked object for an extended time span. After a small period (depending on a “forgetting factor”), the object will become background itself.

That is why additional algorithmic approaches for image interpretation of static objects are needed, especially for aircraft not moving. For this task, classification algorithms were developed. Before realizing the classification itself, it is important to find linearly independent and robust features which can separate the class “aircraft” from other object classes. For this purpose, different assumptions were considered. For example, most aircraft exhibit bright or white shapes on the surface that, in general, exhibits homogenously gray values. Moreover, A/C are mostly brighter than the background (soil, grass, apron, or runway). However, above the horizon, this feature can be inverted: A/C mostly appear darker than the bright sky as background. For this reason, each image is split between above and below the horizon. An automatically calculated binary mask uses different algorithms for the feature generation. In a first step, the total raw image was transformed

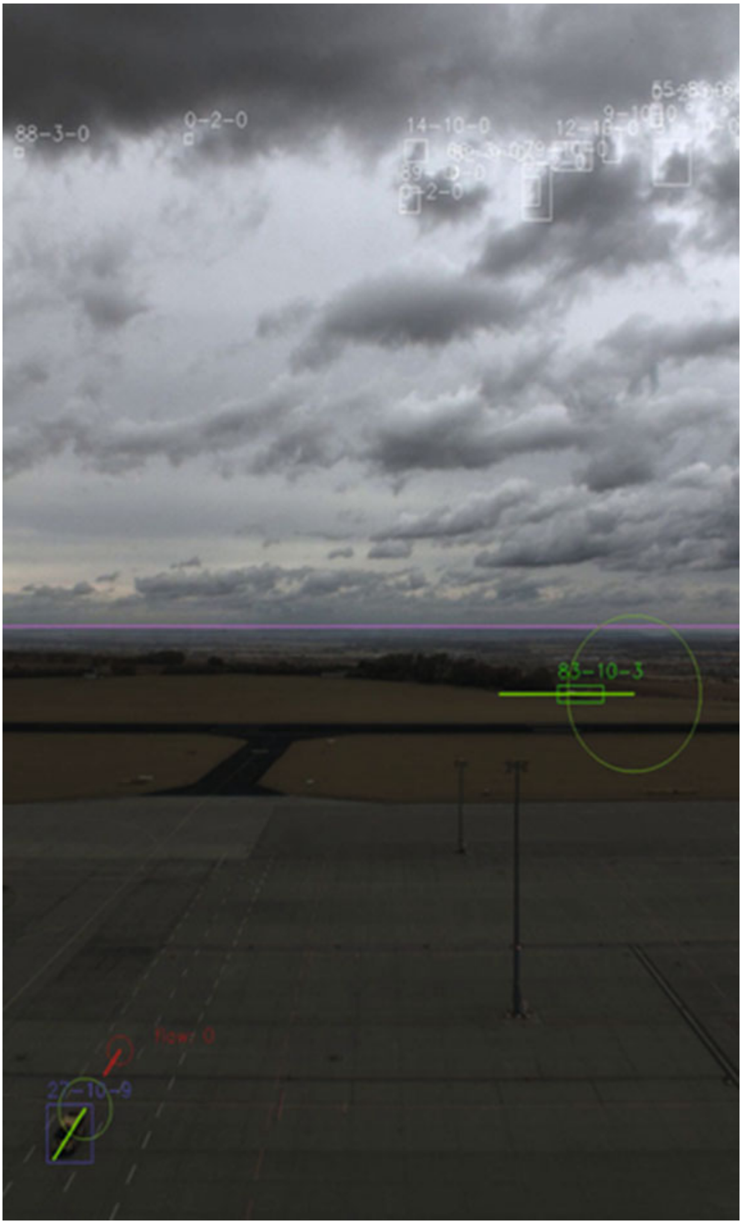

Fig. 8 Information fusion. Combination of optical flow and background estimation algorithms: detected objects in the image colored *green* and *blue*

Fig. 9 Bright color feature characterizing aircraft (upper b/w image, Braunschweig panorama camera 3). Lower image: colored overlay results depict detected objects including one false positive on the left side, indicating the necessity of additional features for discrimination, e.g., area restrictions

from the RGB image into the YUV color space. Thereafter, a new color feature was created: Feature_4 = (abs(yuv_image(2,*,*)* Maske(*,*)−yuv_image(1,*,*)* Maske(*,*))) (see also Fig. 9 below).

For increasing the robustness of the analysis with regard to variations of the illumination in the images (e.g., induced by variable shading through clouds), big clusters were searched which exhibit corresponding similar gray values (these clusters are mostly the apron surfaces or the surrounding vegetation (large grass areas)). Here, the mean illumination can be directly detected and will normalize the classification feature. An example of automatic color feature extraction and overlay is shown in the following Fig. 9.

4.4 Thermal Imaging

The standard CCD-camera chip exhibits a significant sensitivity in the near infrared spectrum (around 1 μm wavelength). In the usual configuration, this part of the spectrum is filtered out by means of an infrared filter because it induces some imbalance in the RGB color fidelity. For low visibility conditions and during nighttime, however, this sensitivity may be utilized by removing the filter if this feature is included in the camera design.

A significantly larger step towards low-visibility object detection improvement can be achieved by including a high-resolution thermal imager. The relevant IR spectral ranges are the atmospheric water windows around 5 and 12 μm. For investigating and demonstrating the thermal imaging potential, a 640 × 512 pixel cooled thermal imager for the 5–7 μm midwave (MWIR) range with three discrete zoom steps (FOV: 1.2°, 4.7°, 15.3°) was included in the advanced videopanorama setup at Braunschweig airport. It was integrated in a common housing together with the visual PTZ (see Fig. 10) Although for the experimental purpose, this relatively high cost military thermal imager (FLIR) was integrated into the system, also a lower cost system is expected to significantly improve the reconstructed far view and to increase the situational awareness of controllers on low traffic airports without any other electronic (SME, multilateration) surveillance systems.

The following figure depicts an example taken with the FLIR PTZ thermal imager. In this example, it is applied for imaging the thermal aircraft signature during landing. Reverse thrust detection and limitation of usage may be required for certain airports due to noise protection regulations. Experiments were performed with the DLR Airbus A320 in order to discriminate thermal signatures for activated/nonactivated reverse thrust after touchdown. The upper and lower pairs of images in Fig. 11 depict examples for landings with reverse thrust enabled (lower pair) and not enabled (upper pair), respectively.

Fig. 10 FLIR thermal imager (large circular Ge-window) as part of the DLR-RTO system at Braunschweig airport, integrated in a remotely controlled housing together with visual PTZ camera

Fig. 11 Thermal image of turbine exhaust without (upper images) and with reverse thrust activated (lower images)

5 Functional Tests and Verification

5.1 *Measuring Camera-Display Latency*

The operational requirement for the upper limit of delay between the situation at the remote airport and the video reconstruction at the controller working position is usually given as $\Delta t < 0.5$ s by the domain experts. It seems worth mentioning that the radar update time typically is 4 s due to rotation time. Also this fact underlines the relevance of the visual information if quick reaction of controllers is required.

5.1.1 LAN Delay in the Braunschweig Airport Experimental System

For the experimental system at Braunschweig Research Airport, a 500 m cable with multiple single mode optical fibers had been installed to realize a GBit LAN, in order to avoid any transmission bandwidth limitations. With this system, it was possible to send light from the display side up to the camera position and illuminate the lens. With a light pulse sent up to the camera, a shutter signal indicating the send time could be used to measure the time difference between the signal arriving at the display and the start time defined by the shutter at the source position. The signals were measured by means of a dual trace oscilloscope yielding a camera-display latency of 230–270 ms.

5.1.2 WAN Delay of the Long-Distance Transmission

For the long-distance transmission time, the measurement was somewhat more demanding. Of course, in this case, no light could be sent directly from the display position to the cameras. The total camera-display latency in Erfurt-Braunschweig was measured by using a small procedure, which sends a defined command (e.g., "close shutter") to one of the panoramic cameras and measures the time until the answer. Therefore, it is necessary to check at first the transmission time by sending a "ping" from Braunschweig to Erfurt to determine the latency without any video image processing. The next step is to monitor the transmission start time of the command sent to the remote camera in Erfurt and stop the instant when the effect of the command ("close shutter" means black display) arrived on the display in Braunschweig. Finally, the real video latency between the camera site and the display site (Braunschweig) is the measured (stop–start) time minus the half command transmission time (for considering the runtime of the command from Braunschweig to Erfurt).

The results of this test procedure are delays between 270 and 330 ms. Considering the fact that the command to close the shutter could reach the camera at the beginning, in the middle or at the end of one frame, with one frame interval ca. 33 ms at a frame rate of 30 frames/s, a mean delay of 300 ms is obtained. This is in rough agreement with the latency measured optically with the fiber-optic LAN of the Braunschweig experimental system.

5.2 Electromagnetic Compatibility

Within the safety critical aviation environment, new electronic systems for operational environments have to fulfill strict requirements concerning electromagnetic compatibility in order to guarantee zero electromagnetic interference with other electronic equipment. That is why electromagnetic emission of the prototype RTO system had to be measured with certified equipment before installation in the operational environment for validation experiments (between antennas at the tower roof). The aim of the measurements was to show that the radio frequencies used at the airport will not be disturbed in a worst case scenario. These frequencies at the Erfurt airport cover a range between 140 and 160 MHz.

The electromagnetic compatibility tests were performed in cooperation with the StudING-UG, a company of the Institute for Electromagnetic Compatibility of Braunschweig Technical University that is certified for this kind of measurement.

All measurements were made with a Rohde & Schwarz ESCS 30 Spectrum Analyzer (Frequency range 9 kHz bis 2.75 GHz) and a Rohde & Schwarz HL023 logarithmic-periodic antenna (Frequency range 80–1300 MHz). The complete camera system (cameras, PTZ camera, air blast cleaner, and electronic equipment) was scanned from all four sides for its electromagnetic emission. The distance from the top of the antenna to the middle of the camera system was always 1 m. The antenna was placed at a height of 1.5 m. The variation of the measuring direction was realized by turning of the camera system in steps of 90° so that a reasonably consistent background radiation can be assumed. Each side of the camera system was measured both with horizontal and vertical polarization of the antenna.

Figure 12 depicts the experimental setup for measuring the spectrum of electromagnetic emissions of the camera system with visual PTZ and air blast cleaner before installation on the Erfurt tower.

The measurements were carried out with the following parameters:

- Frequency range, 100–400 MHz
- Filter bandwidth, 9 kHz
- Scanning steps, 5 kHz
- Scanning time per frequency, 1 ms
- Scan of background radiation with deactivated camera system

A scan of the background radiation with turned off camera system was carried out prior to each single measurement and was compared directly with the measurement of the radiation emission of the activated system.

Due to the long scanning time of nearly 15 min for every scan (more than 8 h in total), it was not possible to measure the radiation of the working PTZ camera and the air blast cleaner without damaging both devices. That is why fast scans were carried out with a different filter bandwidth (120 kHz) and scanning steps of 60 kHz to obtain the emission of PTZ and air blast cleaner.

A typical result of background and emission scan is depicted in Fig. 13, with logarithmic radiation power plotted versus frequency.

The characteristic emission band at 170 MHz occurred more or less clearly in all measurements. After some shutoff tests of single components, the effect could be attributed to the network switch in the electronic box.

Fig. 12 Experimental setup for measuring electromagnetic emission

The measurements demonstrated that strong interferences can occur using various electronic devices (particularly network components) even if these devices are installed in metallic electronic boxes. But the measured interference frequencies in this case were not within critical operational frequency bands of radio frequencies at Erfurt airport. Therefore, the camera system could be used without any restrictions on top of the tower roof close to the antennas of the radio communication system.

5.3 Image Optimization

After initial tests of the redesigned prototype RTO system at the remote airport as a first measure, some public areas (streets, parking) had to be blanked out for reasons of privacy.

For the design and setup of the initial experimental system described in the previous chapter “Remote Tower Experimental System with Augmented Vision Videopanorama,” the theoretical performance prediction and the field tests for verifying the corresponding data had focused on the expected pixel resolution. It was mentioned before that the pixel resolution represents only a very optimistic idealized value, the Nyquist limit in terms of spatial frequency (see Appendix A). It was evident from the beginning, however, that the optimization of contrast and

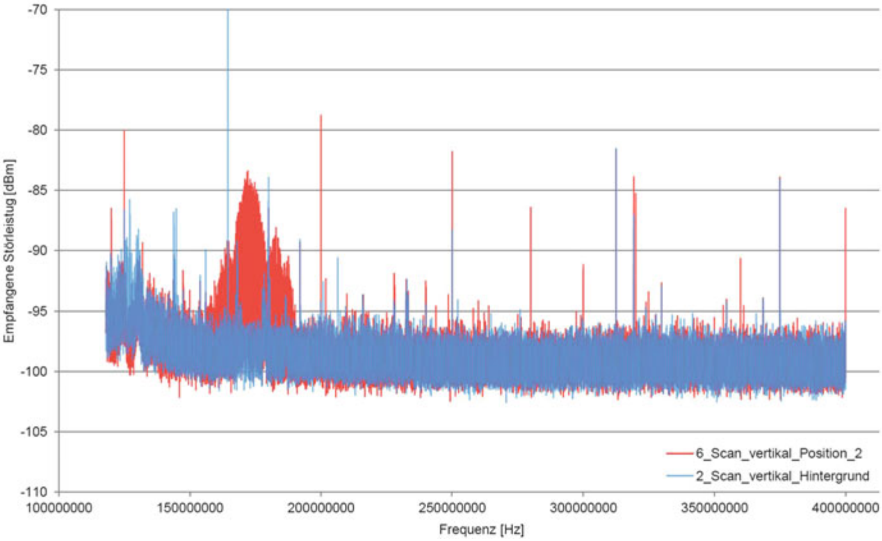

Fig. 13 Example of electromagnetic emission measurement. Horizontal axis: frequency/Hz; vertical axis: radiation power/dBm. Detected emission band (*red*) around 170 MHz

dynamic range would play a crucial role in approaching the required system performance. The realization of the prototype system involved several measures addressing these questions with the goal of systematic improvement of the respective system parameters.

For the panorama optimization, the following display parameters have to be optimized:

1. Working distance (defined by the special requirements of console and panorama display)
2. Display size
3. Pixel resolution [fixed by initial constraints: HD 1920 × (1080 × 6)]
4. Luminance
5. Static contrast
6. Gamma value

Some high-end displays for professional operation offer presets for playback in aligned video modes, where quite a few of these parameters are already optimized.

On the camera side, the image quality is influenced by:

1. Sensor chip/pixel size
2. Minimum aperture to avoid diffraction effects (dependent on illumination in automatic mode)
3. Dynamic range (nominally 8 bit)
4. Gamma value
5. Bayer demosaicing algorithm
6. Codec/Decodec methods

As alternative for using industrial cameras, there are so-called smart cameras available, generally installed in security areas, that are optimized for video recording even under adverse environmental conditions (low contrast, sunlight, twilight, etc.). These cameras contain internal image data processing. The intrinsic latency, however, easily exceeds an unacceptable level of 0.5 s.

In what follows, we will address two aspects which improve the usability of the panorama system with regard to visual object detection: Gamma adjustment and local contrast enhancement.

5.3.1 Gamma Adjustment

In this subsection, we will focus on the Gamma value which should be matched between camera and display for optimum image reconstruction (for details see Appendix A). Due to the nonlinear input–output characteristics of cameras, displays, and the human perception, the optimization of the Gamma values (camera and display), is of particular importance. Besides the usual display controls which include Gamma adjustment, in the experimental system, a control menu is available which includes Gamma adjustment for each camera separately.

Usually, the effective computer display gamma characteristic (output luminance ~ (input signal)$^{\gamma}$, see Appendix A) can be adjusted via settings on the graphics card. Typically, the display exhibits a characteristic with $\gamma = 2$–2.5. This results in low sensitivity with regard to luminance change in the dark range.

With suboptimal γ-value, small luminance differences vanish, dependent on illumination of the scenery, contrast, and dynamic range. This is critical due to the limited dynamical range (8 bit) of the system corresponding to 255 discrete luminance intervals. That is why the camera γ-value should be adjustable to take account of specific local conditions. If the goal is a video reconstruction with 1–1 correspondence of the natural impression (=visual impression of real tower view with $\gamma_{\text{camera}} \approx 0.45$), this should be the setting of the camera. For a linear transfer characteristic of the camera-display system, this requires the display setting $\gamma_{\text{Display}} \approx 2.2$.

A practical example of the effect of gamma adjustment is depicted by the following two photos of Fig. 14 with a high luminance display surrounded by persons in a dark environment.

5.3.2 Local Contrast Enhancement

During the initial field tests, some observability problems became evident which were due to the limited dynamic range and contrast. Specifically, some problematic movement areas with dark asphalt (e.g., heliport) were identified. If, e.g., a dark helicopter was inside these areas, the contrast of the captured images was not sufficient for the controller to recognize the objects in the RTO-CWP. This problem was solved by locally enhancing the contrast at these specific areas to a level where it is possible to detect these objects. As an example, Fig. 15a shows the original

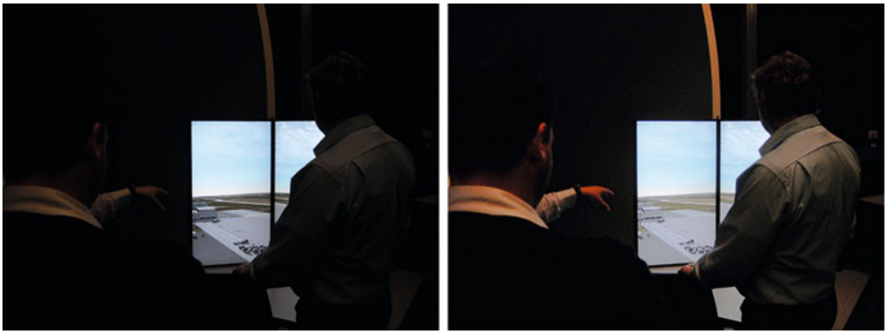

Fig. 14 Effect of decrease of display γ to 2.5 for increasing luminance difference in dark area while keeping contrast in high luminance display area in an acceptable range (see also Appendix A)

Fig. 15 Helicopter on heliport, (**a**) (*top*) original with helicopter not discriminable, and (**b**) (*bottom*) enhanced contrast with helicopter as *black dot* on gray background

image of the heliport with a black helicopter that was not discriminable from the dark background and Fig. 15b with the contrast enhanced image.

6 Conclusion

Important aspects of the design, development, and verification of improved technical features of the Remote Tower prototype system is described that was used for the initial validation experiments at Erfurt airport in 2012 (Friedrich and Möhlenbrink 2013; Fürstenau et al. 2014 and the following chapters “Which Metrics Provide the Insight Needed? A Selection of Remote Tower Evaluation Metrics to Support a Remote Tower Operation Concept Validation” and “Model based Analysis of Two-Alternative Decision Errors in a Videopanorama-based Remote Tower Work Position”). A comparable and extended RTO system replaced the initial experimental one at Braunschweig research airport. The development was accompanied by a detailed work and task analysis, including design workshops with domain experts in cooperation with DFS (the German ANSP). This resulted in an extended requirement list.

The prototype development included all basic RTO features for which at the time of the validation experiments stable and reliable functioning could be expected, such as long distance high bandwidth live videopanorama transmission, remote PTZ- control, and local contrast enhancement. Advanced live raw data processing with new hard and software allowed for 30 Hz videopanorama framerate, approaching the value required for minimizing visual movement-discrimination errors (see chapter “Videopanorama Frame Rate Requirements Derived from Visual Discrimination of Deceleration During Simulated Aircraft Landing”). Due to their lower development status, more advanced features such as automatic movement detection and object tracking were investigated only with the local system at Braunschweig airport and not included in the remote one for shadow mode experiments.

The functional verification confirmed the fulfillment of EMC requirements for camera installation at the operational tower, the latency requirement, and specific local contrast requirements, partly achieved with some modifications after initial testing. The predicted limited visual resolution and contrast of the videopanorama system made it clear that for the operational tests (chapter “Which Metrics Provide the Insight Needed? A Selection of Remote Tower Evaluation Metrics to Support a Remote Tower Operation Concept Validation” and “Model-Based Analysis of Two-Alternative Decision Errors in a Videopanorama-Based Remote Tower Work Position”), the PTZ camera and its usability would play an important role for (visual) situation awareness, certainly exceeding the use of binoculars in the standard tower environment.

Acknowledgement We are indebted to a number of controllers, technicians, and managers from the German air navigation service provider DFS who were involved in the successful setup of the

RTO prototype with the DLR videopanorama system at Erfurt airport within the DLR–DFS cooperation RAiCon. Because it would exceed the available space to mention all of them, we confine ourselves to expressing our particular thanks to controller P. Distelkamp, engineer S. Axt, and ATC experts Nina Becker and T. Heeb, representing all the other colleagues, for excellent support and cooperation during setup and preparation of the experiments.

We also would like to thank Dr. Brigitte Brunner as responsible science officer from the DLR program directorate for continuous support and particularly for granting a half year extension of the project schedule in order to successfully finish the delayed validation activities.

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Which Metrics Provide the Insight Needed? A Selection of Remote Tower Evaluation Metrics to Support a Remote Tower Operation Concept Validation

Maik Friedrich

Abstract This chapter describes the metrics for the validation of a Remote Tower Control workplace. The study shows how Air Traffic Control Officers (ATCOs) observe traffic from a Tower Control Working Position at Airport Erfurt-Weimar in comparison to a Remote Controller Working Position. Shadow-mode trials were used to cover perceptual, operational, and human factors aspects of a Remote Tower System, including a live video panorama and a research aircraft. The aircraft was used to fly different maneuvers within the aerodrome. These maneuvers allow insights on the detectability of an aircraft within different distances from the tower and the gathering of operation information about aircraft status. In addition, a vehicle was used to position static objects on the airfield to determine the detectability of these objects for different distances to the Control Tower (RTO-camera system). Eight ATCOs from the DFS participated in the validation exercise. Time-synchronized questionnaires for the controller working position remote (CWP remote) and the controller working position tower (CWP tower) were applied, addressing operationally relevant questions to the ATCOs. The validation exercise targets the evaluation of metrics that could help standardize the process of testing Remote Controller Working Positions. The results consider expense of realization, comparability, and feasibility as major classifications for the used metrics. Further, an approach for combining the classification into one score is presented to rank the metrics in relation to each other.

Keywords Remote Tower • Field Trial • Passive shadow mode • Validation • Traffic pattern • Evaluation Metrics • Remote tower metrics • RTM score • Test aircraft • Airport circling • Controller working position

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1 Introduction

Future remote control of low traffic airports (Remote Tower Operation, RTO) will rely on the replacement of the conventional Air Traffic Control (ATC) workplace (CWP tower) by a remote controller working position (CWP remote). For short- and midterm-realization of a CWP remote, the out the window (OTW) view will be a digitally reconstructed panoramic view using high resolution video cameras. The DLR-internal project RapTOr (Remote Airport Tower Operation Research, 2005–2007) focused on remote tower control of single airports, while the project RAiCe (Remote Airport traffic control center, 2008–2012) focused on the RTO-prototype development and the idea to control multiple small airports from one remote center (Fürstenau et al. 2008a, 2009; Möhlenbrink et al. 2009, 2012; Schmidt et al. 2007).

In parallel to these projects, remote tower operation was pushed forward by a joint venture project of the Swedish Civil Aviation Administration (LFV) and SAAB called ROT (Remotely Operated Towers, 2006–2008) (Saab Security 2008). SAAB also coordinated the EU-Project ART (Advanced Remote Tower, 2007–2009) (van Schaik et al. 2010) focusing on single remote tower control (see chapter “The Advanced Remote Tower System and Its Validation”). Further, the German Aviation Research Program iPort funded the ViCTOR project (Virtual Control Tower Research Studies, 2009–2012), which was led by DFS and addressed new concepts of remote operation, team work, as well as visualization aspects.

From an American perspective, there is a strong motivation to work out operational and functional requirements (Ellis and Liston 2010), technical/system requirements, and the integration of concepts (Hannon et al. 2008), to ensure the safety when applying RTO. In the USA, concepts on staffed NextGen Tower also explore alternative surveillance systems for the OTW (Friedman-Berg 2012) (see also chapter “Remote Tower Research in the United States”). The same perspective applies for Europe, especially within the Single European Sky ATM Research Program (SESAR). There, remote tower is addressed under a separate Operational Focus Area (OFA, 06.03.01) (Committee Sesar Program 2010). This OFA comprises the different Remote Tower Activities assigned in the Operational Projects.

To test the feasibility of the RTO concept, human-in-the-loop studies have been completed addressing research questions for single remote tower (European Organisation for the Safety of Air Navigation 2010). To complete the analysis of feasibility, research prototypes are tested also within field trials. In 2007, field trials with the first experimental RTO system, consisting of four cameras for reconstructing a panoramic view, were completed at Braunschweig Airport [see chapter “Remote Tower Experimental System with Augmented Vision Videopanorama” and, e.g., (Schmidt et al. 2007)]. The data of the field trials have been used to quantify the effective resolution of that video panorama (Fürstenau et al. 2009). Within the ART Project, van Schaik et al. (2010) assessed the importance of visual cues for remote tower operations and suggested a formula for calculating the required resolution for either detection or recognition of each cue. While we agree that a definition of minimum resolution requirements for RTO is one important issue, it remains unclear whether the calculated minimum resolution requirement can be empirically validated by Air Traffic Control Officers' (ATCO) detection and recognition rates of such items under daylight and good visibility conditions. The problem of visual resolution and the existence of different prototypes developed by different institutions and companies lead the authors to believe that a structured validation concept is needed to enable quantitative comparison.

Considering the different CWA remote projects and their prototypes, we need metrics that measure the discrepancy between out the window (OTW) view and RTO. This way, the different technical solutions could be validated with the same remote tower metrics (RTMs) and made comparable to the ATCOs. This chapter presents a set of RTMs that were evaluated in a validation exercise (Friedrich and Möhlenbrink 2013), which was completed under the scope of the OFA Remote Tower. Two Remote Tower validation exercises under this scope were already completed in Sweden (Mullan et al. 2012a). All three validation exercises contribute to the transition from feasibility to preindustrial development and integration. Therefore, the remote tower operation concept descriptions and the functional/operational requirements have been defined in the Operational Service and Environment Description (OSED) for Remote Provision of Air Traffic Services to Aerodromes (Mullan et al. 2012b). The functional/operational requirements define what the user (here: ATCO) of the system wants the system to do. It is important to note that the functional requirements are independent from the technical solution. Complementary to the functional specification, technical system requirements define whether a specific technical system can provide specific information to the user.

Within this chapter, RTMs for a CWP remote validation are presented and combined with the results from the third validation exercise. This helps not only to evaluate the CWP remote itself but also identify RTMs that are essential for a validation. We used a prototype developed by DFS and DLR in 2012 and explained in detail below.

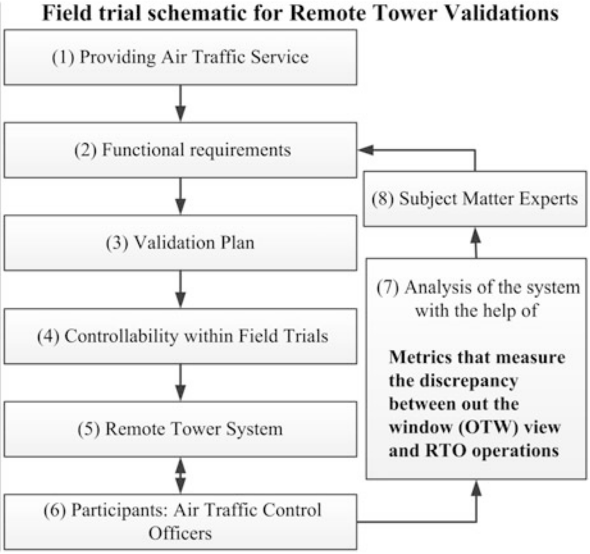
First, an extended schematic will be introduced to improve the metrics evaluation process. Second, the list of RTMs for the CWP remote is presented. Third, the method section covers the experimental setup. Fourth, the results are presented. Fifth, the contribution provided by the RTMs will be discussed. In addition, the methods for validating a remote tower system will be discussed. Sixth, data and methods are summarized as appropriate to judge which RTMs cover the important parts of the ATCOs work.

2 Extended Field Trial Infrastructure

The goal of this chapter is to elaborate and discuss RTMs for a single RTO concept. Previous validation exercises concerning remote towers mainly focused on analyses of subjective data such as questionnaires, interviews, observations, and ATCOs' feedback (Ellis et al. 2011; Mullan et al. 2012a). However, an extended infrastructure for field trials with RTMs can provide additional objective data to support the development and consolidation of specifications for future RTO.

Figure 1 shows the field trial schematics extended with the RTMs that are developed for CWP remote. This schematic description shows the stepwise validation within the project. For (1) providing Air Traffic Service (ATS) (from tower or remote), the (2) functional requirements have been elaborated (Mullan et al. 2012b). For setting up field trials, a validation plan is written and it is defined whether the (3) experimental design includes a control condition besides the experimental condition(s). The control condition is important to have a baseline or reference to evaluate the results of the experimental condition(s). Within field trials, a baseline cannot always be provided for several reasons. However, RTO allows a comparison between CWP tower and CWP remote. In addition, the (4) controllability within a field trial is usually limited. The amount of traffic and flight maneuvers is not under the experimenters' control and the accessibility of operational data thereby limited. Such limitation can be overcome by using a research aircraft which is under the control of the experimenter. Thereby, the experimenter can define the traffic patterns and number of iterations for certain flight maneuvers for a systematic analysis.

Fig. 1 Field trial schematics for development and consolidation of specifications for future remote tower operations



Then, the (5) Remote Tower System is tested within field trials and data is collected from (6) ATCOs. For the (7) analysis of the system or, to be more precise, for the analysis whether the system provides the functional requirements, different kinds of data can be analyzed.

2.1 Remote Tower Metrics

The RTMs are identified by refinement and consolidation of the functional requirements of a CWP remote and in cooperation with ATCOs that serve as system matter experts. The following RTMs have been identified and therefore provide the base for the validation exercise introduced in this chapter. The main difference between CWP tower and CWP remote is the visual presentation of the OTW. Therefore, the RTMs focus on the aspect of visual perception of static and dynamic objects.

The process of identifying the RTMs was performed in three steps. First, types of visual tasks were identified that the ATCOs have to perform via the OTW. These types of visual task are related to the moving aircraft within the control zone (Aircraft) and objects on the apron (Apron Objects). Second, a workshop was conducted with ATCOs to determine specific tasks for each type of visual task. Third, the tasks were transformed into RTMs to allow performance measurement. The eight RTMs were separated into types of visual tasks as followed:

- Aircraft (5 RTMs)
- Objects at the Apron (3 RTMs)

To be consistent with the infrastructure proclaimed in Fig. 1, the RTMs were all used within one validation exercise. For more details on the influence that the RTMs have on the validation objectives and success criteria, see Friedrich and Möhlenbrink (2013). For the purpose of this chapter, we will not concentrate on the results of the validation exercise itself other than to evaluate the RTMs for further use. Table 1 contains a list of all RTMs and a description.

The Aircraft tasks were discussed and specified with pilots to ensure their feasibility. The Apron Objects types of visual tasks were defined without any help of system matter experts.

Table 1 The RTMs divided into types of visual tasks

Types of tasks	Remote tower metric	Description
Aircraft	Dutch roll	The ATCO has to identify if the aircraft performs a Dutch roll
	Route	The ATCO has to identify if the aircraft follows a specific route
	Decline	The ATCO has to identify if the aircraft performs a decline maneuver
	Landing light	The ATCO has to identify the status of the aircraft landing lights
	Flight path	The ATCO has to identify if the aircraft is on or above the flight path
	Gear status	The ATCO has to identify the status of the landing gear
Apron objects	Static objects	The ATCO has to identify specified signs in different distances to the tower
	Runway status lights	The ATCO has to identify the status of runway status lights
	Taxi ways/holding points	The ATCO has to identify the status of taxi ways and holding points

3 Method

3.1 Participants

Eight ATCOs employed by the DFS participated in the validation exercise. The average participants' age was 30 years with a SD of 11.5. The average work experience was 10 years with a SD of 9. All participants worked at local or regional sized airports. Fifty percent of the participants claimed that they had known the project in advance of the validation exercise. The participants received no additional payment and participated during typical working hours.

3.2 Apparatus

The experimental setup to analyze the RTMs consists of the technical setup (CWP remote) and the experimental vehicles (car and aircraft) used for the validation exercise. The technical setup presents an overview of the CWP remote and available information systems. The most important change to the CWPtower is the visual reproduction of the out the window (OTW) view (Fürstenau et al. 2008b, 2009; Schmidt et al. 2007). A camera platform with five HD cameras (1920 × 1200 pixel) in separate temperature controlled housings, each equipped with a 2/3" CCD sensor and $f = 8$ mm lens was used (see chapters "Remote Tower Experimental System with Augmented Vision Videopanorama," "Remote Tower Prototype System and

Automation Perspectives”). The visual resolution of the sensor can be approximated by using the fundamental relationship

$$\frac{G}{B} = \left(\frac{g}{f} - 1\right) \approx \frac{g}{f} \tag{1}$$

with $f =$ focal length $= 8$ mm, $g =$ object distance, $G =$ object size, $B =$ image size, and CCD pixel size of $p = 5.5$ µm. This leads to a vertical object size at $g = 1000$ m distance corresponding to 1 Pixel:

$$\frac{G}{B} \approx \frac{1000\ \text{m}}{0.008\ \text{m}} \geq \frac{0.68\ \text{m}}{5.5\ \mu\text{m}} \geq \frac{0.68\ \text{m}}{1\,\text{Pixel}} \tag{2}$$

vertical or ca. 2 arcmin angular resolution. This approximate value is valid under ideal illumination (i.e., contrast) conditions (see chapter “Remote Tower Experimental System with Augmented Vision Videopanorama” and Appendix A).

In addition to the panorama camera system, a pan–tilt–zoom (PTZ) camera was mounted on the top to allow a detailed look into participant guided areas. The PTZ camera was moveable within the full 360° viewing range and had 12 presets in the range $1 \leq Z \leq 23$ (fixed positions and zoom values) for fast responses. The optical specifications of the PTZ camera is approximated by

$$\alpha_Z = \frac{p_H}{Zf_0} \tag{3}$$

yielding for a zoom setting of, e.g., $Z = 4$ an ideal pixel resolution $\alpha_Z = 1$ arcmin (with $f_0 = 3.6$ mm, $p_\mathrm{H} = 4.4$ mm, viewing angle $2\theta = 15°$, see also chapters “Remote Tower Experimental System with Augmented Vision Videopanorama,” “Remote Tower Prototype System and Automation Perspectives,” and Appendix A1). The PTZ control and video stream were presented via a separate monitor within the CWP remote (Fig. 2). That is why it was expected that due to the limited resolution of the panorama, controllers in the RTO-CWP would make more use of the PTZ than controllers in the Tower-CWP make use of the binoculars for supporting decision making.

The visual reproduction from the five cameras, situated on top of the Erfurt-Weimar tower was displayed on five 40” LCD monitors arranged in a “broken circle” around the CWP remote (Fig. 2), providing a 200° field of view.

A microbus (VW bus T4) and the DLR aircraft (Dornier Do 228–101 twin turboprop engine test aircraft; length 15.03 m, body height × width 1.8 × 1.6 m, wing span 16.97 m, wheel diameter 0.65 m) were used as research vehicles to perform the Aircraft type of tasks. The bus was used to position static objects in predefined distances (250 m, 500 m, and 1000 m) to perform the Apron Objects tasks. The static objects had a diameter of 0.6 m and could be a circle or cross-mounted in the center of a square signage with an edge length of 0.7 m.

Fig. 2 CWP remote at the airport Erfurt

The participants were placed about 1.8 m from the monitors. Besides the panorama as reproduction of the OTW view, the participants were provided with the following additional sources of information:

- Videopanorama
- PTZ camera (controlled via pen input)
- Air situation display
- Flight plan data
- Weather information system

The RTMs were measured by synchronized questioning of two ATCOs working either in CWP tower or CWP remote. This increases the RTMs' significance for the purpose of comparing both workplaces. The survey software "Controlsurvey" was used to question the participants during the trials. Controlsurvey was developed by the DLR for the purpose of synchronized questioning and with the flexibility of reacting to minor deviations from planned scenarios.

The RTMs transform into questions that were used during the validation exercise. Table 2 shows the implementation of RTMs in question. Each RTM connected to the Aircraft tasks is connected to a point or position within the traffic pattern (Fig. 4).

Table 2 Connection between the remote tower metrics and their implementation as a question

Remote tower metric	Traffic pattern	Questions to capture the metrics
Dutch roll	A	"Did the aircraft wag its wings?"
Route	BC, and EF	"When is the aircraft turning?"
Decline	D	"Did the aircraft decline?"
Landing light	G	"Are the landing lights off?"
Flight path	$G_{1,2,3}$	"Is the aircraft on the flight path?"
Gear status	H1–H3	"Is the landing gear pulled up?"
Static objects		"Which symbol can you see next to the car?"
Runway status lights		"Are the runway status lights on?"
Taxi ways/holding points		"Which holding point are you not able to see?"

3.3 Design

The validation exercise was completed as a passive shadow-mode close loop field trial. The experimental design is based on the direct comparison between the CWP tower and CWP remote. The workplace of the participating ATCO within a trial is the independent variable that is measured with the RTMs. Through the comparison of both workplaces and the synchronized questioning (Fig. 3), the effect of the confounding variables, unforeseen traffic events, meteorological conditions, and time of day, was reduced.

The research aircraft flew predefined scenarios within the aerodrome to create authentic monitoring situations. Two mirrored scenarios were defined and switched between the runs. Each scenario was varied by the order of events that the aircraft should perform while flying the traffic pattern (Fig. 4) for 14 times. The aircraft was also equipped with an additional radio to communicate with the experimenter remotely via a research frequency (Fig. 3), to account for unforeseen situations. Besides the research aircraft traffic, additional unplanned traffic could arrive throughout each validation run. This allowed a mixture of scheduled and unscheduled traffic and increases the external validity of the validation exercise.

The design enables the RTMs (Table 1) to work as objective performance measurements in terms of comparing two workplaces against each other. Since the CWP tower is state of the art, this comparison is necessary to judge the influence of CWP remote on visibility and safety. The RTMs' questions can be analyzed for correctness of the given answer and response times. The answers to the RTMs are always unambiguous, whereas the response times depend on the current attention of the participant.

An additional question concerning the used sources of information was used to evaluate the RTMs validity for comparing the two workplaces. The used sources of information were subdivided into the panorama (OTW view or Video panorama), the magnification (binoculars or PTZ camera), and the air situational display (Radar), weather information system (WIS). The participants were instructed to name only the system that they used to make their final decision. This means, e.g., if

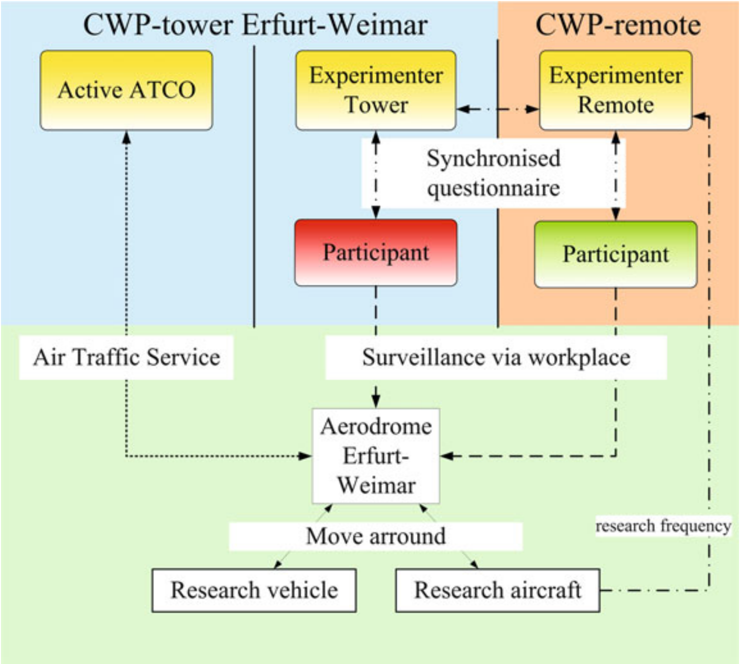


Fig. 3 Experimental procedure for comparing CWP tower and CWP remote

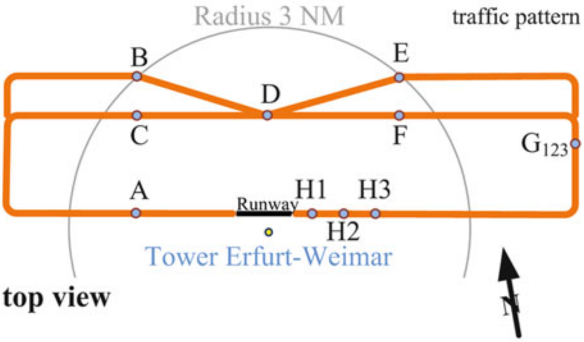


Fig. 4 Traffic pattern of the research aircraft within the aerodrome Erfurt-Weimar

they used the video panorama to position the PTZ camera and then used the PTZ video for their answer, the used source of information was the PTZ camera.

The feasibility of the RTMs was covered by a debriefing questionnaire. The debriefing questionnaire used a 6-point Likert Scale (1 = totally disagree; 6 = totally agree; average of 3.5) to judge each RTM for its feasibility. For each RTM, one question was formulated in the following style: “Did you find the questions concerning the Dutch Roll feasible?”

3.4 Procedure

The participants were randomly divided into four groups (two per group). The validation exercise took place from 17th of July until the 20th of July 2012. Every day a different group took part in the exercise. Each group had to complete two trials. For the first trial, it was randomly decided which participant worked at the CWP tower and CWP remote. Within the second trial, the group members always switched workplaces. Besides the two participants, an active ATCO was needed for every validation run to ensure the provision of ATS (Fig. 3). This was necessary because air traffic safety regulations did not allow active control by the participants of any traffic within the aerodrome.

Within the validation exercise, the procedures for every day were equal. A briefing of the new group was performed and they were instructed about the project and the validation exercise. That was followed by assigning the ATCOs to the different workplaces (Fig. 3). Afterwards, a 30 min PTZ camera training was conducted. Then, the first validation run was performed with duration of 140 min. After that, the participants switched workplaces, and the second validation run was completed. At the end, a 60 min debriefing with a debriefing questionnaire was performed with both participants.

Every validation run started with the research aircraft's first movement away from its apron parking position. The aircraft followed a predefined scenario, while the participants on both workplaces had to answer the same questions addressing the different RTMs (Table 2). All questions, regardless of the type, occurred synchronized to generate two comparable sets of answers that differ only in the used workplace. Every question was placed in a dialog between the participant and the particular experimenter. The experimenters read the questions to the participants. The participants used their workplace to collect the answer. Then they replied the collected answer as fast as possible to the experimenter and added their used source of information. The answers from both CWP were combined into question pairs. Question pairs were generated if both participants answered. In addition to this conservative analysis, Fürstenau et al. (2013) performed a different analysis using signal detection theory and time pressure theory (Fürstenau et al. 2014) and included also the answers that were not provided (nonanswers) as false answers (see chapter "Model Based Analysis of Two-Alternative Decision Errors in a Videopanorama-Based Remote Tower Work Position"). The questions concerning the aircraft maneuvers were asked at predefined points within a standardized traffic pattern (Fig. 4a–h).

4 Results

This section is divided into two parts. In the first part, we show the basic analysis method applied on safety related metrics to give an example of the RTM potential. The Decline, Landing Lights, and Gear Status are the most safety related metrics and will therefore be presented in detail. The second part of the section contains a rating for the proposed RTMs in terms of expense of realization, comparability, and feasibility. As mentioned above, this chapter does not focus on the results of the validation, but on the RTMs. A complete list of all results from the SESAR-JU D36 Project can be found in Friedrich et al. (2012).

Throughout the validation, the RTM leads to a total number of 1326 question pairs (CWP tower and CWP remote). 936 Aircraft RTM questions pairs lead to an average of 117 per trial and an average of 12 completed traffic patterns per run. Figure 5 shows one traffic circle with the corresponding answer times from both workplaces. The letters in Fig. 5 are similar to those in Fig. 4. They do not show the position of planned maneuver but the position of the research aircraft when the participant answered the question related to the maneuver. Therefore, every letter comes in pairs, except for B where no answer was given on the CWP remote.

4.1 Basic Analysis of Safety Related Metrics

Decline, Landing Lights, and Gear Status are the most safety related types of visual tasks. For each of the three RTMs, an average of 12 question pairs per trial were collected. These values were used as a direct comparison between the CWP tower and CWP remote. The results for correct answers are presented in Table 3.

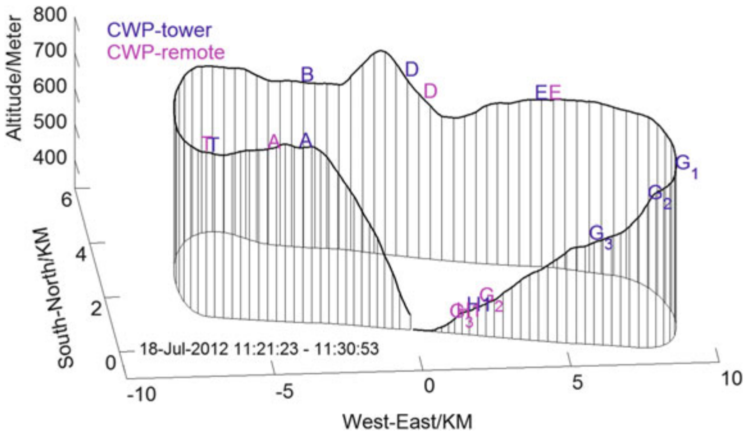


Fig. 5 One traffic circle performed by the research aircraft with Erfurt-Weimar Tower as origin

Table 3 Answers for the safety related maneuvers [% correct answers (standard deviation) from provided answers]

RTM	Mean correct answers (SD) CWP tower	Mean correct answers (SD) CWP remote	Significant difference (*F*-test)
Decline	86.1 % (34.9)	82.4 % (38.3)	$F(1, 7) = 1.62$, n.s.
Landing lights	83.33 % (37.0)	44.3 % (49.37)	$F(1, 7) = 40.45$, $p < 0.05$*
Gear status	94.32 % (23.2)	94.52 % (22.2)	$F(1, 7) = 0.96$, n.s.

As Table 3 shows, the participants' answers given concerning safety related RTMs are not significantly degraded for Decline and Gear Status and are significantly degraded for Landing Lights. Comments from both workplaces indicated that the position of the landing lights at the research aircraft was not easy to identify. These comments are used in the second part of the result section to judge the feasibility of the RTM Landing Lights.

The design of the synchronized questioning allows not only for an analysis of the paired answers but also the reaction times. The reaction time within the validation depended on the time an experimenter needed to read the question out loud and the participant to answer it. Due to reading training before the validation, the influence of the experimenters was reduced to a minimum. The reaction times therefore are mainly influenced by the performance of the participants. As a second basic analysis, the reaction times for Gear Status were analyses for three distances (H_1: H_2: 0.5 NM, H_3: 1.0 NM, 1.5 NM) to the tower when the questions were asked. Figure 6 shows the results separated by workplace. The analysis allows a detailed view on the reaction times and the influence the different workplaces have on them. This analysis is possible for all RTMs, if synchronized capturing is used.

By looking at Landing Lights, we find a metric that shows a decrease in performance. For Landing Light, the correct answers given are significantly lower for CWP remote than for CWP tower[1]. The response times for the Gear Status for CWP remote are also higher at a distance of 0.5 than on the CWP tower. Because safety is always to be the first priority, these results lead to a bad grading of the CWP remote. However, Decline, Landing Lights, and Gear Status are not equal RTMs which will be presented in the next section.

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[1] However, due to the problematic interpretation of the Landing Lights RTM, the % correct analysis in Table 3 shows now significant difference altogether. An extended analysis is discussed in chapter "Model Based Analysis of Two-Alternative Decision Errors in a Videopanorama-Based Remote Tower Work Position."

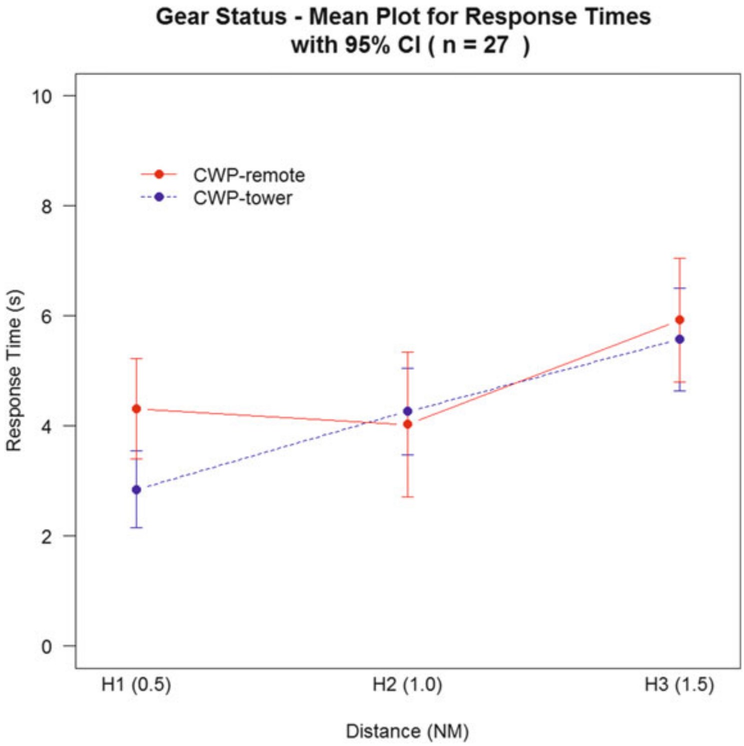

Fig. 6 Gear status—mean plot for response times with 95 % confidence interval ($N = 27$)

4.2 Evaluation for the RTMs

The evaluation of the RTMs is based on the expense of realization (ER), the comparability (C), and feasibility (F). In this section, ER, C, and F are explained, and their connection to the validation exercise is presented. This leads to a comprehensive view of the RTMs connected to the CWP remote. The evaluation of the RTMs results in an overall ranking by combining ER, C, and F into a single score.

ER evaluates the procedure to set up the validation environment and enable situations for the RTMs to be tested. Some RTMs even require an aircraft that follows a defined scenario. ER classifies the RTMs into low, medium, or high expenses to realize the situation. Low means that no special equipment is needed throughout the validation. Medium means that special equipment is needed, but the cost is beneath 1000€ per day. High means that special equipment is needed and the cost is above 1000€ per day. The ER results are summarized in the level of types of visual task. Table 4 presents the types of visual tasks with a detailed explanation on the ER results.

Since the objective data arises from the direct comparison of CWP tower and CWP remote, the C of the RTMs has to be evaluated. C in this case can be defined as the amount of questions answered with the same source of information. C is high,

Table 4 Expense of realization (ER) results for the RTMs, separated by type of visual tasks

Types of visual tasks	Expense of realization (ER)	Detailed explanation
Aircraft	High	The aircraft type of task needs an aircraft that follows a scenario. Therefore, the cost per day is above €1000
Apron objects	Medium	For static objects, the ER is medium, because due to the two possible answers (cross or circle) the static objects metric requires that the objects are disclosed until shortly before questioning. The consequence is that staff and a research vehicle are needed
	Low	Low is true for runway status lights and taxi ways/holding points because the RTMs do not need any special equipment or staff

Table 5 Comparability (C) results for the RTMs, ranked from high to low

Remote tower metric	C	Major switching tendency
Taxi ways/holding points	0.991	None
Landing light	0.878	From OTW to magnification
Route	0.830	From OTW to radar
Flight path	0.710	From OTW to radar
Gear status	0.708	From OTW to magnification
Runway status lights	0.685	None
Dutch roll	0.643	From OTW to magnification
Static objects	0.616	From OTW to magnification
Decline	0.155	From OTW to radar

if the participants use the same source of information and therefore the difference between the two CWP is under test. If C is low, it indicates switching to source of information, and therefore a direct comparison between CWP remote and CWP tower is less significant. The correlation between the used sources of information bases on the amount of usage per source. We also identify a major switching tendency if more than 25 % usages switched category from CWP tower to CWP remote. Table 5 shows the results of the analysis sorted from high to low.

F presents the feasibility of each RTMs during the validation. The rating of F depends on the debriefing questionnaire [6-point Likert Scale (1 = totally not feasible; 6 = totally feasible)] and comments of the experiments concerning the feasibility during the validation trails. Table 6 shows the results from the debriefing questionnaire. All RTMs are above the scale average of 3.5, except the Landing Light.

The final step to summarize the evaluation is to rate the RTMs depending on their ER, C, and F results. Because ER, C, and F have different dimensions, we decided to standardize them. Because ER, C, and F are equally important to judge a metric, we decided merging the standard scores using an equal distribution equation

$$\mathrm{RS} = \frac{1}{3} Z_{\mathrm{ER}} + \frac{1}{3} Z_{\mathrm{C}} + \frac{1}{3} Z_{\mathrm{F}} \tag{4}$$

Table 6 Results from the debriefing questionnaire and the experimenter rating concerning *F*

Remote tower metric	Average *F* (*N* = 8)	Comments by the experimenter
Dutch roll	5.63 (SD = 0.52)	
Route	5.50 (SD = 0.53)	The aircraft was not always visible in the panorama due to the distance to the camera system
Decline	5.63 (SD = 0.52)	
Landing light	2.88 (SD = 0.83)	The position of the aircraft landing light strongly dependent on the type of aircraft. The position of the landing lights has strong influence on detectability
Flight path	5.38 (SD = 0.52)	
Gear status	4.00 (SD = 0.53)	The focusing of the PTZ camera was too long
Static objects	5.25 (SD = 0.71)	
Runway status lights	4.38 (SD = 0.74)	The runway status lights had to be always on and therefore variation in the condition was impossible
Taxi ways/holding points	5.25 (SD = 0.71)	

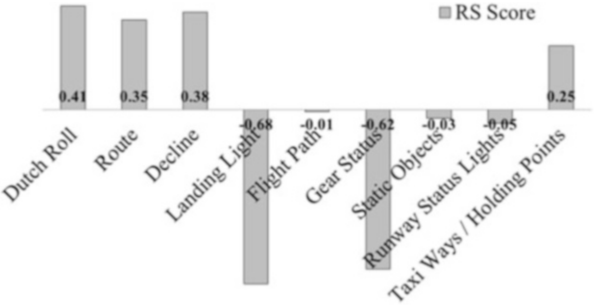

Fig. 7 The ranking of all RTMs in relation to their RS score

The result of the merging is defined as RTMs Score (RS). Figure 7 shows all RTMs and their RS. The results show that each RTM has a different RS score and that there are differences in the quality of a metric.

5 Discussion and Conclusion

In the result section, two different approaches for analyzing the RTMs were presented. The results show that the RTMs are able to distinguish the ATCOs' performances data depending on the used workplace. They allow capturing of the objective data in relation to the workplace, which allows insight on how the ATCOs perceived the different working environments. It has to be discussed in what way the RTMs can be a significant help for analyzing the CWP remote and how the RS can support this task.

5.1 Basic Analysis of Safety Related Metrics

The basic analysis of safety related metrics gives an example of the opportunities provided by the correct measurement for performance, and it also shows the difficulties. The metrics allow insights on the performance of the ATCOs by defining tasks that are necessary for ATC. The results are not only dependent on the performance of the participants but also on the selection of ATC task that were chosen to define the metrics. This is especially important for safety related issues.

The results for Decline, Landing Light, and Gear Status show that there are significant differences between CWP tower and CWP remote. The significant differences are in correct answers (Landing Lights) and also in reaction times (Gear Status). The topic of reaction times is specifically addressed in the following chapter "Model Based Analysis of Two-Alternative Decision Errors in a Videopanorama-Based Remote Tower Work Position" within the Time Pressure Theory-based data analysis (Fürstenau et al. 2014). Initial interpretation of the results could suggest that the CWP remote is not as safe as the CWP tower. As mentioned above, this chapter does not focus on the implications for remote tower operations, but on the RTMs to measure the difference between two workplaces. For completion of the interpretation of our results, we need to evaluate the RTMs.

5.2 Evaluation for the RTMs

As mentioned in the previous section, sometimes different metrics connected to the same domain contradict each other. This leads to inaccurate results because an aggregation of different metrics is almost impossible. Therefore, the evaluation of the RTMs is important to increase and order the validity of complex RTO studies. Only then it becomes possible to measure the differences that exist between the CWP tower and CWP remote. This does not only apply for the CWP remote presented in this chapter but should apply for all CWP remote systems that will be designed and tested in the future.

The ER classification of metrics shows a connection not only to the validation budged but also to the validity of the validation. Of course the cost for a research aircraft is immense, but the task of an ATCO officer is to control flying aircrafts and therefore an aircraft and metrics to capture the performances are needed. The ER for the Aircraft visual tasks could be reduced to "low," if, e.g., the usual traffic on the remotely controlled airport is used. This would lead to a series of adaptation to the metrics and would reduce the between-subject comparability of the results.

The C classification could be interpreted in two directions. The first is to analyze the change in used source of information as an indicator for the major difference of the two CWP. For example, the data of the compatibility tests revealed that the participants moved away from the panorama to the PTZ camera or the radar to gather their information. The second is the demand to compare the RTMs results from each workspace on an equal basis. Therefore, the similarity between used sources of information was analyzed. Stronger variations in the used sources of information are considered as less comparable because the performances do not base on the same systems.

More than ER and C, F quantifies how well the RTM fits into the procedure of the validation. This is shown not only by the subjective rating of the ATCOs but also by the comments of the experimenters. We consider the F classification also as a learning indictor for further changes to the RTM before finalization.

The RS scores show that there are differences between the RTMs in quality and validity. This leads to the proposal of standard metrics that need to be defined for the evaluation of remote tower operations. An individual definition of metrics is misleading because the system developer might have a narrow perspective on their prototype. The authors propose to use the RTMs presented in this chapter for testing them with different prototypes and determine the agreement of the quantitative results.

6 Outlook

In line with the results of the accomplished validation exercises under the operational focus area "Remote Tower," the evaluation of RTMs within this validation exercise provides an additional step for the remote tower concept validation, based on a live video panorama. The chapter focused on the RTMs rather than the results of the validation exercise itself. Those are reported in separate publications (Friedrich and Möhlenbrink 2013; Fürstenau et al. 2013, 2014) and chapter "Model Based Analysis of Two-Alternative Decision Errors in a Videopanorama-Based Remote Tower Work Position." The validation also shows that metrics can be judged differently depending on their quality to distinguish between different systems. After addressing the feasibility of the concept within this exercise, validation activities center on system integration, for which the consolidation of the operational concept and the prototype system is the main goal.

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Model-Based Analysis of Two-Alternative Decision Errors in a Videopanorama-Based Remote Tower Work Position

Norbert Fürstenau

Abstract Initial analysis of Remote Control Tower (RTO) field test with a prototype videopanorama system under quasi-operational conditions [Friedrich and Möhlenbrink (Proceedings of the 10th USA/Europe air traffic management research and development seminar (ATM 2013), 2013] has shown performance deficits quantified by two-alternative aircraft maneuver discrimination tasks [Fürstenau et al (EPCE/HCII 2013, Part II, Lecture Notes in Artificial Intelligence (LNAI) 8020:105–114, 2013)]. Here, we present the quantitative analysis of these results using the complementary methods of Bayes inference, signal detection theory (SDT) with parametric and nonparametric discriminabilities *d′* and *A* and application of time pressure theory [Fürstenau et al (EPCE/HCII 2013, Lecture Notes in Artificial Intelligence (LNAI) 8532:143–154, 2014)]. RTO-controller working position (CWP) performance was directly compared with one of the conventional tower-CWP with direct out-of-windows view by means of simultaneous aircraft maneuver observations within the control zone at both operator positions. For this analysis, we considered correct (hit rate) and incorrect (false alarms, FA) answers to discrimination tasks, and we took into account nonanswers for a pessimistic quantification of RTO performance. As initial working hypothesis, this lead to the concept of time pressure (TP) as one major source of the measured response errors. A fit of experimental error rates with an error function derived from the Hendy et al. information processing (IP/TP) hypothesis [Hendy et al (Hum Factors 39:(1):30–47, 1997)] provides some evidence in support of this model. We expect the RTO performance deficits to decrease with the introduction of certain automation features to reduce time pressure and improve the usability of the videopanorama system.

Keywords Remote tower • Videopanorama • Field testing • Flight maneuvers • Two-alternative decisions • Signal detection theory • Information processing theory • Time pressure

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1 Introduction

The present chapter is based on the results presented in the HCII conferences in Las Vegas (2013) and Crete (2014), published in Fürstenau et al. (2013, 2014). It extends the discussion of the RTO validation experiments in the previous chapter "Which Metrics Provide the Insight Needed? A Selection of Remote Tower Evaluation Metrics to Support a Remote Tower Operation Concept Validation," performed within a DFS–DLR cooperation as the final work package of the DLR project RaiCE [see also (Friedrich and Möhlenbrink 2013)].

Since more than 10 years, remote control of low traffic airports (Remote Tower Operation, RTO) has emerged as a new paradigm to reduce cost of air traffic control (Schmidt et al. 2007; Fürstenau et al. 2009; Hannon et al. 2008). It was suggested that technology may remove the need for local control towers. Controllers could visually supervise airports from remote locations by video links, allowing them to monitor many airports from a remote tower center (RTC) (Fürstenau et al. 2009). It is clear from controller interviews that usually numerous out-the-window visual features are used for control purposes (Ellis and Liston 2010). In fact, these visual features go beyond those required by regulators and ANSPs (air navigation service providers), which typically include only aircraft detection, recognition, and identification (Van Schaik et al. 2010). Potentially important additional visual features identified by controllers in interviews involve subtle aircraft motion. In fact, the dynamic visual requirements for many aerospace tasks have been studied, but most attention has been paid to pilot vision [e.g., (Watson et al. 2009)]. In this work, we investigate a group of visual cues derived from flight maneuvers within the range of observability in the control zone. They might be indicative of aircraft status and pilots' situational awareness which is important with the higher volume of VFR traffic in the vicinity of small airports, the target application of RTO/RTC.

These considerations led to the design of the present validation experiment within the DLR project RAiCe (Remote Airport traffic Control Center, 2008–2012). The field test was realized within a DLR–DFS (German ANSP) Remote Airport Cooperation. Specifically, dual-choice decision tasks [the subset of "Safety related maneuvers" in Friedrich and Möhlenbrink (2013)] were used for quantifying the performance difference between the standard control tower work environment (TWR-CWP) and the new RTO-controller working position (RTO-CWP) based on objective measures from signal detection theory (SDT; parametric and nonparametric discriminability d' and A, respectively) (MacMillan and Creelman 2005) and Bayes inference (Fürstenau et al. 2013, 2014) (a brief summary of the three methods is presented in Appendix B). These analyses are complemented by an error model derived from the information processing/time pressure (IP/TP) hypothesis of Hendy et al. (1997) for quantifying the measured performance deficit of the RTO-CWP as compared with the Tower-CWP.

Experimental methods are reviewed in Sect. 2 followed by the results in Sect. 3 (response times, hit and false alarm rates, and nonanswers). Using these data in Sect. 4, we present the analysis with the three complementary Bayes and SDT methods, and we introduce a modified time pressure-based error function for fitting the measured error rates. We finish with a conclusion and outlook in Sect. 5.

2 Methods

In what follows, we briefly review the experimental design for two-alternative decision tasks as part of the remote tower validation experiment and present additional details relevant for the IP theory-based analysis. Further details of the full passive shadow-mode validation trial are reported in Friedrich and Möhlenbrink (2013) and chapter “Which Metrics Provide the Insight Needed? A Selection of Remote Tower Evaluation Metrics to Support a Remote Tower Operation Concept Validation.”

2.1 Participants

Eight tower controllers (ATCOs) from the German air navigation service provider, DFS, were recruited as volunteer participants for the experiment. The average age was 30 (stddev 12) years with 10 (stddev 10) years of work experience, and they came from different small and medium airports. They took part in the experiment during normal working hours and received no extra payment. They were divided into 4 experimental pairs for simultaneously staffing the control tower (TWR-CWP) and the RTO-CWP.

2.2 Experimental Environment and Conditions

The experiment was performed as passive shadow-mode test under quasi-operational conditions on the 4 days July 17–20, 2012. The remote tower system was located at the DFS-operated Erfurt-Weimar (EDDE) control tower. It was an improved version of the initial RTO-experimental system tested at Braunschweig airport which was in use since 2004 for initial verification and validation trials (Schmidt et al. 2007; Fürstenau et al. 2009) (see chapter “Remote Tower Experimental System with Augmented Vision Videopanorama”), and it corresponded to the prototype system described in chapter “Remote Tower Prototype System and Automation Perspectives.” A comparable advanced design was located at DLR facilities in Braunschweig with RTO-CWP in the Tower-Lab simulation environment that was used for verification of system functions during the setup of the quasi-operational system (see chapters “Remote Tower Simulation Environment” and “Remote Tower Prototype System and Automation Perspectives”).

Fig. 1 Remote tower installation with 200° panorama and pan-tilt-zoom camera sensor system at the tower roof (*left photo*) and operators' workplace with 40″ HD-format displays (*right*). Reprinted from (Fürstenau et al. 2013), with permission

Figure 1 shows the sensor system and the RTO-CWP with ca. 200 videopanorama and operator console based on a reconstructed far view with five HD format 40″ displays (892 × 504 mm, 1920 × 1080 pixel, pixel distance = 0.47 mm). A separate monitor (left console side) displays the pan-tilt-zoom camera which is controlled via a pen–input interaction display with virtual joystick. Twelve preset viewing directions and four zoom factors $Z = 2$, 4, 8, 16 (viewing angles 26°–3°) could be selected. Additional monitors include (middle row from right to left): flight plan data, approach radar, and weather display. In contrast to the experimental TWR-CWP, the RTO-CWP was on the TWR ground floor in a separate room without visual contact to the airfield. The TWR-CWP was located close to the operational ATCO, but they were instructed not to communicate with each other.

Predefined flight maneuvers were generated with a DLR DO228 twin turboprop engine test aircraft (D-CODE, length 15.03 m, body height × width 1.8 × 1.6 m, wing span 16.97 m, wheel diam. 0.65 m) performing aerodrome circling.

The set of five well-defined flight maneuvers as stimuli for decision tasks at given positions within the EDDE control zone is indicated in Fig. 2 with a 3D plot of the logged on board GPS trajectory. Trajectory minimum altitude represents a runway overflight at about 30 m above ground. The two types of maneuver stimuli at the respective positions ($S_1/S_2 =$ maneuver/no maneuver) could be observed either visually only (e.g., landing gear down) or visually and by radar (altitude change). During the experiment, sometimes additional low volume normal traffic took place which now and then leads to delays in the traffic circle. Average duration of a full circle (=one run) was ca. 10 min, yielding typically 140 min of experiment duration per participant pair for the nominally 14 full circles.

Radio communication between D-CODE pilots and flight engineer and the experimenter at the tower was realized with a separate research frequency in addition to the standard A/C-TWR radio channel. The available time for

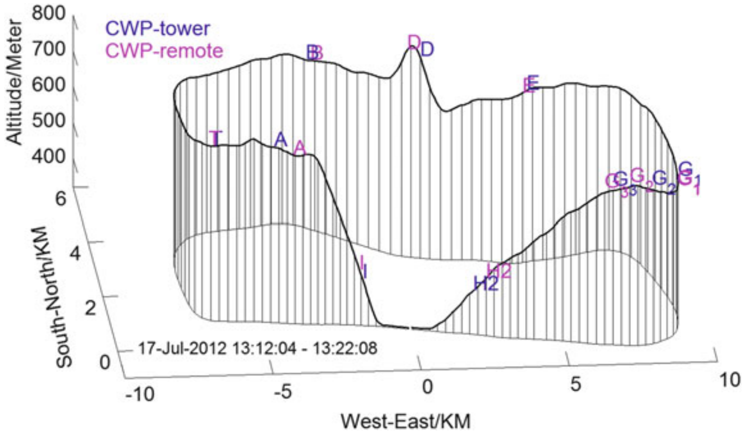

Fig. 2 DCODE trajectory measured with onboard satellite navigation. Letters indicate event positions with logged answers of TWR-CWP (*blue*) and RTO-CWP (*red*) operators to simultaneous task oriented online questioning. Distance between vertical lines = 5 s projected to trajectory altitude minimum at ca. 350 m (above sea level). Tower position (0, 0), height = 30 m. Reprinted from (Fürstenau et al. 2013), with permission

participant's responses to decision tasks was limited so that correct, incorrect, and nonanswers were possible.

2.3 Experimental Design and Task

Based on the fixed set of evaluated two-alternative events (A, D, G_1, G_2, $H_{1,2,3}$) at fixed positions during a single circle, the concrete event situation (stimulus alternative S_1 = maneuver/event, S_2 = no maneuver/no event) for decision making was switched statistically between runs according to two mirrored scenarios with different task sequences. In this way, during the 10–14 circles per experiment/participant for each event with two alternative stimuli (S_1, S_2, in random succession) per task, 5–7 answers per event alternative and per participant were obtained for the analysis (TWR and RTO-CWP condition as independent variables). The within-subjects design (TWR versus RTO-CWP) yields N = 40–56 answers (correct, incorrect, and nonanswers for averaging with the eight participants).

During one aerodrome circling, the two participants at the TWR and RTO-CWP had to simultaneously answer 19 different types of questions concerning the D-CODE maneuvers (events), object detection, and weather status. The following subset of 5 of the 9 event related questions is evaluated with regard to hit and false alarm rates using Bayes inference, signal detection theory (discriminability indices d' and A), and IP/TP theory-based error model (in brackets: maximum response time Ta = interval until next task/question): (1) Does A/C perform repeated bank angle changes? (event position A; Ta = 20 s), (2) altitude variation? (by 300 ft, event pos. D; 20 s), (3) landing light-off? Report status (event pos. G_1; 180 s: switching-off not observable), (4) A/C on glide path? (event pos. G_2; 90 s), (5) landing gear down? Report during final approach (event pos. $H_{1,2,3}$, distance 1.5, 1, 0.5 km; 10 s). A subjective certainty rating on a 5-point scale was not evaluated for the present analysis.

Every pair of participants had to complete two experimental trials. For the first trial (duration approximately 140 min) in the morning till noon, the participants were randomly assigned to one of the two CWPs. Positions were changed for the second trial in the afternoon. The present data analysis was focused on deriving objective measures for the two-alternative decision tasks. Additional data evaluation was presented in Friedrich and Möhlenbrink (2013) (see also previous chapter "Which Metrics Provide the Insight Needed? A Selection of Remote Tower Evaluation Metrics to Support a Remote Tower Operation Concept Validation") addressing performance (answers given, response times, and sources of information) and subjective measures (debriefing, questionnaires).

3 Results

The response matrices of the measured estimates of conditional probabilities $p(\mathrm{y}|S_1) =$ hit rate H, $p(\mathrm{n}|S_1) =$ misses M, $p(\mathrm{n}|S_2) =$ correct rejections CR, $p(\mathrm{y}|S_2) =$ false alarms FA, for the two alternative situations (stimuli), S_1, S_2, structure the results of each of the five events. The evaluation of the answers on the five decision tasks of the eight participants, i.e., the percentage correct analysis in (Watson et al. 2009) $(H + \mathrm{CR})/(p(S_1) + p(S_2))$ with neglection of nonanswers (i.e., no decision during the available time Ta) had suggested no significant performance difference between TWR-CWP and RTO-CWP. A closer look into the statistics of the nonanswers, however, revealed a significant increase under RTO-CWP as compared to TWR-CWP conditions, as shown in Fig. 3. It depicts the relative frequency of nonanswers separated for the TWR-CWP and RTO-CWP condition.

This result suggested to analyze two types of response matrices: (a) (optimistic) neglecting nonanswers, (b) (pessimistic) interpreting nonanswers as false decisions (M or FA). In this way, we obtain for each of the decision tasks an optimistic and a pessimistic estimate with regard to decision errors. The interpretation of the nonanswers as erroneous responses appears to be justified due to increased uncertainty about the correct answer resulting in hesitation to respond at all because tower controllers' work ethics require decision making with high certainty.

Table 1 lists the measured hit and false alarm rates (H, FA ± standard deviations derived from binomial distributions) for the five events to be analyzed, together with the average response times Tr and available response times Ta. In addition to H and FA, the rate of misses $M = 1–H$ is required for calculating the total number of errors to be compared with the formal time–pressure error model in Sect. 4.3.

Comparing the measured hit and false alarm rates for all five events under TWR and RTO conditions with nonanswers not considered [optimistic case (a): left two

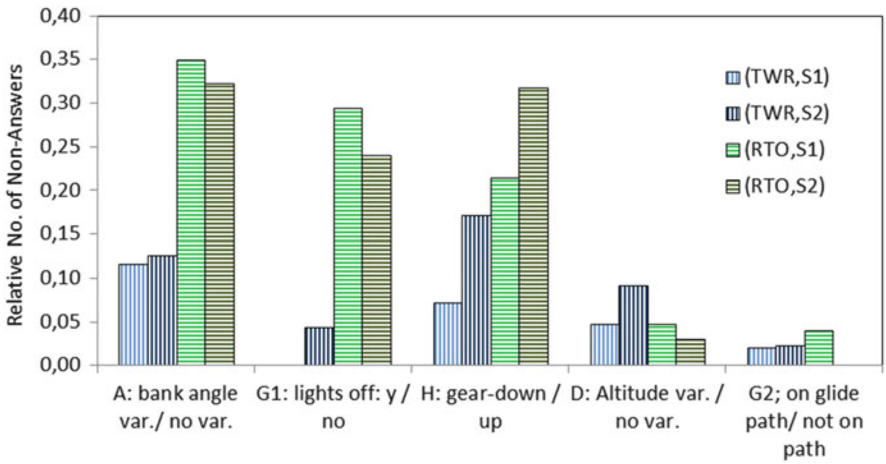

Fig. 3 Relative number of nonanswers (included in the set of false answers ($M(S_1)$, FA(S_2) for the pessimistic analysis = maximum errors) for the five analyzed decision tasks, separated for the two conditions TWR-CWP (*left two columns, blue, vertical lines*), RTO-CWP (*right columns, green, horizontal lines*), normalized with regard to the two respective alternative situations S_1 (flight maneuver @ stimulus position, *light color*), S_2 (no flight maneuver @ stimulus position, *dark color*). Reprinted from (Fürstenau et al. 2014), with permission

Table 1 Measured hit and false alarm rates ($H = p(\mathrm{y}|S_1)$, FA $= p(\mathrm{y}|S_2)$, ±stddev from binomial distribution according to MacMillan and Creelman (2005) for five events and two conditions (TWR, RTO-CWP) with (a) nonanswers excluded and (b) nonanswers added to error rates FA and M

Event with alternatives S_1/S_2 (Ta/s)	Tr/s ± stderr	CWP	(a) Nonanswers excluded		(b) Nonanswers included	
			$p(\mathrm{y}|S_1)$	$p(\mathrm{y}|S_2)$	$p(\mathrm{y}|S_1)$	$p(\mathrm{y}|S_2)$
A: bank angle var.: y/n (20)	13.8 ± 1.7	TWR	0.92 ± .04	0.08 ± .04	0.81 ± .06	0.20 ± .05
	14.0 ± 1.1	RTO	0.93 ± .05	0.11 ± .05	0.60 ± .07	0.39 ± .07
D: altitude var.: y/n (20)	8.8 ± 1.4	TWR	0.80 ± .06	0.03 ± .03	0.77 ± .06	0.12 ± .06
	12.4 ± 1.5	RTO	0.73 ± .07	0.03 ± .03	0.70 ± .07	0.06 ± .04
G_1: lights off: y/n (180)	27.0 ± 6.6	TWR	0.94 ± .04	0.25 ± .07	0.94 ± .04	0.28 ± .07
	95.4 ± 7.4	RTO	0.92 ± .06	0.63 ± .08	0.65 ± .08	0.72 ± .07
G_2: glide path y/n (90)	21.6 ± 6.4	TWR	0.90 ± .04	0.32 ± .07	0.88 ± .05	0.33 ± .07
	34.2 ± 8.1	RTO	0.92 ± .04	0.22 ± .06	0.88 ± .05	0.22 ± .06
H: gear down: y/n (10)	8.1 ± 0.9	TWR	0.98 ± .02	0.06 ± .04	0.91 ± .04	0.22 ± .06
	9.2 ± 0.5	RTO	0.98 ± .02	0.07 ± .05	0.77 ± .06	0.37 ± .08

Ta = available decision time, Tr = required average decision time with stderror of mean per seconds. Reprinted from (Fürstenau et al. 2014), with permission

data columns], the RTO-CWP exhibits no significant difference as compared to the TWR-CWP. If, however, the nonanswers are interpreted as erroneous responses and correspondingly attributed to rates FA and M [pessimistic case (b): right two data columns], significant differences TWR versus RTO are obtained [smaller H (RTO), larger FA(RTO)] for event/task A (bank angle variation?), H (gear down?), G_1 (lights off?), whereas for event/tasks D and G_2 responses again exhibit no significant difference. The latter two tasks reflect the fact that altitude information could be read directly from the radar display, and operators were free to select their appropriate information source. An extremely high FA difference TWR versus RTO is observed for both cases (a) and (b) for the "lights-off" event which is reflected also in a large difference of decision distance (correlated with response time). This was already reported in the previous chapter "Which Metrics Provide the Insight Needed? A Selection of Remote Tower Evaluation Metrics to Support a Remote Tower Operation Concept Validation," where percentage correct analysis for the optimistic case (a) analysis (without nonanswers) was evaluated.

4 Data Analysis and Discussion

4.1 Technical Limitations

Technical parameters of the reconstructed far view with videopanorama and PTZ (Schmidt et al. 2007; Fürstenau et al. 2009) lead to predictions concerning performance differences under the two conditions, TWR and RTO-CWP. The measured performance also depends on the usage of the different available information sources, in particular videopanorama, PTZ, and approach radar, and the general system usability. The relevance of the used RTO metrics is discussed in the previous chapter "Which Metrics Provide the Insight Needed? A Selection of Remote Tower Evaluation Metrics to Support a Remote Tower Operation Concept Validation."

The visibility limitations of the videopanorama are quantified by the modulation transfer characteristic (MTF, see Appendix A), with the digital (pixel) camera resolution providing the basic limit (Nyquist criterion) for detectable objects and maneuvers: angular resolution was estimated as $\delta\alpha \approx 2$ arc min $\approx 1/30° \approx 0.6$ m object size/km distance per pixel under maximum visibility and contrast [about half as good as the human eye (1 arcmin)]. Reduced contrast of course reduces the discriminability according to the MTF, and the question arises how the discriminability difference TWR versus RTO-CWP is affected. The gear-down situation at positions H1–H3 with wheel diameter 0.65 m, e.g., can certainly not be detected before the wheel occupies, say, 4 pixels which for the 40$''$ display (0.55 mm pixel size) means a viewing angle of ca. 1 mm/2 m ≈ 0.5 mrad corresponding to the visual resolution of the eye (1 arcmin) under optimum contrast. This estimate results in a panorama-based gear-down detectability distance of <500 m. It means that under RTO conditions, this task requires usage of PTZ in any case in order to allow for a decision. The same argument is valid for the detection of bank angle changes at position A following the overflight of the runway because it requires optical resolution of the *A*/*C* wings. The “lights-off?” decision (G_1) has a somewhat different character because in situation S_1 (lights off, answer “yes” = hit), observers usually wait until they actually detect the *A*/*C*, whereas situation S_2 can be recognized at a larger *A*/*C* distance due to the higher contrast ratio of landing light-on/background luminance.

4.2 Bayes Inference: Risk of Unexpected World State

A brief overview of this method is provided in Appendix B. Measured rates of hits, misses, correct rejections, and false alarms (*H*, *M*, CR, FA) are estimates of conditional probabilities $p(d_i|S_j)$ $(i \neq j)$ which by means of the Bayes theorem are used after the measurement by multiplying with the a priori knowledge $p(S_i)$ for calculating the inverse probabilities, i.e., risk of an actual situation contradicting the decision based on the perceived evidence:

$$p\left(S_i|d_j\right) \; = \; p\left(d_j|S_i\right) p(S_i) \; / \; p\left(d_j\right) \tag{1}$$

with responses d_i, $i = 1, 2$, d_1 = yes, d_2 = no, $p(\mathrm{y}) + p(\mathrm{n}) = 1$ for a given situation S_i, and the probability of any of the two possible situations (world states) $p(S_1) + p(S_2) = 1$, under TWR and RTO conditions of the experiment. Of particular interest are the two probabilities for the risk of a situation contradicting the decision based on the observed evidence on the nature of the observed event. $p(S_1|\mathrm{n})$ is the probability of, e.g., the aircraft with bank angle variation (situation S_1, e.g., signaling some special situation during radio interruption) conditional on the case that no variation is perceived (i.e., a Miss). $p(S_2|\mathrm{y})$ is the probability for a situation with *a*/*c* not performing bank angle variation conditional on the false response “variation perceived”(i.e., a False Alarm). The following Figs. 4 and 5 depict the corresponding Bayes inference results (risk) for the five events for analysis case (b), i.e., nonanswers treated as errors (S_1: nonanswer = *M*; S_2: nonanswer = FA). It clearly shows that the risks for world states not corresponding the observed evidence (decision, averaged over the eight participants and seven decisions per situation S_i) are at least two times as high for the RTO-CWP as compared to TWR-CWP, with the exception of the events *D* and G_2 (altitude variation and deviation from glide path occurring in 7 of the 14 circles).

Table 2 lists the calculated Bayes inference values (averaged over participants and repeated observations) for the five different stimuli (events) and two conditions (TWR, RTO) for cases (a) nonanswers not considered and (b) nonanswers taken as wrong answers.

As expected from Table 1, significant differences are observed for the Bayes inference analysis of RTO versus TWR performance with analysis case (b) (i.e., with nonanswers included, right two columns). The calculated risk for the actual world state occurring to be in contradiction to the perceived (hypothetical) situation

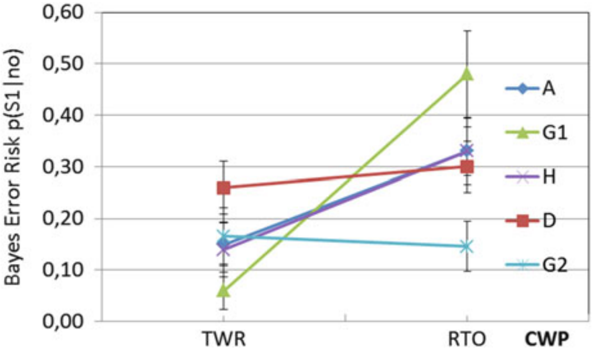

Fig. 4 Bayes inference on probability (±stddev) of world state S_1 (event/maneuver occurring) conditional on (false) decision $d_2 =$ event not occurring, based on perceived evidence [case (b)]

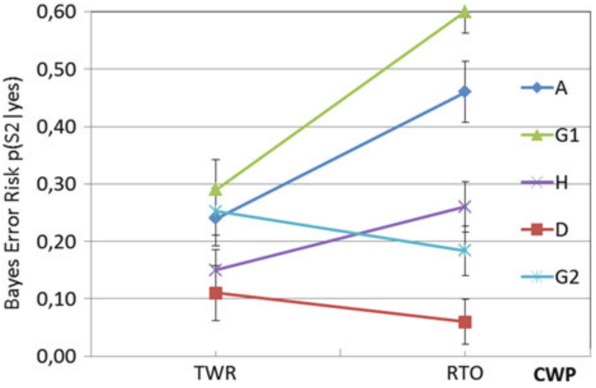

Fig. 5 Bayes inference on probability (±stddev) of world state S_2 (event/maneuver not occurring) conditional on (false) decision $d_1 =$ event occurring, based on perceived evidence [case (b)]

Table 2 Bayes inference for TWR and RTO-CWP from response data, for cases (a) and (b). Stddev estimates from binomial distribution

Event with S_1 or S_2	CWP	(a) Nonanswers excluded		(b) Nonanswers included	
		$p(S_1\|n)$	$p(S_2\|y)$	$p(S_1\|n)$	$p(S_2\|y)$
A: bank angle var.	TWR	0.06	0.10	0.15 (0.04)	0.24 (0.05)
	RTO	0.06	0.13	0.33 (0.05)	0.46 (0.05)
G_1: lights off	TWR	0.06	0.26	0.06 (0.04)	0.29 (0.05)
	RTO	0.13	0.50	0.48 (0.09)	0.60 (0.04)
H: gear down	TWR	0.03	0.04	0.14 (0.05)	0.15 (0.04)
	RTO	0.04	0.04	0.33 (0.06)	0.26 (0.04)
D: altitude var.	TWR	0.22	0.03	0.26 (0.05)	0.11 (0.05)
	RTO	0.26	0.03	0.30 (0.05)	0.06 (0.04)
G_2: above glide path	TWR	0.14	0.24	0.17 (0.06)	0.25 (0.04)
	RTO	0.10	0.18	0.15 (0.05)	0.18 (0.04)

is very low for nonanswers excluded (analysis case (a)) for both TWR and RTO conditions, and no significant TWR–RTO difference is observed, with the exception of stimulus G_1(lights off). The error risk increases significantly with nonanswers included (case (b)), which in fact is not surprising. Not expected was the result that in the RTO-CWP the risk in most cases at least doubles as compared to TWR-CWP. The altitude variation (event D) and deviation from glide path (G2) in contrast exhibit no significant difference which can be explained by the fact that in both cases, the majority of decisions were made based on MODE-S secondary radar display information which includes altitude information in the labels with typically 25 ft interval and 4 s update rate.

4.3 Discriminability d' of Aircraft Maneuvers

The results of the Bayes inference analysis is supported by a more sophisticated evaluation of data from Table 1 using signal detection theory (SDT). In contrast, e.g., to percentage correct (p_c) evaluation of subjects decisions on dual-choice tasks, it separates the decision maker's discriminability d' from the subjective decision bias c (=decision criterion or individual tendency to more conservative, i.e., avoiding FA at the cost of decreasing H, or more liberal decisions) (MacMillan and Creelman 2005).

Within the theoretical framework of SDT, the two alternative stimuli S_1, S_2 for each event define independent statistical variables. Each set of decisions of a single subject for the 14 aerodrome circles with one of the events A, D, G_1, G_2, H represents a sample of the randomly presented S_1- and S_2 alternatives. For calculation of (parametric) discriminability d', the subjective responses are assumed to be drawn from independent equal variance Gaussian ($\mu_{1,2}$, σ) densities modeling the familiarity with situations S_1 and S_2 (MacMillan and Creelman 2005). Any discriminability difference between TWR and RTO may be quantified by corresponding coefficients $d = \mu_1 – \mu_2 = z(H) – z(\mathrm{FA})$ and subjective decision bias (criterion) $c = 0.5(z(H) + z(\mathrm{FA}))$, with $z() = z$ score as calculated from the inverse cumulative densities.

Figure 6 depicts for analysis of case (b) and the average (H, FA) data of the three visual discrimination tasks at positions A, G_1, H in the receiver operating characteristic (ROC) space together with two sets of pair wise ROC curves (one pair for TWR and RTO conditions each). One set (solid lines) is parameterized by discriminability d' and the other (dashed) by the subjective decision bias c. For example, $d' = 3$ means that the Gaussian densities mean values of perceived situations S_1, S_2 differ by 3 normalized stddev ($\sigma = 1$). Under the above-mentioned conditions, each (d', c) ROC curve pair is unambiguously determined by the single average (H, FA) point. The d' and c values are calculated via standard procedures [inverse cumulative densities from the (H, FA) data]. Dotted lines indicate estimates of standard deviations $s(d')$ as described in MacMillan and Creelman (2005), based on the binomial variation of measured proportions from sample to sample.

The following Table 3 summarizes the discriminability d' and criteria c (decision bias) corresponding to Fig. 6, and like Table 2, it includes tasks D (altitude

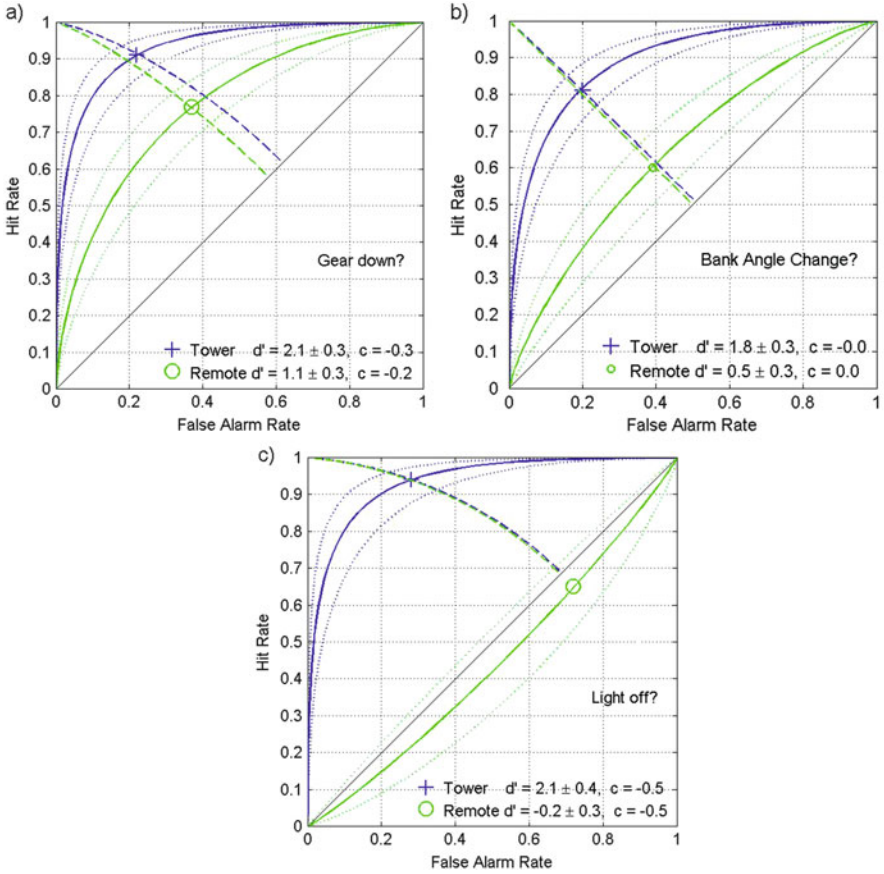

Fig. 6 Measured data points in ROC space of average hit and false alarm rates [pessimistic analysis case (b)] of visual-only events/tasks (**a**) gear down, (**b**) bank angle variation, (**c**) lights-off for TWR (cross) and RTO (*circle*) conditions, together with the isosensitivity and isobias curves parameterized by discriminability d' (*solid lines*) and criteria c (*dashed*), respectively. *Dotted lines* are stddev based on procedures described in MacMillan and Creelman (2005). Redrawn from Fürstenau et al. (2013) with permission

variation) and G_2 and includes both data analysis cases: optimistic (a) and pessimistic (b).

Again, both data analysis cases are listed: optimistic (a) and pessimistic (b). In agreement with the Bayes inference, the case (a) analysis (nonanswers are not considered in the data analysis) shows no significant difference between TWR and RTO-CWP conditions, with the exception of task G_1: for the lights-off stimulus even with nonanswers not considered, RTO exhibits a significant decrease of discriminability. This was already reported in MacMillan and Creelman (2005) for the percentage correct analysis.

Table 3 Discriminability d' (±stddev) and criteria c for both (a) optimistic and (b) pessimistic analysis as obtained from z scores based on response matrices (hit and false alarm rates)

		(a) Nonanswers excluded		(b) Nonanswers included	
Event	CWP	d' (±stddev)	c	d' (±stddev)	c
A	TWR	2.81 (0.39)	−0.01	1.75 (0.30)	−0.02
	RTO	2.72 (0.45)	−0.11	0.54 (0.26)	0.00
G_1	TWR	2.24 (0.40)	−0.45	2.14 (0.40)	−0.49
	RTO	1.05 (0.43)	−0.86	−0.20 (0.30)	−0.48
H	TWR	3.63 (0.53)	−0.30	2.12 (0.32)	−0.30
	RTO	3.47 (0.55)	−0.30	1.07 (0.27)	−0.20
D	TWR	2.69 (0.50)	0.49	1.90 (0.35)	0.22
	RTO	2.48 (0.48)	0.62	2.07 (0.40)	0.52
G_2	TWR	1.74 (0.31)	−0.40	1.61 (0.30)	−0.37
	RTO	2.15 (0.33)	−0.31	1.94 (0.31)	−0.21

Also for case (b) analysis, the Bayes inference results are confirmed: again a significant decrease of visual discriminability is observed if nonanswers are attributed to erroneous decision (M, FA), for task G_1 (landing lights-off) even zero detectability. As expected, tasks D and G_2 requiring decisions on altitude (change) again exhibit no significant difference TWR versus RTO-CWP. Decision bias in most cases does not exhibit significant differences between TWR and RTO-CWP.

Figure 7 depicts the discriminabilities d' with standard deviations derived from binomial distributions (MacMillan and Creelman 2005) for analysis case (b): nonanswers included. The figure summarizes and highlights the significant performance deficit of the RTO-CWP with respect to the visual-only information tasks (A, G_1, H, solid lines). The increased RTO-CWP probability $p(S_i|d_j)$, $i \neq j$ for drawing erroneous conclusions based on subjectively perceived evidence in the case of Bayes analysis (Figs. 4 and 5) is reproduced here by the decreased visual parametric discriminability d' (based on the Gaussian (μ_i, σ) assumption for criterion distribution). Again, also the difference between visual only and visual and radar information source (D, G_2) is confirmed for the RTO case, however, not for the TWR-CWP, indicating a usability deficit of the former.

The d' calculation presupposes equal variance Gaussian densities for the subjective responses or familiarities with the two stimulus alternatives which was not possible to verify with our limited data set. We can obtain additional confidence in our results by means of the nonparametric discriminability index A with bias/criterion parameter b which is independent of the mentioned precondition.

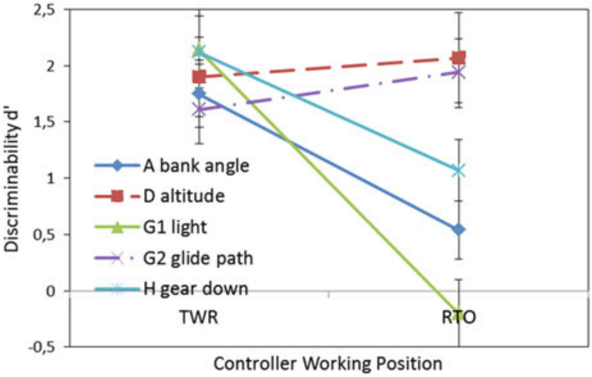

Fig. 7 Discriminability d' (units = normalized stddev σ/μ, μ = mean) according to SDT derived from hit and false alarm rates in Table 1, for case (b): nonanswers := false answers. D and G_2 (*dash–dotted lines*): decisions about altitude (variations). A, G_1, H = visual-only information (*solid lines*). *Error bars* = stddev based on binomial distribution (MacMillan and Creelman 2005)

4.4 Nonparametric Discriminability A

In this section, we will confirm the parametric discriminability (d') analysis with an additional one using the nonparametric discriminability index **A** (not to be confused with aircraft maneuver A; generally assumed independent of the Gaussian (μ, σ) assumption for familiarity). Discriminability **A** is defined as the average of the areas under the maximum and the minimum proper ROC–isosensitivity curve (constant d', Fürstenau et al. 2013; MacMillan and Creelman 2005) defined by a single (H, FA) data point and varies between 0.5 ($d' = 0$) and 1 ($\lim d' \to \infty$). For the calculation of **A** and b, we use corrected algorithms (functions of H, FA) derived in Zhang and Mueller (2005). Figure 8 shows one example (stimulus A: bank angle variation) of (**A**, b)-parameterized isopleths determined by the two TWR and RTO-CWP data points. Figure 9 depicts the **A** values of the five tasks at A, D, G_1, G_2, and H for the two conditions TWR-CWP and RTO-CWP [again pessimistic analysis case (b): nonanswers included as false answers].

The example (**A**, b)-isopleths in Fig. 8 for maneuver **A** shows zero decision bias ($b = 1$), however, a significant discriminability decrease for RTO-CWP (minimum $A = 0.5$ = positive diagonal), as expected.

In agreement with the d'-discriminabilities in the previous section, the nonparametric indices **A** in Fig. 9 exhibit no significant differences between TWR and RTO-CWP conditions for events D, G_2 (event subset with altitude stimulus; altitude information additionally provided by radar via Mode-S transponder), whereas the A-decrease for the visual-only subset $\{A, G_1, H\}$ is again evident. Moreover, even a reduction of the number of erroneous decisions by attributing a 50 % chance to nonanswers to be correct instead of assuming 100 % wrong answers leaves the RTO performance decrease for visual-only tasks significant. The drop to chance level of RTO-CWP discriminability for case G_1 is again confirmed and attributed to the

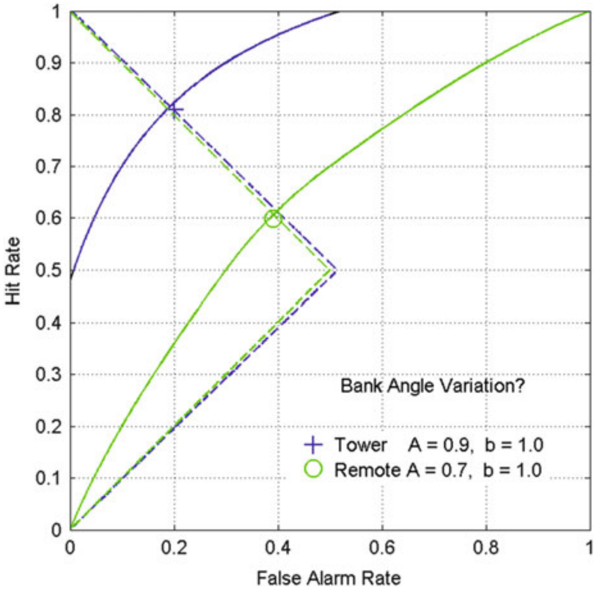

Fig. 8 Maneuver A as example of isosensitivity curves for TWR and RTO case (b) analysis (*straight lines*, *A*-isopleths) and decision bias (*dashed*, *b*-isopleths). Reprinted from Fürstenau et al. (2014) with permission

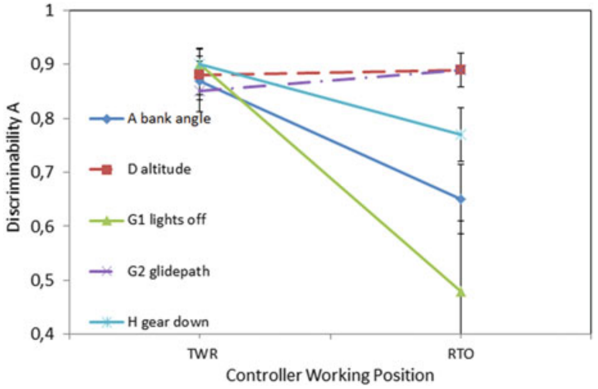

Fig. 9 A as calculated according to Zhang and Mueller (2005) from hit and false alarm rates in Table 1, case (b). *D* and G_2 (*dash–dotted lines*): decisions about altitude (variations). *A*, G_1, $H =$ visual-only information (*straight lines*). *Error bars* = stddev based on binomial distribution (MacMillan and Creelman 2005). Reprinted from Fürstenau et al. (2014) with permission

RTO resolution and contrast deficit which prohibits recognition of *A*/*C* even with lights on for short response times Tr: when participants at RTO-CWP after task initialization had waited some 10 s or so without recognizing landing lights, they often simply guessed lights to be off or gave no answer, contributing to FA errors.

4.5 Error Prediction Using the Information Processing/Time Pressure Hypothesis

In order to determine appropriate solutions for rising the RTO-CWP performance to at least the level of the TWR-CWP, we have to find explanations for the measured discriminability deficits. The RTO-CWP performance for decision making using videopanorama and PTZ replacement of the tower far-view should be at least as good as the TWR-CWP, so that users can be certain that replacement of the out-of-windows view has a potential of even improving their work condition. Referring to Figs. 4, 5, 7, and 9, this means that the decision error and discriminability differences between TWR and RTO-CWP of the visual discrimination tasks have to vanish in the final improved RTO-CWP design. In order to approach the required improvements in a scientifically founded way, we tried to narrow down the origin of this deficit via an information processing hypothesis.

A (algorithmically) simple theoretical model with some potential for explaining the observed performance differences quantified in terms of decision-error probability is based on the perceptual control/information processing theory (PCT/IP) of Hendy et al. (1997). Because our experiment was not initially designed for testing this theory, we can only expect a first impression on the relevance of the corresponding assumptions. The core idea is to formalize the information processed as part of the total information required for a correct answer (Br measured in bits) as function of time pressure TP. TP is the ratio of required time Tr (to acquire Br) and the available time Ta: TP = Tr/Ta. Assuming constant cognitive processing rate (channel capacity C: Tr = Br/C), the rate of information processing demanded (RID) is related to TP via TP = RID/C, with RID = Br/Ta. Hendy et al. (1997) derived simple algorithms for modeling dependent variables like operator workload (OWL), success ratio, and number of errors as function of TP. For the latter, they suggested an exponential dependency for the increase of decision errors with TP, where TP increases linearly with the number N of objects to be analyzed (in our case $N = 1$): $\mathrm{TP} = t_0(1 + b_1 N)/\mathrm{Ta}$, and t_0 = minimal decision time for $N = 0$. For error probabilities, we modify Hendy's algorithm in order to use our maximum error probability p_{err} (lim $\mathrm{TP} \to 0) = 0 = p_{\min}$ (=zero error for vanishing time pressure) and p_{err} $(\mathrm{TP} >> 1) = 0.5 = p_{\max}$ (=just guessing, no information available) as boundary conditions. Keeping the original assumption that errors start to grow exponentially with TP but then level off at $p_{\max}$, we arrive at a logistic function with threshold and sensitivity parameters as one possible model:

$$p_{\mathrm{err}} = 0.5\left(1 + \exp\left\{-\left(\frac{\mathrm{TP} - \mu}{\beta}\right)\right\}\right)^{-1} \tag{2}$$

$\mu (0 \leq \mu \leq 1)$ models the threshold where the observer starts shedding most information due to increasing workload (stress due to TP increase). It fulfills the conditions that lim$(\mathrm{TP} >> \mu)$ $p_{\mathrm{err}} \to 0.5$ and lim$(\mathrm{TP} \to 0)$ $p_{\mathrm{err}} \to 0$. The latter condition is fulfilled as long as $\mu/\beta >> 1$, i.e., steep slope (=error sensitivity $dp_{\mathrm{err}}/d\mathrm{TP} = 1/8\beta$ at $\mathrm{TP} = \mu$ and/or large threshold). Figure 10 shows for the three

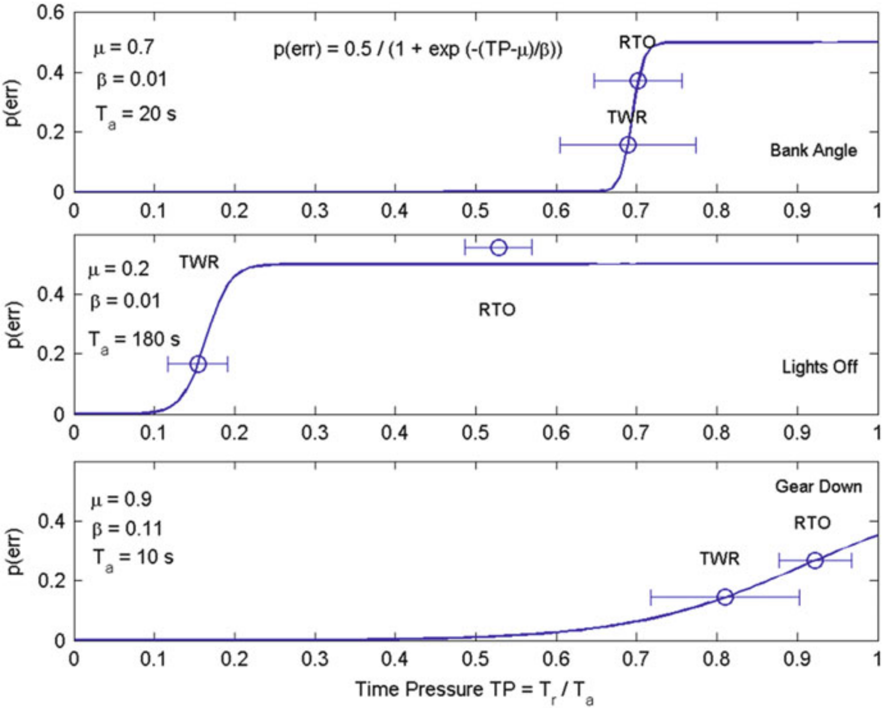

Fig. 10 Decision error probabilities for TWR and RTO-CWP versus time pressure TP (±stderr of mean, $n = n(\text{error}) + n(\text{correct}) = 80\text{–}100$) for tasks where visual/PTZ information was used for decision making. Standard errors of p(error) are smaller than the circles of data points. Logistic error model [Eq. (1)] derived from IP/TP theory (Hendy et al. 1997) for fitting p_{err}(TP). Reprinted from Fürstenau et al. (2014) with permission

visual discrimination tasks, the results of nonlinear fitting of the respective two data points p_{err}(TP) at TP(Tr(TWR)), TP(Tr(RTO)) with the two boundary conditions ($p_{\text{err}}(\lim \text{TP} \to 0) = 0$, $p_{\text{err}}(\lim \text{TP} \to \infty) = 0.5$) using model equation (2) for the three visual-only tasks. For characterizing the experimental results in terms of (μ, β), we have to use the total number of erroneous decisions for the full set ($n(S_1) + n(S_2)$) of trials per subject instead of the conditional probabilities, misses, and false alarm rates $M = 1\text{–}H$, FA: $\text{p}_{\text{err}} = (n_1\ M + n_2\ \text{FA})/(n_1 + n_2)$ as used for the SDT analysis.

The results indicate the principal applicability of the logistic error model because all three cases yield reasonable threshold ($\mu \leq \text{TP} = 1$) and error sensitivity parameters β. The RTO performance deficit always seems to correlate with some kind of time pressure. According to IP theory, decision errors should increase significantly due to increasing stress when Tr approaches Ta and to shedding of information when Tr > Ta. This is reflected by our results only for event H (gear down) with the shortest Ta = 10 s. Variation of threshold μ with event(stimulus) can be explained by the fact that the three specific events provide quite different stimulus conditions for the decision making as described in Sects. 2 and 3. The fact that only for the gear-down task, an approximately exponential increase of errors is observed at TP ≈ 1 according to Hendy et al. (1997) with $\mu \approx 1$, whereas a threshold behavior at lower μ is quantified by the IP/TP model for tasks A, G_1. This indicates at least one more performance limiting factor besides time pressure, such as PTZ camera contrast/resolution and operator training. For lights-off decision, the RTO-HMI contrast deficit should play a major role: the average response appears completely at random. Nevertheless, also in this case, a long waiting time of the observer (until first A/C sighting) before beginning to gather visual evidence might lead to increasing stress due to uncertainty.

5 Conclusion

The present analysis of two-alternative decision making with safety related aircraft maneuvers explains the observed discrepancy in the percentage correct analysis of the corresponding observation data (p_c, neglecting nonanswers), as compared to the subjective success criteria (Friedrich and Möhlenbrink 2013). The perceived safety in Friedrich and Möhlenbrink (2013) was rated as insufficient by participants which agrees with the objective data analysis presented in this chapter.

The detailed analysis, based on detection theory (SDT) and Bayes inference, confirms the vanishing of the difference between TWR- and RTO-CWP (suggesting sufficient RTO performance) when neglecting nondecisions during simultaneous decision making at TWR- and RTO-CWP. If, however, nondecisions are taken into account and interpreted as false responses [misses(S_1) or false alarms(S_2)], we arrive at significant error increase under RTO as compared to TWR conditions. Correspondingly, reduced discriminability indices A (nonparametric) and d' (parametric, Gaussian assumption for familiarity with stimulus) are obtained and confirmed by Bayes inference, the latter quantifying the probability of a world state in contradiction to the evidence-based decision.

The results indicate a usability deficit of the RTO-HMI (videopanorama and PTZ) in its present version due to time pressure as one possible reason. Data analysis with a modified version of the Hendy et al. information processing/time pressure (IP/TP) theory (Hendy et al. 1997) indicates additional origins of performance decrease due to threshold behavior of decision errors significantly below the TP $= 1$ value. It is expected that increased automation (e.g., automatic PTZ-object tracking and augmented vision, e.g., data fusion with approach radar) will increase usability, and in combination with improved operator training could solve the performance problem. This is supported by the analysis of the remote tower metrics (RTM) as discussed in the previous chapter "Which Metrics Provide the Insight Needed? A Selection of Remote Tower Evaluation Metrics to Support a Remote Tower Operation Concept Validation." There a difference was found in usage of information sources between TWR- and RTO-CWP. As expected from the visual resolution deficit of the RTO-videopanorama, a major switching tendency was found from panorama to PTZ camera as information source for decision making (chapter "Which Metrics Provide the Insight Needed? A Selection of Remote Tower Evaluation Metrics to Support a Remote Tower Operation Concept Validation," Table 5). In any case, further experiments are required for clarifying the role of time pressure and validating the effect of a higher level of automation and/or measures for improved usability. Experiments are preferably realized as human-in-the loop simulations with appropriate design for quantifying time pressure variation, with a task design that avoids nonanswers.

Because of the significant effort required for the HITL experiments and field tests, the initial results of the IP/TP model suggest as intermediate step model-based computer simulations for preparing corresponding HITL and field experiments. For this purpose, the commercial tool IPME [Integrated Performance Modeling Environment (Fowles-Winkler 2003)] appears useful which integrates the PCT/IP-based approach together with a resource-based theory so that by means of simulations it would allow for further clarification of the influence of different performance shaping functions.

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Part IV
Alternative Approaches and Perspectives

The Advanced Remote Tower System and Its Validation

F. J. van Schaik, J. J. M. Roessingh, J. Bengtsson, G. Lindqvist, and K. Fält

Abstract The Advanced Remote Tower (ART) project studied enhancements to an existing LFV prototype facility (ROT) for a single airport remotely operated tower: projection on a 360° panorama screen, adding synthesised geographic information and meteorological information, video tracking, fusion of video and radar tracks, labelling, visibility enhancement and surveillance operations with a remotely controlled Pan Tilt Zoom camera. The ART functions have been embedded in the existing Swedish test facility for single airport remote tower operations in Malmö airport Sturup observing Ängelholm traffic about 100 km to the North. These functions were tuned and validated during tests with 15 operational tower air traffic controllers. Emphasis was on the traffic and situation awareness of the tower controllers using remote cameras and a projection system for safe operational tower control, replacing direct view on the airport and its traffic. The validation results give valuable information for further development and operational application even outside the Remote Tower application area.

Keywords Advanced Remote Tower • Remote Tower Operations • LFV prototype • Validation • Panorama screen • Video tracking and fusion • Pan Tilt Zoom camera • Synthetic overlay • Safety

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1 Introduction

The Advanced Remote Tower (ART) (ART 2006) project studied, from 2008 to early 2010, the concept of remotely operated Air Traffic Control (ATC) towers and supporting technologies in order to enhance regularity during low visibility operations and to substantially decrease the ATC-related costs at airports. The ART enhancements are prototype functions with different levels of maturity. They are supposed to be good candidates for application in remote tower control. This contribution is an extension of the paper presented in the IFAC HMS 2010 conference (IFAC 2010).

ART was co-funded by the European Commission (Directorate General for Transport and Energy, TREN/07/FP6AE/S07.73580/037179). Partners in the ART project were: Saab (Project Coordination and system integrator), the Swedish Air navigation Service Provider LFV (Operational input and hosting the ART trials and ART facilities), the National Aerospace Laboratory of the Netherlands NLR (Validation and Safety Assessment), LYYN Sweden (Visibility Enhancement Technology VET) and Equipe Ltd. UK (projection facility).

The purpose of ART was to explore the concept of remotely operated towers and to prototype and validate additional sensors and the Human Machine Interface (HMI) that were supposed to enhance the air traffic controllers' situational awareness at reduced visibility conditions due to weather and darkness. ART evaluated promising new technologies, as well as technologies of today, applied and presented in an innovative and more efficient manner. The enhanced situational awareness was one of the main prerequisites for enhanced regularity at the aerodrome, which has proven to be one of the bottlenecks in today's Air Traffic Management (ATM) system.

A cost benefit analysis (LFV-ROT 2008) regarding remotely operated towers had been performed by the LFV Group. It showed substantial economic benefits compared to traditional ATC operations at airports. These benefits for the Air Navigation Service Provider (ANSP) will in turn reduce the cost for airline operators and travellers.

The concept and technology were tested in low-density areas in order to explore the applicability in medium- and high-density traffic areas. The ART concept was in turn one of the bricks in the future concept of highly automated ATM at airports.

The concept of ART will also have spin-off effects in the area of training and investigation after incidents and accidents. ART opened the possibility to not only use recorded voice communication but also to reproduce the course of events with audio and video of the controllers' situation.

Major deliverables were the ART concept of operations, system design, incorporation and adaptation of sensors and an ART demonstrator on a single low-density airport in Sweden with the possibility to explore the concept at any low- to medium-density airport. The associated reports can be found in TRIP-ART (2010).

The following steps have been made to achieve these objectives: design and construction of a remote tower cab, evaluation by end-users of controller workload and situational awareness, evaluation of operational benefits with new possibilities to present information, identification of vital parameters for remote airport operations and evaluation of technical and operational safety issues.

Remote tower concepts were rather unexplored when the ART study was performed. LFV pioneered the hardware aspects for Remotely Operated Towers (ROT) in 2006. Brinton and Atkins (2006) provided a requirement analysis approach for remote airport traffic services. The German Aerospace Center DLR was performing remote airport tower operation research (Fürstenau et al. 2007) in a national programme. US activity could be found in Ellis (2006). The ART project enabled NLR to perform a parallel study on detection and recognition by Tower Controllers; see IFAC (2010) and chapter "Assessing Operational Validity of Remote Tower Control in High-Fidelity Simulation" of this book.

Next sections explain the ART functions, the test and validation programme, the results and the analysis and recommendations.

2 ART Functions

The ART project prototyped the following enhancements for Remote Tower Control.

2.1 360° Circular Panorama Display

Nine video cameras were mounted on top of the real tower to observe the total airport and Control Zone (CTZ). Images were projected on a circular projection screen (9 times 42° including overlap between projected images, 6 m diameter, 1360 × 1024 pixel resolution per projected camera image, 20–30 frames per second, Fig. 1).

2.2 Visibility Enhancement Technology

A sizeable part of a projected image could be improved by a digital real time VET; see Fig. 2.

Fig. 1 Part of the panorama screen and one of the video cameras

Fig. 2 Visibility enhancement for a part of the image

2.3 Presentation of Airport and Geographic Information

Synthetic contour lines could be activated enhancing the runway and taxiway edges in low visibility conditions; see Fig. 3.

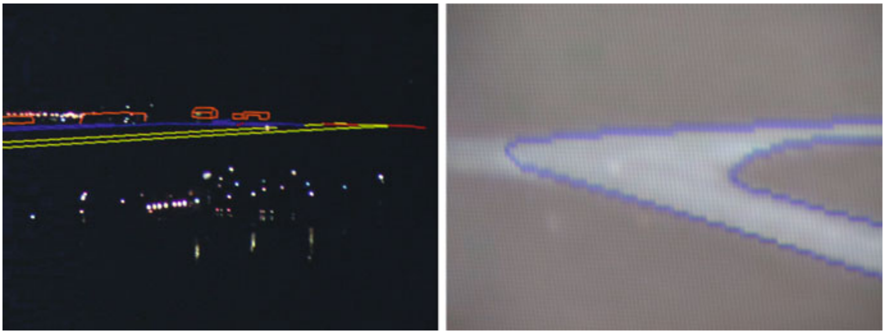

Fig. 3 Overlaid geographic information

2.4 Presentation of Weather Information

Actual weather information was projected on the circular panoramic screen on places without covering traffic; see Fig. 4. Actual wind direction and speed are displayed, including 2-min average and minimum and maximum values. Runway Visual Ranges were displayed in the lowest part of the panorama screen.

2.5 Sensor Data Fusion

Objects observed by the video cameras were tracked in the central tracking unit. Radar tracks from the Approach Radar were merged with the video tracks; see Fig. 5 *right part*.

2.6 Presentation of Aircraft and Vehicles

Aircraft and vehicles were automatically marked with a rectangle around their observed shape and were labelled with a track number when observed by the video tracker (Fig. 5 *middle* section). The track number (ID1234) could be changed into flight identity manually or by the automatic merge with the radar track. Radar information was added to the label if the track was detected by the radar (Fig. 5 *left* section) and when inside the airspace with specified range and altitude from the field. Aircraft both tracked by video and radar carried a rectangle–diamond contour and a radar label.

Fig. 4 Meteorological overlay with actual wind speed, direction, 2-min average and minimum–maximum values

Fig. 5 *Left*: Aircraft tracked only by the terminal approach radar (labels with call sign or SSR code and altitude in hundreds of feet); *Middle*: aircraft tracked by the video camera only (label with track number); *Right*: aircraft tracked by both radar and video

Fig. 6 PTZ camera human machine interface (*left*) and picture-in-picture (*right*)

2.7 Pan Tilt Zoom (PTZ) Camera

The PTZ camera could be remotely controlled from its HMI; see Fig. 6 *left*. It had 768 × 576 pixel resolution and a zoom factor of 36 (1.7° minimum view angle). The PTZ camera would sweep 180° in 2 s in order to catch an object quickly. The PTZ monitor (Fig. 6 *left*) provided presets for hot spots on the field (tiles around the PTZ image). Manual steering of the camera could be done by the mouse on either the PTZ monitor or the panorama screen. The actual heading direction and zoom factor of the camera were graphically indicated on a compass rose at the right top corner of the PTZ monitor (see Fig. 6 *left*). The PTZ camera could be slaved to a track and its image was also displayed on the panorama screen as a Picture-in-Picture (PIP) (Fig. 6).

3 Test and Validation Programme

The requirements for the ART functions had been derived from “problem driven” operational concept procedures for remote tower control, having in mind that solutions should be acceptable for remote tower controllers and cost beneficial. Emphasis was on safety and situational awareness. Both should be at least equal or better as compared to real tower operations. A preliminary safety assessment was part of the ART project. It was updated with the validation results and used in further research and development.

Early implementations of the ART functions were evaluated by air traffic controllers and further developed in at least two cycles before entering the evaluation and validation programme. Fifteen air traffic controllers participated in the validation, each spending two days in the remote cabin in groups of 2–3 controllers. Seven controllers came from the Swedish field Ängelholm that was remotely displayed. Seven controllers came from other Swedish airfields and one controller came from a Dutch military airport. Their average age was 45 years, ranging from

28 to 58 years and they had an average job experience of 20 years as an air traffic controller, varying from 1 to 32 years.

Due to safety restrictions, only passive shadow mode for single airport remote control was possible, meaning that actual control of traffic was done from the Ängelholm real tower, while controllers in the remote position in Malmö judged their function as if they were in full control.

The proper functioning of the ART functions was verified by testing against requirements. The validation was conducted by distant real time observation of traffic at the Swedish Ängelholm airport. Recordings were used to evaluate less frequently occurring visibility conditions. The European Operational Concept validation Methodology (E-OCVM 2007) was applied. E-OCVM is a strict validation methodology leading to definition of objectives and hypotheses to be validated. For the ART functions, about 70 had been defined and worked out in two questionnaires with about 138 statements ranking from "1" for complete disagreement to "6" for full compliance with the statement. Data were collected via debriefings, questionnaires for, during, and after the test runs and observations. Observations were carried out by Subject Matter Experts and Human Factors specialists.

The validation programme consisted of a familiarisation and training phase during which the controllers could make themselves familiar with the proper operation of the ART functions. The ART functions were validated incrementally and in combinations:

Part A: Validation of: Panorama Display, Weather Presentation and Geographic Information display
Part B: Traffic Presentation (Labelling) and PTZ functions
Part C: Pan Tilt Zoom Camera and Tracking functions
Part D: Validation of the Visual Enhancement Technology
Part E: Validation of the combination of all previously mentioned ART functions
Part F: Expert Judgement Workshop

The Expert Judgement Workshop, with an international audience of ANSP management and policy makers, covered all validation aspects that required involvement from such audience.

Ängelholm airport is an airport in southern Sweden with one runway, taxiways on both sides of the runway and an apron with passenger terminal on the opposite side of the runway about 1500 m from the tower. The tower has an elevation of 30 m above the field. The shortest distance from the tower to the runway is 700 m and the distance to the thresholds is about 1400 m.

4 Results

The prototype ART functions were validated during typical autumn conditions: rain, low visibility, dispersed showers and low cloud base conditions. Main emphasis was on the controller appreciation of working conditions and their situational and safety awareness. The programme spent also several hours with each group of controllers during night-time conditions. The traffic for Ängelholm consisted of about 20–30 aircraft per day. Aircraft movements consisted of a mix of scheduled flights, training flights and occasionally charters and business flights. Additionally, movements of vehicles on the taxiway and runway were surveyed. These movements could mainly be attributed to runway inspection cars, maintenance vehicles and towing trucks (either with or without rotating and flashing lights). The following results originate from the answers to the questionnaires and debriefings. In the context of this limited publication, only the highlights are given. An extensive version of the ART prototyping results with more quantitative and descriptive details is being published as part of the project documentation (TRIP-ART 2010).

4.1 Results for the Panorama Display

Visibility in the remote tower was found to be of less quality than in the real tower. Overall, the confidence in the projection system was anyhow high among the controllers. The controllers found the small distortions of the panorama image due to the composition from nine cameras acceptable. The camera–display combination was not performing sufficiently in resolution and in detection capability to survey all objects and movements in and around the airfield, compared to real tower operations (for a quantification of the performance difference between DLR's RTO-video panorama and real tower out-of-windows view, see chapters "Which Metrics Provide the Insight Needed? A Selection of Remote Tower Evaluation Metrics to Support a Remote Tower Operation Concept Validation" and "Remote Tower Research in the United States"). The controllers complained about missing depth of view. It was difficult for them to estimate distance and to judge which aircraft was closer. The controllers found the nine cameras in combination with the panorama display acceptable for ATC operations of single aircraft only. They expressed, however, to have problems to use this panorama set-up for handling multiple aircraft. The automatic camera adjustments for changing light conditions did not interfere much with the controllers' tasks, but a risk existed that controllers are not fully aware of the real daylight conditions, especially during twilight. During twilight, remote controllers might think that it is daylight condition. Overall, the controllers' awareness of the meteorological conditions was less; they also expressed to have some difficulties to judge visual aspects of the clouds.

4.2 Geographic Information Display

There was no consistent opinion among the controllers on the use of geographic overlays. Controllers familiar with Ängelholm said that they didn't need extra synthetic reference information. This contrasted with non-Ängelholm controllers, who found the extra reference lines helpful. The participants slightly agreed that geographical information can be useful during darkness and low visibility though it has to improve. They judged it would not significantly benefit capacity. The overlay may obscure other important information, and it is felt slightly cluttering the display.

4.3 Weather Presentation

The controllers slightly agreed that weather information on the display is useful. Controllers preferred to position the weather information at a location of the panorama display of their own choice, for instance, close to the touchdown zones. Overlaid weather information would be helpful to keep their eyes on the screen e.g. in gusty conditions. It would not cause more workload, but it could eventually cover other important information. The presentation of the Runway Visual Range was appropriate and controllers felt confident about it.

4.4 Results of Traffic Presentation (Labelling and Tracking)

Controllers preferred labels, irrespective of the sensor source from which these were derived. Target tracks and labels were considered useful, but mostly during night and low visibility. Their source (radar, video or both) should be indicated in the target symbol. Labels tended to increase controller's situational awareness, but controllers did not judge tracking performance good enough (so far) to increase capacity and to improve safety in low visibility conditions (visibility < 2000 m). Workload was judged slightly increased. Labels for aircraft and vehicles were expected to improve the capability of controllers to follow, monitor and control traffic. Controllers considered the risk to obscure important information with labels as slight. When labels overlapped, controllers were able to manually put them apart and make them legible. However, automatic label de-conflicting would be preferred. Label swops were considered a safety risk. Any mismatch between video and radar target should be removed. Adding a label, editing the label content and switching the label appearance were considered easy, which also applied to manual track termination. Display of different target symbols and labels for aircraft and vehicles was found intuitive with respect to the source of the track (video, radar or combined).

4.5 Results of Validation of the VET

VET increased the luminance of higher intensity areas with a factor 2 and lowered the lower intensity areas also with factor 2, providing more contrast between the high and the low brightness areas. The controller expectations were high (see through fog, make the invisible visible). Controllers wanted the whole picture to be enhanced in contrast and the effect should be larger. VET produced noisy pictures during night. In contrast, the PTZ turned out to be much more light sensitive in the dark than the visibility enhanced panorama cameras. This effect was enlarged due to automatic exposure control of the cameras, which worked better for the PTZ (optimising a zoomed-in part) and less well for the panorama cameras (averaging the whole image).

VET did not convince the participating controllers to improve visibility and awareness in the way it was set-up in these validation exercises. This finding was irrespective of the visibility and day/night conditions. VET did not allow operating at lower visibility thresholds as compared to standard Low Visibility Procedures. In low visibility, the additional visibility offered by VET didn't enable seeing all objects that controllers need to see at and around the airfield with sufficient detail. VET neither enabled earlier detection.

4.6 Results for the PTZ Camera and Object Tracking

The controllers found the PTZ rather useful for searching and detecting aircraft and vehicles, for manual and automatic runway inspection and for inspection of aircraft and vehicles, most of all during daylight and good visibility. The PTZ picture-in-picture should be moveable to any position on the panorama screen. The response of the PTZ camera was considered good enough and residual time delays were acceptable. The automatic tracking capability of the PTZ depended on the choice made for central video tracking and thus its performance. Controllers did not expect to handle more traffic with PTZ. The availability of the PTZ picture-in-picture camera favoured to keep a better focus on the panoramic display, but there was a risk to stay too long with the PTZ. Controllers found the PTZ operating procedures easy to use and felt confident using the PTZ camera.

4.7 Results of Validation of the Combination of all ART Functions

In comparison with real manned tower operations, the controllers could not stay ahead of traffic with the ART functions in the form that they were tested in these live trials. They had a slight tendency to focus too much and too long on the new

ART functions. Controllers expressed a thought that in an ART environment (=more synthetic), there is a risk of forgetting something important since you don't have all "real" visual inputs in the same way. They also expressed a feeling of not being able to plan and organise tower control in the same manner as in the real tower. Despite the ART functions, controllers searched for information that is easier to find in the real tower. The ART functions, therefore, need more development and better integration before being accepted. Using just one mouse for all integrated ART TWR operations/systems, as tested in these trials, was somewhat complicated. The mouse had to be positioned on the appropriate screen before the desired effect was obtained. On the one hand, controllers expected to learn quickly how to use these tools. On the other hand, they expressed the need for a lot of training. The ART facility was judged moderately realistic in reproducing the Ängelholm airport.

Some controllers experienced too much workload overall in the ART cabin. Fatigue was said to be caused by sitting in the cab with tempered light and noise from the cooling fans in the projectors.

4.8 Results from the Expert Judgement Workshop

About 25 subject matter experts participated in the Expert Judgement Workshop to share their opinion on matters not directly related to hands-on air traffic control. They worked out their opinions in three ART-related discussion blocks: (1) implementation of remote tower functions, (2) costs/benefits as expected for remote tower applications and (3) opportunities as seen for ART.

The experts found that the implementation of ART functions can be broadened to non-remote applications at large airports (extra surveillance and contingency applications) and remote applications in areas with an extreme climate, as there are, e.g. airports in Polar Regions. Airports with Flight Information Service (AFIS) only can be enhanced in service with a selection of ART functions, giving better flight information remotely. The experts agreed on better resolution and detection capability in next maturity level of ART. ART procedures need to be further developed and special airspace for remote tower operations is given a thought. More elaborated safety and human factor cases were on the wish list, as were the development and implementation of ART regulations and licensing.

The experts expected a reduction in cost of tower operations on small and medium size airports. Also more opening hours were expected in low visibility giving a better business case and probably attracting more customers. ART functions would benefit safety and thus save lives and avoid the costs of accidents and incidents. The ART technology would also be of benefit for airport and aviation security. The ART realisation could bring more uniformity in training and operations. However, working remotely increases the gap between the remote controllers and local personnel and decreases the "on-the-spot" knowledge of the field.

Remotely operated airports might be specifically applicable for hosting of emergency openings at unmanned airfields and at airport with comparable geographical locations such as closely connected grouped airports (with similar weather and traffic conditions), airports with a similar infrastructure and airports at unfavourable locations.

Next steps for ART as suggested by the expert group are better performance (resolution, depth of view, visibility enhancement, tracking, better positions for the cameras, better working conditions). Cooperation with other Air Navigation Service Providers was promoted. Study is needed to apply ART on more than one airport at a time and to introduce ART in active control. The PTZ was most preferred for application of ART functions on manned towers. This result is in agreement with findings of the DLR-DFS shadow mode validation experiment as reported in chapters "The Advanced Remote Tower System and Its Validation" and "Remote Tower Research in the United States".

5 Analysis and Recommendations

5.1 Observations

The ART validation programme was executed with live trials in "passive shadow mode". Live trials with a more active role for the air traffic controller were not possible because of time constrains and safety reasons.

The statistical analysis of the responses showed high standard deviations in the answers of the controllers on 100 of the 138 statements that were judged in the questionnaires. Possible explanations for the large standard deviation are insufficient exposure to the scenario needed for testing the hypothesis, not sufficient familiarisation and training, system immaturity or misunderstanding of the questions. Further analysis showed a bias between controllers from Ängelholm and the other controllers. The local controllers from Ängelholm were on average less positive on the ART functions.

5.2 System Maturity

The ART project tested advanced functions with different maturity. The ART functions were not yet mature enough for operational integration. ART was just a step in the evolutionary process to develop optimal remote tower control facilities and procedures. Most of the ART functions needed further development and testing. ART participants were generally positive about the PTZ and presentation of targets and labels. ART participants were somewhat negative about the current resolution of the panorama display, VET and the tracking performance.

5.3 Operational Aspects and Recommendations

The ART operational evaluation by 15 active controllers and 25 subject matter experts revealed valuable operational knowledge about the application of remote tower technology. The experiments showed that the ART level of maturity would, at this time, allow for single aircraft VFR and IFR operations only.

Resolution (1360 × 1024 pixels per camera) and detection capabilities with ART video cameras would need to be improved. Controllers suffered from lack of situation awareness when surveying traffic on the panorama screen. Higher resolution would require extra bandwidth of the data transmission channels. Smart data compression algorithms might be required to fit all data in existing and near future data communication means. This could be more expensive in application.

The optimal positioning of cameras is open for further investigation, mainly in order to keep camera costs low while optimising the camera output.

With the ART functions as tested, performance of remote tower operations was perceived inferior to performance of real manned tower operations. This would be the main subject of investigation during the research and development phase for the next maturity level.

The automatic exposure of the surveillance cameras might lead to wrong controller perception of daylight conditions. A study could be undertaken to find the right automation in this context.

The overlaid geographic or synthetic information should be further explored. Controllers were happy with the option to switch it on or leave it off, but they asked for thinner and/or dashed lines. This might be favourable in combination with higher picture resolutions.

Controllers liked to have weather information projected on the panorama screen but had no other preference for display of wind and runway visual range information on the panorama screen other than a copy of the existing instruments on their desk in the real tower.

Tracking of video objects and fusion of video with radar data are required to perform to high standards as this is giving the controllers confidence in automatic surveillance. Tracking is safety and critical when controllers use it for decision making. High performance tracking is needed for reliable track stability and track identity. In this context, the ART video tracking and data fusion should be improved. When it provides a better surveillance performance, controllers will make more use of it and they will get the benefit of improved detection capability as compared to visual surveillance. Installing cameras for video tracking of targets closer to the runways, taxiways and aprons should be investigated.

The track labels should be designed to automatically de-conflict with other labels or other objects. It will reduce the risk to cover important surveillance information.

To increase capacity in low visibility, the ART Visibility Enhancement Technology (VET) was expected to look through fog. In the few validation occasions of low visibility, controllers wanted more effect and to a greater extent, preferably on all images. The VET was performed, but not to controllers' expectations. The intrinsic noise of video cameras in low light conditions made VET in the current form less useful. Further enhanced trials need to be set up, and other sensors or combination with sensors, like infrared would need to be tested.

The Pan Tilt Zoom (PTZ) camera was the best of class in the ART evaluation. Controllers wanted to have it for real manned towers also, already in its current set-up mode. If supplied with reliable automatic tracking control, it would even be more appreciated. Its feature to project a zoomed in enlarged picture on the panorama screen should get more flexibility in choice of position. The positive judgement regarding the PTZ camera and the requirement for automatic tracking agrees with the findings within the DLR-DFS shadow mode validation trials (with 8 participating active controllers, see chapters "The Advanced Remote Tower System and Its Validation", "Remote Tower Research in the United States").

Working with the integrated ART tools could be improved by further research and development to improve the working conditions. The dimmed lighting conditions (in a dark room environment) and the 9 projectors with continuous noise seemed to make controllers tired in comparison to the real environment. It is also possible that the picture frame update rate of 20 frames per second was visually tiresome. This is supported by the results of video frame rate experiments at DLR, analysing two-alternative decision errors as dependent on frame rate. These experiments indicated a minimum frame rate between 35 and 40 Hz for minimising decision errors under observation of dynamic events (aircraft landing, see chapter "Planning Remote Multi-Airport Control–Design and Evaluation of a Controller-Friendly Assistance System"). The mouse operation as the central operation device for many ART functions should be further optimised. It should not be needed to drag the mouse over a large distance to activate a function on a specific screen.

The ART type of operations could be applied in other areas: in climate unfriendly areas, as contingency for large airports, possibilities to perform remote aerodrome control simultaneously for more than one small airport for a controller and to improve the information provision on airports with only Flight Information Service (AFIS).

Additional to earlier detected cost benefits, ART could widen opening hours of airports and attract more users by providing punctuality in services. Also security can benefit from this technology.

It is recommended to continue to develop the remote tower procedures, to investigate multi-airport operations and to expand on safety and human factor cases, regulations, training and licensing.

It is recommended to investigate the need of visual information quality in relation to sensor data information for control of aerodrome traffic.

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Remote Tower Research in the United States

Vilas Nene

Abstract The United States (U.S.) Federal Aviation Administration (FAA) has been conducting remote tower research since 2006. The focus of this effort has changed multiple times since the inception of the research. As a result, a number of different remote tower concepts were developed and validated to varying degrees. These included the Staffed NextGen Tower concept for all sized airports, the Select Services Concept for non-towered airports, and the Full Services Concept for non-towered airports. In 2013, the direction of the research changed again, and the FAA began to work on a Colorado initiative that envisions the use of their Wide Area Multilateration (WAM) for improving services at the non-towered ski airports in Colorado. Currently, the FAA is also initiating the evaluation of the camera-based concept at Leesburg, Virginia. All these efforts are described in the following sections.

Keywords Aircraft derived data • Automated NextGen tower • Colorado initiative • Decision support tools • Leesburg executive airport • Non-towered airports • Off-nominal events • Remote tower demonstration • Select services concept • SNT configurations • SNT facility • SNT walkthrough • Staffed NextGen tower • Verbal protocol analysis

1 Background

The early remote tower work in the United States (U.S.) began in response to the concept of the Next Generation Air Transportation System (NextGen) developed by the Joint Planning and Development Office (JPDO), which was established in 2003 by the White House to manage the partnerships between the private sector, academia, and government agencies required to realize the NextGen vision. Some high-end estimates by JPDO indicated that the passenger enplanements would more than double, and total aircraft operations would triple by the year 2025 in comparison to the traffic in 2005 (FAA 2006). Historically, any such increases in demand were addressed by constructing new runways and new Air Traffic Control Tower

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(ATCT) facilities across the National Airspace System (NAS). In addition to the projected increases in passenger enplanements and aircraft operations, the Federal Aviation Administration (FAA) was also facing the need for replacing a significant number of aging ATCT facilities that were rapidly approaching the end of their useful life. At the same time, the cost of new tower construction was escalating rapidly, and the requirements for facility construction and refurbishment were exceeding the available budgets.

Therefore, in 2006, the FAA began the development of a concept of NextGen Tower (NT) facilities where airport traffic control services could be provided remotely without the need for constructing a tower on the airport property. Initially, the FAA envisioned two types of NT facilities:

- A Staffed NextGen Tower (SNT), a ground-level facility from where controllers would provide full air traffic management (ATM) services to flights in and out of one or more airports
- An Automated NextGen Tower (ANT), a fully automated ground-level facility that would provide a limited number of basic ATM services without any human participation. The ANT automation systems would use available traffic, surveillance, and weather data to generate appropriate sequences, clearances, and advisories for transmission to the aircraft via synthetic voice and/or data link.

It was envisioned that an SNT would provide services for the presently towered airports, and an ANT would provide services mainly to small non-towered airports and possibly to towered airports during off-peak hours when tower services are terminated. Initially, however, the FAA focused its effort on the development of the SNT concept.

2 Present Use of the Out-the-Window (OTW) View

A tower controller typically uses his/her eyes and ears to maintain situational awareness (SA) of surface operations, arrivals and departures, and operations in the vicinity of the airport. In fact, the FAA requires (FAA 2008a) the Local controllers to visually scan runways to the maximum extent possible and the Ground controllers to assist the Local controllers in visually scanning runways, especially when runways are in close proximity to other movement areas. The controllers also use visual scanning to observe changing weather between manual and automated weather updates, to check for animals, birds, and foreign objects and debris (FOD) on runways and taxiways, and to check for any emergencies on runways such as engine fire, smoking, blown tires, and other hazardous situations. In reduced visibility, however, the OTW view is of limited use; the controllers then supplement the OTW view by soliciting pilot position reports.

Based on the concept developed by the FAA in 2008 (FAA 2008b), air traffic controllers in an SNT facility would not have an out-the-window (OTW) view from a tower cab. They would, therefore, need to obtain all the information they get from the OTW view from some other sources. In the past, there have been several studies to examine controller use of OTW view in controlling traffic (Cardosi and Yost

2001; Pinska and Bourgois 2005). In support of the SNT-related work, the FAA sponsored two investigations of controller activities in the tower to specifically identify the different types of data they get from the OTW view and to understand the potential impact of removing this source of information.

2.1 SNT Walkthrough (FAA 2009)

A team of 12 controllers participated in a walkthrough study conducted by a team of researchers led by George Mason University (GMU) in Fairfax, VA. These controllers had experience in controlling traffic from ATCTs as well as from Terminal Radar Approach Control (TRACON) facilities. These controllers were first presented with the general concept of SNT operations. Then the controllers filled out questionnaires related to the use of specific information that is required to conduct Ground and Local control operations; they also indicated how that information was obtained during three visibility conditions—daytime good visibility, nighttime good visibility, and low visibility. The controllers were then presented with a list of potential off-nominal conditions and were asked to describe how their need for information would change under these conditions.

The controller's responses indicated that the information they need can be grouped into three general categories:

1. Information about aircraft: type, size, capabilities, and related air carrier.
2. Information about aircraft location: location, orientation, distance from other aircraft, and their position in the sequence.
3. Information on constraints in effect: status of runways and taxiways, traffic management initiatives (TMIs) such as ground delays and stops, and flights requiring individual requests for approval (APREQ) from the overlying facility.

The above information enables controllers to predict and/or confirm an aircraft's route, threshold crossing, touchdown point, exit off the runway, and takeoff point; in turn, these predictions help controllers in making tactical control decisions.

Most large airports in the U.S. and abroad, with high complexity and volumes of traffic, use integrated surface surveillance systems consisting of a surface movement radar (SMR), multilateration (MLAT) system, and Automatic Dependent Surveillance-broadcast (ADS-B). Such surveillance provides a two-dimensional (2-D) display of surface operations that controllers use to augment the OTW view. However, at all other towered airports, the controllers exclusively use the OTW view to obtain the SA of surface operations. In the SNT operations, therefore, in the absence of the OTW view, controllers would need to find alternative ways of obtaining the necessary information that they would normally obtain via the OTW view. The SNT walkthrough asked the controllers to provide guidance on the characteristics of any future display that may be useful for this purpose. The controllers thought that an intuitive, immersive, adaptive three-dimensional (3-D) representation of air traffic would be more useful than the current 2-D displays.

2.2 Verbal Protocol Analysis (Boehm-Davis et al. 2010)

In a verbal protocol analysis (VPA), verbal data about cognitive processing are collected and analyzed in an effort to understand how humans perform certain tasks. In support of the SNT concept development, GMU researchers conducted such a VPA to evaluate towered operations. As a part of the VPA, a number of controllers used the ATCT simulator at the Ronald Reagan Washington National Airport (KDCA) in Washington, District of Columbia (D.C.) to control simulated traffic under varying scenarios. The scenarios covered many visibility conditions: daytime good and poor visibility; and Category (CAT) IIIC conditions. The scenarios also covered traffic volumes of 50–85 % of the normal operations. Both the Local and Ground controllers "talked aloud" to provide a verbal protocol while they performed their tasks. A video recorder placed behind the controllers recorded the audio communications, as well as various gestures made by the controllers.

The video tapes were analyzed and every utterance was examined to determine (1) where the specific information was coming from (OTW view, head-down display, or auditory); (2) what information the controllers were looking at (scanning without a specific object in mind; specific object such as runway, gate, weather, etc.); and (3) why they were using the information (monitoring for potential conflict; aircraft compliance with control instructions, and SA).

As expected, the findings from the walkthrough indicate that tower controllers consider direct visual surveillance via the OTW view as an indispensable element of achieving full SA. Consequently, they use displays and other cues only when the OTW view is compromised under poor visibility. Although all controllers tend to use the information for all above purposes, the Local controllers tend to use it more for detecting potential conflicts while the Ground controllers tend to use it more for ensuring compliance.

The controllers like to know, under all visibility conditions, information about aircraft movements on taxiways and about all departing and arriving aircraft. Another common activity observed during the walkthrough was the act of scanning runways and taxiways. Under CAT IIIC simulated conditions, controllers were scanning surveillance displays and looking for speed and altitude information about aircraft. During the high traffic level condition, there were fewer pauses between the control instructions.

As expected, both the Walkthrough and Verbal Protocol studies essentially confirmed the conclusions of the past studies (Cardosi and Yost 2001; Pinska and Bourgois 2005), which is that controllers seek various information elements in order to maintain SA of surface and surrounding traffic; to avoid aircraft-to-aircraft and aircraft-to-airspace conflicts and other potentially hazardous movements; and to monitor and confirm aircraft compliance with control instructions.

3 The Operational Concept for SNT (FAA 2008b)

Tower controllers today depend on visual surveillance via the OTW view; on supplemental information provided by terminal radar, weather sensors, and displays; on flight data provided on the flight strips; and on air–ground verbal communications. At large airports, they also depend on surface surveillance information presented to them on a 2-D display.

The SNT operational concept (FAA 2008b), as a first step, did not include camera surveillance but envisioned providing the information required by the controllers for controlling nominal tower operations with only cooperative surveillance. It was decided to visit at a later date the information needs of tower controllers during off-nominal events such as, for example, aircraft emergencies and aircraft non-conformance. It was felt that possibly some of the responsibility of off-nominal operations may be reassigned to airport personnel, and if necessary, the use of camera surveillance could be added to this concept as the concept matured.

3.1 Assumptions Related to the SNT Concept

The SNT concept was based on the following assumptions:

- There would be a fundamental shift in the roles and responsibilities of the Air Traffic Management (ATM) service provider, aircraft/pilot, and flight operations center personnel. Presently, the service provider has a proportionately much larger influence on ATM decisions. Although the aircraft and the flight operations center share a lot of information between them, they share little information with the service provider. In the future, these three entities would share all the information in a net-centric environment and influence, somewhat equally, the ATM decisions.
- Some form of a cooperative surface surveillance system would be present at the airport. The status of all ground movement of aircraft and other vehicles would be presented on a two-dimensional (2-D) display for ATM personnel. Such a display would also present the necessary weather information.
- All aircraft operating in and out of *large* SNT-serviced airports would be equipped with a transponder. A significant number of aircraft may also carry multifunctional flight deck displays and data link equipment; these aircraft would be capable of providing aircraft-derived data (ADD) requested by the ATM system. However, the SNT concept would continue to accommodate aircraft unequipped with the multifunction display and those that could not provide ADD. Aircraft without a transponder or with a failed transponder would be accommodated at large airports only under emergency conditions.
- A significant majority of aircraft operating in and out of *small* SNT-serviced airports would be expected to be equipped with a transponder; however, the SNT concept would accommodate aircraft without a transponder. This would be

accomplished by having either some form of noncooperative surveillance or visual surveillance using digital cameras or other available technologies.

- Airports would be required to implement perimeter security to minimize runway/taxiway incursion by animals, pedestrians, and other unauthorized vehicles. Airports would also be required to minimize the presence of FOD on runways and taxiways.
- Necessary Decision Support Tools (DSTs) would be available to ATM personnel for minimizing the capacity/demand imbalances, balancing demand loads across runways, implementing traffic management initiatives, and generally improving the airport operational efficiency.
- Airports would be certified for SNT service, aircraft would be certified for operating in and out of SNT-serviced airports, and ATM personnel would be certified for providing services at these airports.
- The envisioned integrated tower display for presenting weather and traffic would be certified for use by ATM personnel for providing separation services in the absence of the view from the cab window.

3.2 Substituting for the Window View

In a remote ground-level SNT facility, there would be no tower cab and no OTW view. Consequently, ATM personnel must be provided with an alternative means of obtaining the information they depend on and get from the OTW view. Some form of cooperative surface surveillance can provide locations and velocities of aircraft and ground vehicles on the apron and movement areas including the runways. Consequently, such surveillance can help the controller to determine aircraft conformance with ATM instructions. However, such surveillance would be of minimal use with aircraft emergencies and with unequipped aircraft. Information on a number of emergencies related to aircraft could be obtained from the aircraft itself; this would require aircraft to be equipped with a form of data link capability, although presumably such information could be sent via voice as well. If a significant population of aircraft could not provide ADD, and if one must accommodate aircraft without a transponder, one would then need to provide some form of noncooperative surveillance or camera surveillance for the terminal area and for the airport surface. However, it was not clear at the time if such cameras could provide sufficient fidelity and update rate for use at airports with high volume and complexity of traffic. Consequently, various options for substituting the window view would have to be examined in detail in laboratory and operational tests before determining an acceptable NextGen Tower configuration.

The concept of such an SNT facility would represent a paradigm shift and would require a fundamental change of the present ATM culture. In addition, changes in policy and procedures would require a partnership between the service provider, aircraft operators, and airport operators. Some roles and responsibilities of the ATC personnel may have to be shifted to airport and/or aircraft operator personnel located at the airport. The level and the extent of such changes would depend on the surveillance infrastructure at the airport, ATM automation system capabilities, capabilities of the aircraft operating in and out of the airport, and the volume and complexity of the traffic at the airport being served.

There are a number of different options for substituting the OTW view. For example, relevant weather could be displayed on the SNT display and the time period between weather updates could be reduced. Also, digital cameras could be used to scan the weather between updates; such cameras are already in use to monitor weather in Alaska. Digital cameras could also be used to scan runways and taxiways or airport authorities could implement sensors for scanning these areas. Although digital cameras did not provide sufficient fidelity and update rates at the time for use at large airports, it was assumed they could be quite suitable for low- and medium-traffic airports. Also, performance of digital cameras was assumed to continue to improve in the future. Another option that was considered for the concept was for the aircraft to provide emergency-related aircraft status information to SNT automation. Such ADD may assist controllers in identifying emergencies on runways and taxiways; however, it was assumed that not all aircraft would be equipped to provide ADD. Also, some aircraft might not have onboard sensors to detect certain events such as wheel assembly fire and tire blowout; therefore, certain responsibility for handling emergencies would possibly have to be shared between service provider and airport/aircraft operators.

Clearly, all the above options for substituting OTW view would have to be validated by rigorous safety analysis and extended laboratory and operational trials; only then could these options be considered feasible.

3.3 2-D Surveillance Display for the Controllers

The proposed SNT concept envisioned the use of a large 2-D display that would present surveillance information (surface and surrounding airspace) and weather information integrated together in appropriate formats. Surveillance may consist of noncooperative surveillance such as radar, inductive loops, and magnetometers; cooperative surveillance such as radar, MLAT, and ADS-B; and/or, if necessary, camera surveillance with or without image enhancement. The proposed concept did not specify or require any specific elements of surveillance. Controllers presently use 2-D displays and the altitude/speed information to create in their minds a 3-D picture of the airspace and the traffic within it. Such a mental 3-D picture is critical in maintaining the full SA required for controlling traffic. Researchers have long felt that the controllers may be able to avoid these mental computations if the traffic is presented to them in some form of a 3-D display. A number of 3-D and four-dimensional (4-D) presentations have been developed and examined by researchers around the world (Nene 2007). A virtual tower cab mimicking an OTW view has also been developed (Nene 2007). These studies have shown that these technologies must address several technical issues before these ideas can be tested in field trials.

Also, it is difficult to tell if these types of displays will be deemed acceptable within the present controller community. Consequently, this SNT concept was based on the conventional 2-D display.

3.4 Decision Support Tools

Increasing airport capacity and efficient arrival/departure management were two important elements within the SNT concept. It was envisioned that ATM personnel would use different DST capabilities in achieving these two goals. Clearly, the list of these capabilities would evolve as the SNT technology evolved. Some candidate SNT DST capabilities were defined for, but not limited to, providing support for the following activities:

- Deciding the most efficient airport configuration for a given set of traffic and weather patterns
- Early planning of runway/taxiway assignments based on projected runway loading, surface congestion, user runway and gate preferences, and other relevant factors
- Arrival and departure management for accommodating all traffic management constraints resulting from anticipated weather conditions and resource loading
- Providing information about airport weather conditions, runway visual range, surface conditions, braking action, current precipitation, runway availability, wake turbulence, and wind shear advisories to the aircraft via data link
- Providing predeparture clearances, taxi clearances, and any revisions to clearances to the aircraft via data link
- Providing a coded taxi route to the aircraft via data link
- Monitoring aircraft conformance with ATM instructions and appropriately alerting aircraft and ATM personnel
- Updating flight trajectories based on rerouting, ground holding, and other TMIs
- Generally, creating a common situational awareness between ATM personnel, ramp personnel, airport operators, and flight operations personnel should greatly improve the efficiency of all surface operations including deicing operations.

Some of the functionality provided by automation within the SNT concept would be more effective if it could receive ADD from the aircraft. If, however, some aircraft were not equipped to provide ADD, it would reduce the performance of the tools, and such aircraft may not receive services in full. The reduction in the performance of the tools would depend on the proportion of the unequipped aircraft, and in turn would reduce the overall throughput and efficiency of airport operations. The effectiveness of these DSTs would clearly depend on the quality and accuracy of the data used by the DSTs. If DST inputs exhibit large variability, the controllers may find these tools unreliable and unusable. Consequently, the tools themselves would need extensive validation before their implementation within NextGen tower automation systems.

3.5 Use of Aircraft Derived Data

It has been mentioned earlier that aircraft can provide some of the data that controllers presently obtain from visual surveillance. It was expected that in the future, the aircraft could provide an extensive amount of data that would improve the overall performance of the ATM system at the NAS level. Any available media of transmission could be used for such data transfer. A number of candidate data items for such data transfer had been identified at the time. These included, among others: aircraft identification (ID), route in the onboard flight management system (FMS), taxi route, aircraft braking performance, distance required for landing, and information on aircraft emergencies if applicable. It may not be necessary to obtain all of this information directly from the aircraft; some may be obtained from flight operations center handling the aircraft operations. Furthermore, it was assumed that this list would have evolved as the SNT technology matured over the coming years.

It must be noted here that the ADD technology would be useful well beyond its use in remote towers. However, presently there are no common formatting or communications standards for providing ADD to the ground ATM system, and existing air–ground communications links may have to address bandwidth issues for such use. Consequently, if the use of ADD is envisioned going forward, the FAA may have to develop some commonly acceptable frameworks for its distribution and use by future ATM systems.

3.6 SNT Configurations

US airports exhibit a large variability in volume and complexity of traffic. As an example, in 2009, the peak hourly traffic varied from a high of 216 operations at Hartsfield-Jackson Atlanta International Airport, Georgia (KATL), to a low of 15 operations at Branson Airport, Missouri (KBBG) (Nene 2009). It would, therefore, be necessary to tailor the SNT configuration to fit the operational needs of the airport. The SNT concept proposed the following three configurations:

a. Display-only Configuration

   The display-only configuration would be suitable for implementation at small airports with low volume and complexity of traffic. An aircraft unequipped with a transponder would not be detected by cooperative surveillance. Consequently, either a mandate would be required for all aircraft to carry a transponder or some form of noncooperative surveillance or visual surveillance by digital camera (s) would need to be implemented at these airports for accommodating unequipped aircraft. It was envisioned that this configuration may also be useful in providing tower-like services at presently non-towered airports (NTAs) or in continuing tower services at towered airports when the tower facility is not in use.

b. Display + DST Configuration
   This configuration would be similar to the display-only configuration, except that the automation system would provide some limited DST capability. The DST capability could include, for example, early runway/taxiway assignments, predeparture clearance, and coded taxi route delivery. This configuration was assumed to be mostly applicable to medium-sized airports.
c. Display + DST + ADD Configuration
   This configuration would include a surface surveillance display, a variety of DST capabilities, and the availability of ADD. Clearly, this configuration would be considered for implementation only at large airports with high volume and complexity of traffic. Although aircraft will not be required to carry ADS-B equipage, all aircraft operating in and out of these candidate airports would be expected to carry ADS-B-Out avionics; some aircraft may also carry ADS-B-In avionics. The airports would also have some form of noncooperative surveillance for accommodating aircraft experiencing equipment failure.

4 Summary of the SNT Concept

The SNT concept was developed for a range of airports. It was envisioned to support all ATC functions presently performed by tower personnel under nominal operations. Table 1 describes how various functions are currently performed by different tower personnel and how they would be performed in an SNT facility.

5 Assessment of the SNT Concept

The SNT concept was the first attempt to comprehensively understand potential remote control of airport operations without the benefit of an OTW view from the tower cab. It also attempted to provide all tower services without the use of a digital camera, exclusively depending on the use of cooperative surveillance on the airport surface. In addition, the concept required that either all ground vehicles operating on the movement area and all aircraft operating in and out of the airport would be required to carry a transponder or noncooperative surveillance would be implemented at the airport. Furthermore, the concept was envisioned to be applicable for all sizes of airports.

There were clearly a number of issues that needed to be addressed before the concept could proceed toward implementation, such as:

- Would the concept be able to handle off-nominal operations such as, for example, engine fire during takeoff and unauthorized person or vehicle on the runway?
- Would the concept assure operational safety?

Table 1 Differences between present tower operations and SNT operations

Tower personnel	Functions that would be different	Present tower operation	SNT operations
Flight data controller	Weather sensing	• Automated weather updates with the use of variety of sensors are available at many airports • Controllers visually monitor changing weather between automatic updates	• Weather information would have to be updated at a faster rate than the present rate • Use of a digital camera may also be an option
Ground controller	• Push back into movement area • Taxi instruction	• SA is achieved mainly by visual surveillance via the OTW view • Limited SA is possible via ground surveillance systems if it covers the necessary gate areas and all taxiways and runways	• SA would be mainly via secondary surveillance that will cover the necessary gate areas and all taxiways and runways • Either all ground vehicles operating on the movement area would be required to carry a transponder or primary surveillance would be provided
Local controller	• Take-off clearance • Runway obstruction alerts • Separation assurance	• SA based primarily on visual surveillance via OTW view • At some airports, a surface surveillance system is available for supplemental SA • The surveillance system detects a limited class of runway obstructions and provides appropriate alarms • Automated alerts are issued to cover a limited number of potential runway incursion scenarios	• Secondary surveillance would be available at the airport to cover all runways • Primary surveillance would be provided to accommodate unequipped aircraft • Automated alerting would be available at large airports
Traffic management coordinator (TMC) or tower supervisor (TS)	Traffic flow synchronization	• Surface congestion and gridlock conditions are noticeable via the OTW view and surveillance display if available • Flight plans, radar data, and applicable TMIs are available to TMCs and TSs	• Surface congestion and gridlock would be noticeable on the surveillance display • Flight plan, radar data, and applicable TMIs would be available to SNT personnel • DSTs would be available at some airports that would assist TMCs/TSs in implementing the TMIs

- Would the controllers accept the absence of both the OTW view and visual surveillance by a camera?
- If camera surveillance was found to be necessary, what images should be presented to the controllers and how?
- Would the passengers accept remote control of traffic in and out of large airports?

In an effort to examine some of the above issues, the FAA conducted a number of studies aimed at answering the following questions: how would controllers remotely respond to off-nominal events at the airport, what are the safety impacts of SNT operations, and what are the different ways to effectively present camera images to the controllers. These studies and related results are presented in the following sections.

5.1 Off-Nominal Events in SNT Operations (Nene 2009)

ATCT controllers must be able to respond to a number of off-nominal events such as, for example, aircraft non-conformance, failure of aircraft systems, and failure of ATC systems. Under present tower operations, controllers depend on the OTW view in responding to these off-nominal events. A number of off-nominal events typically occurring at airports were first identified (Nene 2009) and possible ways in which an SNT controller would respond to these events in the absence of the OTW view were examined. The results of this study are summarized in Table 2. The study indicated that SNT controllers would be able to use available surface and terminal surveillance to detect and respond to a number of off-nominal events occurring at the airport, even without the presence of the OTW view. Under certain scenarios, it was assumed that visual surveillance with a pan-tilt-zoom (PTZ) camera would be useful although not required because of the availability of alternate means in dealing with the off-nominal events. However, there still would be a number of off-nominal events such as aircraft system failures, emergencies or accidents on the airport surface, and unauthorized presence on the airport surface of person or vehicle, especially with nefarious intent, that controllers would not be able to respond effectively without camera surveillance. As a result, this study concluded that if SNT has to provide all the functionality of the present towers, visual surveillance by digital camera(s) would be necessary.

5.2 SNT Safety Impact Assessment (Colavito and Nene 2010; Cheng et al. 2010)

As a part of an overall effort to validate the SNT concept, a preliminary safety impact assessment of SNT operation was conducted (Colavito and Nene 2010).

Table 2 Response to off-nominal events in the SNT environment (Nene 2009)

		Role of camera surveillance in the response of SNT controller		
Number	Event	Not required	Would be useful but alternatives available	Required
1	Aircraft non-conformance		Monitor via surveillance display with or without automated taxi conformance monitoring and alerting; initiate appropriate action to remedy the situation	
2	Aircraft altitude falls below the minimum safe value		Controller would use radar position in relation to known terrain or obstruction to validate alerts issued by the automation system	
3	Potential collision between aircraft under tower control		• Automation system would issue conflict alert based on terminal area and surface surveillance information • Traffic and Collision Avoidance System (TCAS) would also alert the flight crew	
4	Aircraft in-flight system failure			Controller must use pan-tilt-zoom (PTZ) camera to observe and confirm aircraft problems with landing gear or flap control
5	Aircraft configuration problems such as a non-extended landing gear			Controller must use PTZ camera to observe and confirm aircraft problems with landing gear
6	Emergency during takeoff			Controller must use PTZ camera to monitor and confirm emergency

(continued)

Table 2 (continued)

		Role of camera surveillance in the response of SNT controller		
Number	Event	Not required	Would be useful but alternatives available	Required
7	Aircraft accident on the surface			Since surface surveillance cannot detect all accidents, controllers must use PTZ camera to detect and confirm accident on the surface
8	Aircraft accident within the vicinity of the airport		Controllers may use radar surveillance, reports by other pilots, and reports by airport personnel to know of the accident and initiate necessary response	
9	Primary surface surveillance radar out of service			Although cooperative surface surveillance and terminal radar would continue their coverage, detecting noncooperative targets, possibly with nefarious intent, would require the use of PTZ camera
10	Unauthorized person or vehicle on the airport surface			Detecting an unauthorized person would require the use of a PTZ camera
11	There is a need to move an aircraft on the ground to a designated area	Controllers can use surface surveillance display to relocate aircraft due to bomb threats, hazardous cargo, or any other reason		
12	There is a need to expedite the landing of an aircraft	Controllers can use surface surveillance and terminal surveillance displays to expedite any landing		

This was not a full-fledged operational safety assessment of SNT operations as defined by the FAA's Safety Management System process that would be necessary as part of a formal acquisition program for an SNT facility.

In support of the safety impact assessment, a formal functional analysis of SNT operations was performed (Cheng et al. 2010). A number of specific functions were first identified as being necessary to be able to provide SNT services. These functions were then decomposed into subfunctions and were organized into a hierarchy of functions. At every level, functional flow diagrams and N^2 interface diagrams were then developed for the SNT functions; the N^2 diagrams were drawn to identify and represent all the functional interfaces within the system. The 11 first level functions and the related flow diagram are presented in Fig. 1. The first level N^2 diagram is illustrated in Fig. 2. The functional analysis did not address the allocation of functions to the physical elements of the SNT system.

The functional analysis formed the basis of the safety impact analysis. Each function was evaluated in the present tower environment and in the proposed SNT environment. Potential safety impacts of the difference between the two environments were then identified. The SNT functions that were determined to have a negative safety impact from the loss of the OTW view are presented in Table 3.

A Massachusetts Institute of Technology (MIT) Lincoln Laboratory study (Grappel 2009) also identified specific hazards associated with the use of surveillance radars, for example:

- Missing data—no surveillance data is provided for a real target
- Erroneous data—partly or fully incorrect or inaccurate data is provided for a real target
- False data—data is presented on the controller display that does not correspond to any real target on the airport.

These fundamental issues are also present for terminal radar coverage for the conventional tower operations. However, the surface surveillance radars add to the safety risk in SNT operations; camera surveillance may not be able to sufficiently mitigate these risks.

5.3 Use of Digital Camera for Surface Surveillance (Grappel 2009; FAA 2011a)

The functional hazard analysis of SNT operations suggested that some form of digital camera surveillance may be required if an SNT facility were to provide all tower services to an airport.

Any SNT concept would require a surface surveillance display for the controller to obtain the necessary SA for controlling the surface operations. With added camera surveillance, the SNT concept was in need of updates to address the following issues:

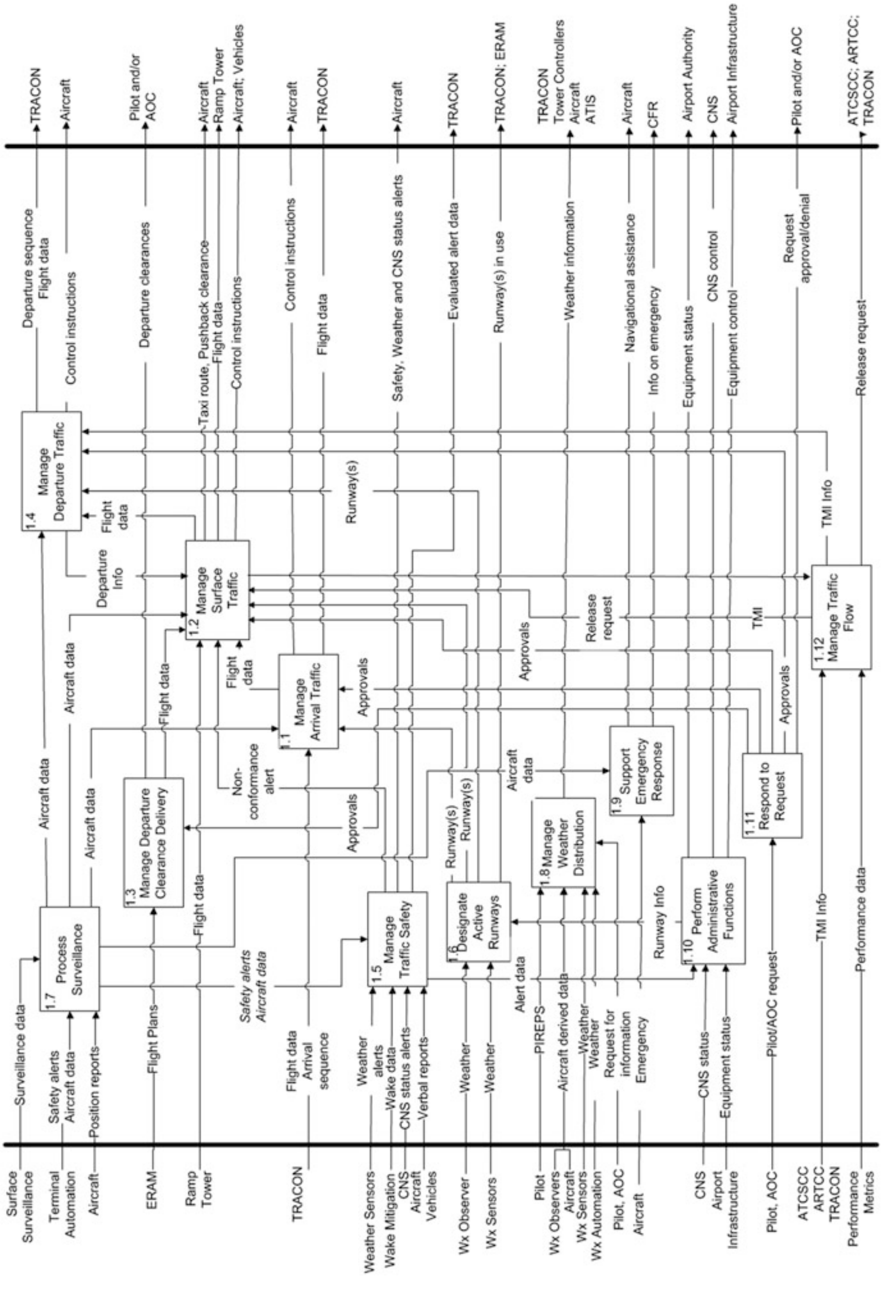
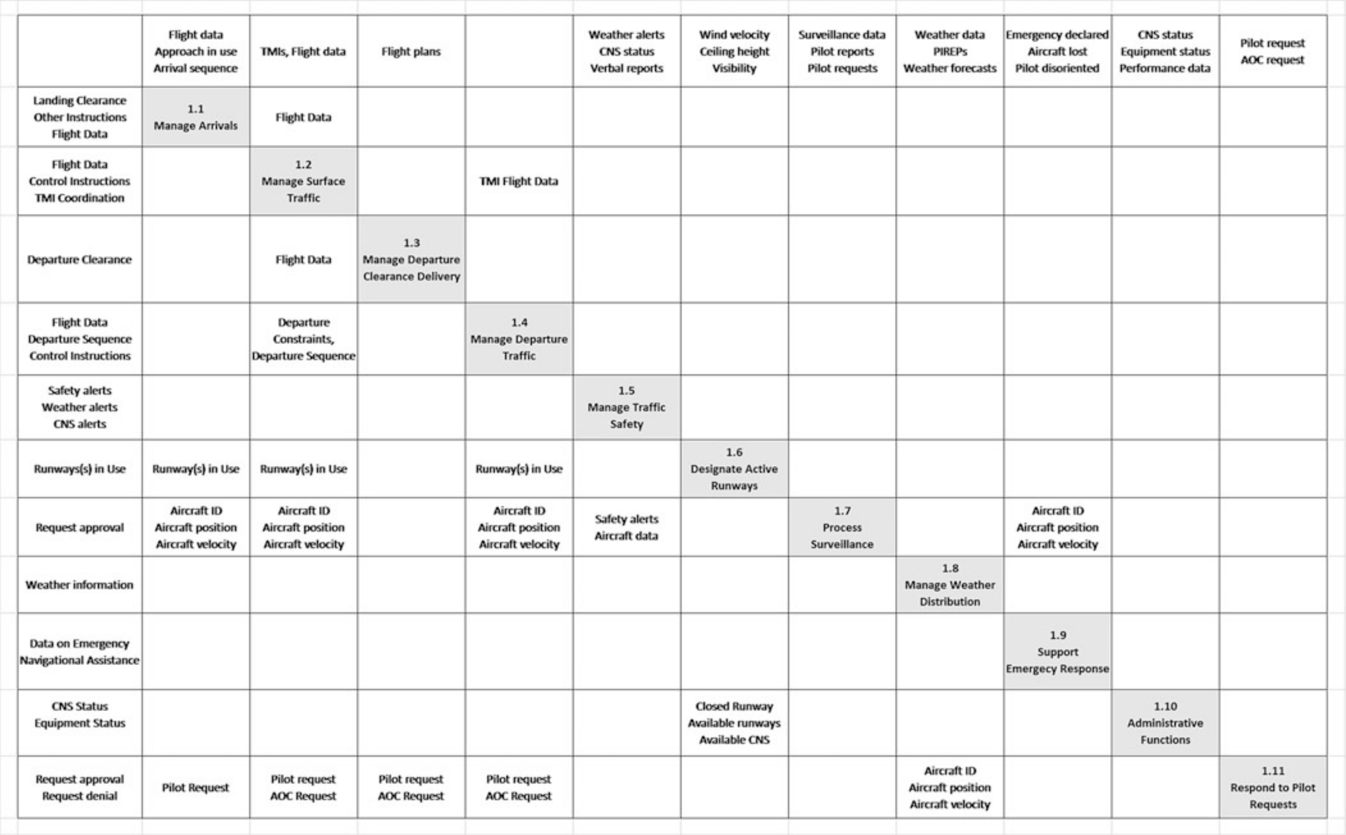


Fig. 1 First level functional block diagram of SNT operations (Cheng and Nene 2009)



	Flight data Approach in use Arrival sequence	TMIs, Flight data	Flight plans		Weather alerts CNS status Verbal reports	Wind velocity Ceiling height Visibility	Surveillance data Pilot reports Pilot requests	Weather data PIREPs Weather forecasts	Emergency declared Aircraft lost Pilot disoriented	CNS status Equipment status Performance data	Pilot request AOC request
Landing Clearance Other Instructions Flight Data	1.1 Manage Arrivals	Flight Data									
Flight Data Control Instructions TMI Coordination		1.2 Manage Surface Traffic		TMI Flight Data							
Departure Clearance		Flight Data	1.3 Manage Departure Clearance Delivery								
Flight Data Departure Sequence Control Instructions		Departure Constraints, Departure Sequence		1.4 Manage Departure Traffic							
Safety alerts Weather alerts CNS alerts					1.5 Manage Traffic Safety						
Runways(s) in Use	Runway(s) in Use	Runway(s) in Use		Runway(s) in Use		1.6 Designate Active Runways					
Request approval	Aircraft ID Aircraft position Aircraft velocity	Aircraft ID Aircraft position Aircraft velocity		Aircraft ID Aircraft position Aircraft velocity	Safety alerts Aircraft data		1.7 Process Surveillance		Aircraft ID Aircraft position Aircraft velocity		
Weather information								1.8 Manage Weather Distribution			
Data on Emergency Navigational Assistance									1.9 Support Emergecy Response		
CNS Status Equipment Status						Closed Runway Available runways Available CNS				1.10 Administrative Functions	
Request approval Request denial	Pilot Request	Pilot request AOC Request	Pilot request AOC Request	Pilot request AOC Request				Aircraft ID Aircraft position Aircraft velocity			1.11 Respond to Pilot Requests

Fig. 2 First level N^2 diagram (Cheng and Nene 2009)

Table 3 SNT functions with negative safety impact (Cheng et al. 2010)

Function	Conventional tower operation	SNT operation	Negative safety impact
Monitoring surface condition (e.g., braking, FOD, Snow)	Controllers fully rely on the visual surveillance via OTW view	Controllers would depend on third party surveillance such as by aircraft personnel and pilots	The loss of OTW view significantly would reduce SA related to surface condition. Controllers may not be able to make a safe judgment on airport surface conditions with the use of camera surveillance
Verifying system safety and non-conformance alerts	Controllers use OTW view to verify potential conflict or other hazardous conditions when the automation system issues such an alert. If verified, controller alerts the pilot	Controllers would depend on the 2-D surface surveillance display and any available camera images to verify the automation alerts	Controllers may not be able to verify all alerts with the use of the display and camera images. The controllers may have to issue unverified alerts that may eventually turn out to be false. The pilots may lose confidence in alerts and may tend to ignore them, potentially compromising safety
Scanning for emergencies	Controllers use OTW view to scan for emergencies on the surface and in the surrounding airspace	Controllers would depend on camera surveillance and third party reports	Controllers would not be able to scan for a number of emergencies such as, for example, aircraft system malfunction

- How should the camera images be presented to the controllers?
- How should the camera images be integrated with the surveillance display?

Consequently, possible alternate ways of presenting camera images to controllers were examined with the help of human-in-the-loop (HITL) tests in the laboratory and shadow-operation field tests.

5.3.1 Camera Integration CHI Evaluation (Grappel 2009)

In order to begin to address the camera-related issues noted in the section above, a study was conducted at the NextGen Integration and Evaluation Capability (NIEC) laboratory located at the FAA's William J. Hughes Technical Center (WJHTC), Atlantic City, New Jersey (Grappel 2009). This part-task simulation had a limited scope: evaluation of the computer human interface (CHI) for the display systems, evaluation of a concept for integrating cameras and other surveillance and related displays, and evaluation of the use of SNT displays for responding to off-nominal events.

There are essentially three basic approaches to displaying camera images:

- A separate monitor to display a local image of a fixed or a pan-tilt-zoom (PTZ) camera
- A picture-in-picture (PIP) display of camera image(s) on the surface surveillance display
- A panoramic display of surface operations by using a number of cameras to cover the entire airport surface

The part task simulation examined the first two approaches.

The tests were based on a simulation of the East Tower operations at the Dallas-Fort Worth International Airport (KDFW or DFW). The SNT supplemental configuration was used meaning that the controllers used the SNT displays in addition to the OTW view. An electronic flight strip (EFS) capability was included in the simulation although DFW presently does not use this capability; an EFS capability was expected to be introduced at the large US airports before any SNT implementation.

DFW airport is divided into the East and the West sides. The traffic on these two sides is independently controlled from two separate control towers. An older Center Tower is presently not in use; it is currently used as a back-up facility. A number of controllers were asked to control simulated East side traffic using nine 15-min scenarios with moderate traffic levels. Both daytime and nighttime operations under Visual Flight Rules (VFR) were simulated. All scenarios contained one off-nominal event from the scripted events listed in Table 4. The basic surveillance display used

Table 4 List of off-nominal events (FAA 2011a)

ID	Off-nominal description
1	Aircraft initiates missed approach/go around
2	Aircraft deviates from taxi route
3	Aircraft takes wrong heading after takeoff (Flight Management System [FMS] programmed incorrectly)
4	Aircraft side-steps to alternate parallel runway during final approach without clearance
5	Aircraft rejects takeoff
6	Aircraft fails to continue to climb after wheels up, continues on a runway heading at a low altitude
7	Aircraft initiates takeoff roll after clearance to taxi and hold
8	Aircraft fails to hold short of active runway crossing
9	Aircraft crashes on airport and on taxiway(s) or runways(s)
10	Controller issues go-around. Vehicle entering movement area w/o clearance
11	Aircraft altitude falls below the minimum safe value
12	Aircraft taxis to the end of runway after rollout
13	Smoke coming from aircraft/brakes during landing or takeoff

Fig. 3 Controller basic surveillance display (*Source*: MIT-LL)

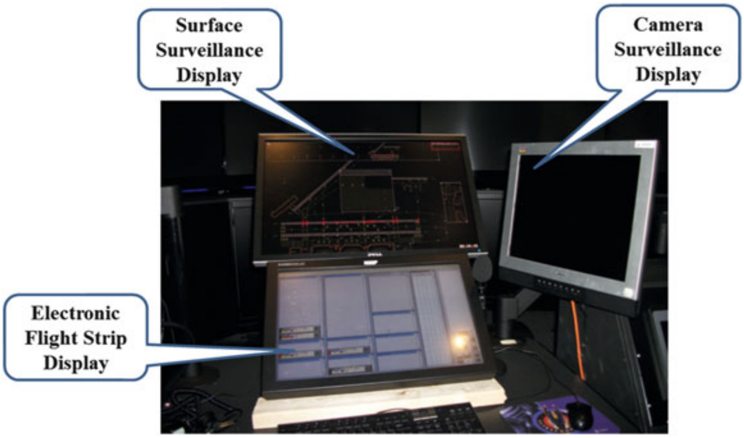


Fig. 4 Controller display configuration 1 (*Source*: MIT-LL)

by the controllers is illustrated in Fig. 3; the controllers also used an EFS display and a camera display. The two display configurations are illustrated in Figs. 4 and 5.

At the end of each scenario, the controllers rated different displays for their effectiveness in helping controllers maintain SA, as well as efficient and safe operations. In general, the controllers gave poor ratings for the use of all camera images—stand-alone, PIP, and PIP + stand-alone. They also did not believe that the

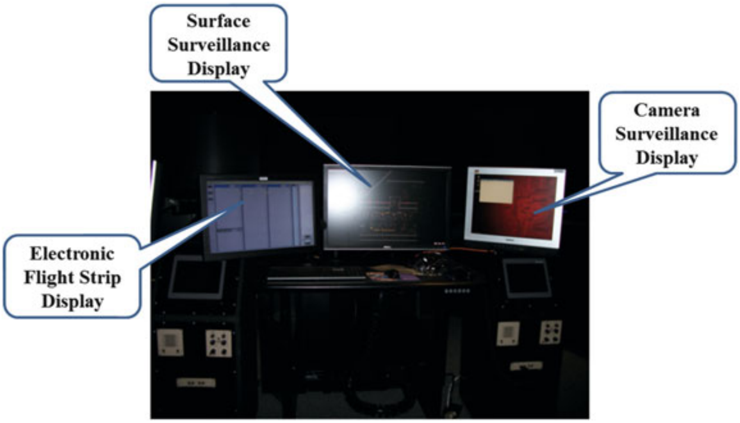


Fig. 5 Controller display configuration 2 (*Source*: MIT-LL)

camera surveillance in the current configurations helped them in detecting runway incursion events.

5.3.2 Field Demonstration at DFW

Shadow-operation tests were conducted at the DFW Center Tower during a few days in the spring of 2011 to provide a proof of concept for the supplemental SNT configuration. A number of controllers participated in the shadow operation tests during normal DFW East side operations. The display suite used by the controllers is illustrated in Fig. 6. The display suite included a typical ASDE-X display, a terminal radar display, an EFS display, an SNT surface surveillance display, a camera display, and a communications panel.

The surveillance display was similar to the one shown earlier in Fig. 3. The controllers were also able to use a PIP window to display a selected camera view. The separate camera display was divided into three images as illustrated in Fig. 7. The top half presented a panoramic view of approximately 180° of the east side of DFW as seen from the Center Tower by stitching individual images from four fixed zoom cameras into a single picture (FAA 2011b); the controllers were not able to change the presented image. The bottom half presented two different views. The left half presented a fixed view of the departure thresholds of the main parallel runways; the right half presented a view from the PTZ camera under the control of Local and Ground controllers. The PTZ image could also be shown on the surveillance display in a PIP window. It must be noted that the camera placement was not optimum and simply used available options for mounting the camera on the tower.

Each controller evaluated alternate ways of using the camera images. As with the part-task evaluation conducted at the WJHTC's NIEC laboratory, the controllers during this shadow-operations test did not see the potential for the use of

Fig. 6 DFW-2 controller workstation (*Source*: MIT-LL)

Fig. 7 DFW-2 camera images (*source*: MIT-LL)

camera for the SNT supplemental configuration. The study concluded that controller opinions were the result of, at least in part, technical problems such as an unresponsive interface, poor performance of camera control, lack of sufficient display resolution, and the inability to track targets during windy conditions.

6 Some Observations Related to the SNT Concept

A number of observations can be made with reference to the SNT concept and related HITL tests:

- The concept was very ambitious to envision its application to all sized airports, including large airports
- Although it would be theoretically possible to control multiple airports from a single remote facility, it would not be feasible in the U.S. for the foreseeable future.
- Since the concept focused on large airports that were likely to have surface surveillance, the concept initially focused more on DSTs, the use of ADD, and surface surveillance and less on the use of cameras to provide panoramic view on multiple monitors
- The display of camera images during tests was not optimal
- Due to the dependence on surface surveillance, the testing was done with operational scenarios related to a large airport (i.e., DFW)
- The tests resulted in lack of controller support and acceptance of camera images for the supplemental SNT configuration

7 Change in Focus of the FAA's Remote Tower Research

At the end of the SNT tests and evaluation described above, it was becoming increasingly clear that full remote control of towered airports, especially of the large airports, may not be possible in the U.S. for the foreseeable future. Surface surveillance technology that can be certified for separation does not exist today, and there are presently no plans to develop and implement such a technology across the NAS. Controllers that participated in the studies mentioned above also did not see significant use for cameras as a part of a supplemental SNT configuration; the use of cameras in the absence of the OTW view was not a part of any SNT-related HITL. Furthermore, the controller community in the U.S. did not support any concept for remote control of presently towered airports (http://natca.org/natca_insider.aspx?zone=NATCA-Insider&nID=4737). Therefore, given these challenges and perhaps others, the FAA changed the direction of its remote tower research and focused it on improving the services at the presently NTAs. It was thought that the remote tower technology could address some of the operational shortfalls at the NTAs, and since these NTAs do not presently receive tower services, remotely improving services may be acceptable to the ATC community. As a first step in this effort, present NTA operations were analyzed for defining the need, if any, for improving services provided to these airports.

7.1 Current Operations at NTAs

NTAs predominantly serve unscheduled VFR traffic, although some of them also serve scheduled IFR traffic. The VFR traffic in and out of these airports is uncontrolled and cooperatively organizes itself to maintain safety. The pilots are jointly responsible for collision avoidance, sequencing, and following local procedures. Separation services are provided by controllers only to the IFR traffic; these are provided from the overlaying Air Route Traffic Control Center (ARTCC) or TRACON facility. IFR pilots are still responsible for safely merging with VFR flights operating in and around the airport.

The surrounding airspace is normally below 2500 ft. Above Ground Level (AGL) and within approximately a 5-mile radius from the airport center. Each pilot gathers information about nearby aircraft operations primarily by looking out the cockpit window. Pilots also listen to traffic advisories and airport information that may be provided over the radio by other participating pilots or a ground station, if present. Due to the complexity of operations, right-of-way rules, traffic patterns, and other procedures exist at NTAs primarily to prevent collisions in the air and on the ground.

VFR traffic is not required to participate with ATC at these airports, and as a result, adequate ATC radio coverage is often not available at many NTAs. Some airports, however, do provide some auxiliary channels to fill the communications gap. When available, TRACON or ARTCC personnel use a designated ATC frequency to communicate with IFR pilots at some airports for the purpose of clearance delivery. But at airports where surface radio coverage is not available, IFR pilots typically contact ATC personnel using various telephone media. Surveillance at NTAs varies widely and in many cases does not exist at lower altitudes or on the surface.

Airport advisories are typically broadcast for pilots via the common traffic advisory frequency (CTAF). The CTAF is normally the frequency for a Universal Integrated Community (UNICOM), MULTICOM, or Flight Service Station (FSS); it could also be the tower frequency, when used at times outside of the tower's hours of operation. The advisories include airport information, weather information, wind direction, or upon pilot request, the recommended runway or current runway in use, when known.

NTAs typically feature a mix of air traffic types, including general aviation (GA), helicopter, air carrier, air taxi, and military. Nonstandard flight operations, such as ultra-light, parachute, balloon, and lighter-than-air, are also common. Aircraft performance can vary significantly among traffic types at these airports. Air carrier and air taxi operators typically operate large, heavy, and fast aircraft. In contrast, a large portion of GA traffic consists of light, single-engine piston aircraft that move at low speeds. Equipage levels also differ, as some aircraft are radio and transponder equipped, while others do not even have an electrical system and therefore lack such equipment. Furthermore, pilot experience and skill level differ between professionals conducting passenger services, amateurs flying as a hobby, and students at a flight school.

Aircraft that operate in the controlled airspace beyond the NTA commonly receive ATC services from the ARTCC or TRACON controller associated with the non-towered airport. In controlled airspace, controllers communicate with the pilots on a designated radio frequency separated from the CTAF. Once in controlled airspace, VFR flights typically contact ATC to receive updates on traffic or weather information or request VFR flight following services. These services are simple compared to those requested by IFR flights, which require ATC clearance prior to departing or approaching the NTA. Controllers provide departure and approach services using one-in one-out procedures in order to ensure separation between IFR flights. The difference between VFR and IFR operations at NTAs is summarized as follows:

a. *VFR Operations at an NTA*: The VFR traffic is not required to communicate with ATC and essentially organizes itself by following the right-of-way rules mentioned earlier. The pilots obtain their SA of the traffic around them via visual observations and CTAF communications.
b. *IFR Departures from an NTA*: The FAA requires IFR flights to file a flight plan in order to operate at NTAs. Prior to take off, IFR departures require a departure clearance from ATC. If the clearance is not immediate, ATC will then issue a departure release time and a clearance void time. The clearance is voided if the aircraft is not airborne by the specified void time, and the pilot must then request a new clearance from ATC. If there are radio coverage gaps at the airport, pilots typically call ATC via telephone or coordinate through the FSS via CTAF if available. Prior to departure, the pilot typically tunes the radio to the CTAF and therefore is unable to communicate further with ATC until clear of the traffic pattern.
c. *IFR Arrivals to an NTA*: Pilots of IFR arrivals that are approaching an NTA but that are still in controlled airspace are in communication with ATC, and in turn, ATC monitors the position of the aircraft via available surveillance and provides instructions along the arrival procedure. Typically, prior to reaching the boundary of the controlled airspace, ATC clears the flight for approach and releases it to the CTAF. The ATC terminates radio communication with the pilot, and the pilot lands the aircraft following the right-of-way rules described earlier. The pilot then contacts ATC and cancels the IFR flight plan. Alternately, if the pilot executes a missed approach, he/she climbs to an altitude when communication with ATC is possible and reports the missed approach. ATC then directs the pilot to either repeat the approach procedure, hold, or divert to an alternate airport. When operating in Visual Meteorological Condition (VMC), the pilot has the option to terminate ATC services by canceling the IFR flight plan and operating the remainder of the flight by following the procedures described earlier; the pilots often choose this option if continuing with the IFR flight plan would result in unacceptable delays.

7.2 Present Shortfalls in NTA Operations (Colavito et al. 2013)

A number of NTAs have sizable IFR operations. Some ski airports in Colorado, for example, have high levels of peak hourly IFR traffic during the ski season. The traffic in and out of these airports is also predominantly unscheduled and, as a result, there is large variability in the hourly demand for arrivals and departures. In view of these operational characteristics, the NTAs exhibit a number of operational shortfalls. The restrictive one-in one-out operations severely limit the IFR capacity resulting in significant holding and vectoring around the airport and ground delays. The combination of unscheduled demand and low IFR capacity also introduces inefficiency in operations. Delays and inefficiency, in turn, result in excessive operating costs, increased fuel consumption, and increased emissions. Decentralized self-coordination of traffic, traffic complexity, and other factors also lead to flaws in SA of pilots, resulting in heightened safety concerns at these airports.

7.3 Concept for Remotely Providing Selected NTA Services

There are two possible approaches to remotely improving ATC services provided to the NTA airports. One is to provide all services presently provided at a towered airport. Another approach is to provide only a set of select services and establish an operational environment somewhere between an uncontrolled NTA and a fully controlled towered airport. A concept for providing a select set of services, referred to as the Select Services Concept, has been developed as part of the FAA's NextGen research efforts and is presented in this section.

7.3.1 An Overview of the Select Services Concept (Nene et al. 2013a)

Under the Select Services Concept, ATC would organize both the IFR and VFR aircraft to and from the NTA airport, sequence the IFR aircraft closer together than when using the classical one-in one-out operations, and maintain safe separation on the airport runways. ATC would not provide the control of aircraft/vehicle movement on taxiways.

The proposed concept leverages three foundational air traffic control principles in use throughout the NAS today: an established area of ATC jurisdiction, use of surveillance information to monitor and separate traffic, and instantaneous two-way radio communication between controller and pilots. Under the concept, controllers would use surveillance data to determine position information of aircraft in the airspace immediately surrounding the airport and of aircraft and vehicles on key airport surface areas. Controllers would use the surveillance data just as they do today to provide separation between airborne IFR aircraft and to provide traffic information to IFR and VFR pilots operating near the airport. In addition, controllers would use surface surveillance information to improve SA of operations on or near the runways. Although surface surveillance would depict aircraft on the surface, controllers would use two-way radio communications to obtain pilot position reports regarding key surface information such as *clear of the runway* upon runway exit or *holding short of the runway* when approaching a runway.

The operational environment under this concept is compared with the non-towered and towered environment in Table 5.

Table 5 Operating environment for the proposed select services concept (Nene et al. 2013a)

Item	Current non-towered operations	Proposed select services concept	Current towered operations
Surface movement	ATC does not control surface movements on taxiways and parking/apron areas. Controllers do not issue taxi instructions. Pilots use taxiways and runways at their discretion	ATC would not issue taxi instructions; they would instruct pilots to report holding short of the assigned runway and report clear of active runways	ATC issues taxi instructions to pilots; they observe surface movements and that aircraft are holding short and are clear of the runway
Control of airspace surrounding the airport	ATC separates IFR aircraft from other IFR aircraft. IFR and VFR aircraft self-organize in the airspace and in the VFR traffic pattern. Aircraft execute the basic turns in the pattern on their own	ATC would determine the landing order of all aircraft. ATC would control and integrate IFR and VFR aircraft in the airspace and establish a VFR pattern using control instructions based on the radar information. Aircraft on frequency but not displayed on radar would be managed based on other traffic	ATC determines the landing order of all aircraft. ATC controls and integrates IFR and VFR aircraft in the airspace and VFR pattern using direct viewing of the aircraft and uses radar information as an aid
Runway configuration	Pilots are free to determine their arrival and departure runway	ATC determines the active runway(s) and runway use	
Control of runway operations	IFR arrivals are instructed to proceed for landing; IFR departures released for departure with a void time VFR traffic self-organizes and is not controlled at all	Both VFR and IFR traffic receive landing and departure clearances. ATC ensures runway is clear of all known conflicts. Pilots self-separate on the uncontrolled taxiways and apron areas	
ATC participation	VFR aircraft are not required to participate in ATC operations or communicate with ATC	All aircraft are required to participate in ATC operations and communicate with ATC	
Transponder equipage	Aircraft are not required to carry a transponder. Unequipped aircraft receive service as they currently do in Class D airspace		

7.3.2 Assumptions and Constraints

The Select Services Concept is based on the following assumptions:

- ATC services will be provided by controllers located at a facility away from the airport; such a facility may be located at the overlying ARTCC or TRACON facility.
- The controllers at the remote facility will be radar controllers and will accept hand-offs from ARTCC or TRACON radar controllers providing approach services to the airport.
- If the airspace around the airport is presently designated as Class E or Class G, it will be designated as Class D. If the airspace classification is already higher than Class D, it shall remain unchanged.
- Consistent with the airspace classification, all aircraft operating in and out of the airport will be required to carry radio communication equipment and will be required to communicate with ATC and follow ATC instructions. However, aircraft without such communications equipment or with failed equipment will be accommodated, although they may receive a reduced level of services than those provided to radio-equipped aircraft.
- A unique frequency will be assigned to the airport for air-to-ground ATC communications; communication coverage will extend to all airport surface areas and the airspace immediately surrounding the airport.
- Secondary surveillance will cover all Runway Safety Areas (RSAs) and taxiways that are adjacent to or cross the runways.
- The status of all ground movements of transponder-equipped aircraft and other transponder-equipped vehicles in the movement area will be presented to the controllers on a 2-D display.
- The airborne location of transponder-equipped aircraft will be presented to the controllers on a 2-D display certified for separation.
- Consistent with current operations in Class D airspace, aircraft will not be required to carry a transponder to be able to operate in and out of the airport. Aircraft unequipped with a transponder will be accommodated, although they may receive a reduced level of services than those provided to transponder-equipped aircraft.
- The airport will be required to have an automated weather observation system.
- Controllers will determine the active runway configuration at the airport and issue clearance for landing on and takeoff from the active runways; ATC may authorize pilots to use other-than-active runway(s).

7.3.3 Changes to NTA Operations

There are three significant ways in which the Select Services Concept would change the present NTA operations:

- All aircraft would be required to carry radio equipment onboard and participate in the ATC. This would be accomplished by making necessary changes in the airspace designation.
- Pilots would not be able to select the runway they use; the controllers would determine the runway configuration.
- The VFR traffic would no longer be able to land or takeoff at will. All VFR and IFR runway operations would be under ATC control.

7.3.4 Airspace Jurisdiction

The airspace around the airport operating under the Select Services Concept would be classified as Class D as usually found around the small towered airports. Such a classification will require pilots to establish and maintain radio communication with ATC. Based on the local needs to effectively integrate IFR and VFR operations, the exact shape and volume of airspace might be larger than that found at towered airports.

7.3.5 Surface Jurisdiction

Under the Select Services Concept, all runway surfaces and taxiways within the RSA would be under ATC jurisdiction. A typical RSA may extend up to 1000 ft beyond each runway end. All aircraft and vehicles would be required to receive a clearance from ATC to enter and move within the RSA. All other airport surface area outside the RSA would be designated as non-movement area and will be uncontrolled. These areas at a notional airport are illustrated in Fig. 8.

7.3.6 Surveillance Coverage

The Select Services Concept envisions that airborne surveillance would be continuous and seamless from the overlying en route airspace, cover all charted paths to the Class D airspace, and cover the full extent of the Class D airspace.

The surface surveillance requirements would be defined for three distinct zones as illustrated in Fig. 9.

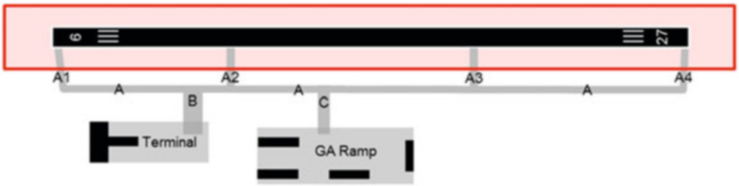


Fig. 8 Airport surface under ATC jurisdiction at a notional airport (Nene et al. 2013a)

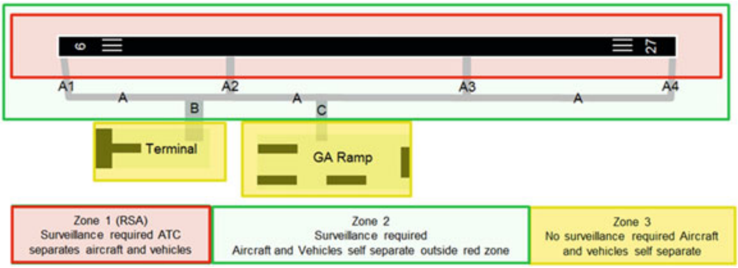


Fig. 9 Three surface surveillance zones for a national airport (Nene et al. 2013a)

Zone 1 is the RSA area defined earlier; surveillance would be required here and ATC would provide separation service. Zone 2 would typically cover all the taxiways in proximity to Zone 1. It would provide a buffer for ATC to detect when aircraft enters or leaves its area of jurisdiction. However, aircraft and vehicles would self-separate in this area. Surveillance would be required for Zone 2 as well. Zone 3 is for all other airport surface that would be uncontrolled and would not require surveillance.

As with the current surface surveillance systems at the high-end airports, the proposed surveillance would not be certified for use in separating aircraft. It would provide surface SA for the controller. The controller would use verbal pilot reports to determine if an aircraft is clear of a runway.

7.3.7 Surface Surveillance Display

The location of aircraft on the specified portion of the airport surface (runways and all taxiways that are directly adjacent to or that cross the runways) would be obtained from cooperative surveillance. The aircraft position in the terminal airspace around the airport would also be obtained from radar and other sensors that may be in use around the airport. The aircraft would be shown on a 2-D display overlaid on the geographical map of the airport. The display would appropriately differentiate between aircraft in the air and on the ground, as well as between arrivals and departures. All aircraft would also be tagged with the necessary data block showing the aircraft ID, altitude, speed, and other parameters. Appropriate weather maps and necessary weather information may also be made available on the surveillance display. The display would also be configurable to accommodate individual controller preferences. Applicable safety alerts would also be presented on the surveillance display.

Any aircraft unequipped with a transponder and any aircraft with failed onboard radio would be accommodated the same way as they are in today's tower environment.

7.3.8 Expected Benefits

Since all IFR and VFR would be under ATC control in the Select Services Concept, the IFR capacity is expected to increase significantly, and aircraft are expected to experience a reduction in holding and vectoring around the airport. The use of surface surveillance display would also significantly increase controller SA and operational safety at the airport.

7.3.9 Concept for Remotely Providing Full Services (Nene et al. 2013b)

If full tower services are provided remotely at the NTAs, rather than only select services, surface surveillance must be expanded to include noncooperative surveillance as well as camera surveillance. This additional surveillance would provide additional SA that would be necessary for providing control instructions related to taxi movements and for accommodating unequipped aircraft. Camera images could be presented to the controller in a variety of ways such as by displaying a panoramic view of the airport surface on multiple monitors or on a separate single monitor, and/or through a PIP window on the surveillance display.

7.3.10 Status of Remote Tower Concepts for NTAs

In 2013, as the FAA was examining alternate paths for continuing remote tower research, the State of Colorado began an initiative for remotely improving services at its non-towered ski airports and requested the FAA to initiate a joint development program for such a concept. As a result, the FAA is currently not pursuing the development or validation of the Select Service or Full Service Concepts described above.

8 Present Effort on the Colorado Initiative

There are a number of non-towered ski airports in the mountainous areas of the State of Colorado that exhibit high traffic levels during the ski season. The lack of conventional radar coverage coupled with the one-in one-out operations resulted in limited capacity at these airports. During some periods of time, the single runway IFR arrival rate reached only 4–6 per hour (Payne 2011). This low capacity resulted in limited access to the airports and in significant vectoring, holding, and delays.

As a response to the above shortfalls, the State of Colorado and the FAA jointly began the development and deployment of Wide Area Multilateration (WAM) and ADS-B in the mountainous areas of Colorado. The use of WAM now provides surveillance down to 500’ AGL at eight airports (Payne 2013) and has improved operations at these airports. Presently, WAM coverage extends almost to the ground level at a few airports, and it can be extended to the ground at all airports if additional transmitters/receivers are installed at these airports.

Currently, the State of Colorado is interested in a remote tower-like concept which would help achieve additional operational benefits at the non-tower airports now covered by WAM. The initiative seeks to use WAM surveillance information, knowledge of surface traffic, and appropriate ATC rules to allow a controller to manage traffic to and from a non-towered airport in an integrated and seamless manner across the airspace. The controllers handling the traffic at these non-towered airports could be located away from the airports, or in a nearby TRACON or ARTCC facility.

The FAA is presently pursuing the Colorado initiative to decide if a formal FAA acquisition process should be undertaken to implement the initiative. The acquisition management system (AMS) process requires the FAA to develop specific formal documentation such as an operational concept, functional and safety analyses, operational requirements, and cost and benefit analyses.

The Colorado initiative development began with the review of the earlier developed concepts for remote NTA operations (Nene et al. 2013a, b) and is presently formulating its own operational concept. It conducted independent HITL and other studies to examine surveillance requirements, safety impacts, and the necessary controller interfaces. Although the concept is still under development, it is expected that a field demonstration will be conducted at an airport in Colorado sometime in the year 2016.

9 Remote Tower Demonstration Project at the Leesburg Executive Airport (KJYO), Leesburg, Virginia

The Leesburg Executive Airport is one of the busiest NTA on the US east coast. In view of the high cost of building a new tower, The Town of Leesburg is exploring the possibility of establishing a camera-based remote tower facility for improving the services at Leesburg Airport. The Virginia Department of Transportation's (VDOT) public–private research arm, called Virginia Small Aircraft Transportation System (VSATS), has agreed to help fund a test of such a remote tower facility. VSATS and the Saab Sensis Corporation have installed a remote tower (rTower) workstation inside a room at the airport terminal; the related camera array is located on the rooftop. A temporary trailer-mounted physical control tower would also be located on the ramp area so that safety of rTower operations could be compared to the safety achieved by the use of a traditional tower. The traffic in and out of Leesburg Airport would be controlled for approximately 12 hours per day during a 3-month test period while the FAA collects safety-related data (Town of Leesburg 2014). If the FAA finds the safety level of rTower operations acceptable, it is expected that the FAA would approve the use of the facility for normal operations.

This demonstration project is still being organized and no additional information is presently available.

10 Future of Remote Towers in the USA

The FAA research to date on remote tower technology has clearly identified significant technical and operational issues that must be addressed before this technology can be implemented within the NAS. The first and the foremost is the need to unequivocally decide if there is a need for camera surveillance, and if so, determine appropriate ways of presenting camera images to the controllers. Some of the outstanding issues to be resolved include, among others, determining the best ways of remotely responding to off-nominal events in airport operations, addressing the need for requiring transponder equipage irrespective of the airspace classification at the airport, and determining if the remote tower concepts should accommodate only a subset of the services presently provided at the towered airports.

Both the Colorado initiative and the Leesburg effort are expected to continue to examine these issues for the next several years. It is, therefore, not clear at this time if one or both of these concepts will be developed and implemented across the NAS in the future.

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Appendix A: Basic Optics for RTO Videopanorama Design

In this technical appendix, we will provide some basic optics for the design of a digital video panorama reconstruction of the out-of-windows view with a visual resolution comparable to the human eye, i.e., an angular resolution of the order of $\alpha_E \approx 1$ arcmin $= 1/60° = 0.3$ mrad, corresponding to 30 cm object size at 1 km distance. Besides satisfying resolution and contrast requirements, the system design including data processing and transmission infrastructure should be realizable under acceptable cost which has to be considerably below that one of a physical control tower building of several M€ for a medium size airport. Typically, each single camera of the panorama system has its own display at the operator working position, plus hard and software for high performance image processing at the transmitter and receiver side of the high bandwidth data transmission infrastructure.

Geometrical Optics for Panorama Design and Pixel Resolution

Estimates for the camera optics design including the visual (pixel) resolution of the RTO videopanorama may be derived to first order from the simple paraxial geometrical optics approximation (neglecting the wave character of light, see Sect. 2 for limitation) via Newton's fundamental thin lens equation:

$$\frac{1}{f} = \frac{1}{g} + \frac{1}{b} \tag{A.1}$$

with f = focal width, g = lens–object distance, and b = lens–image distance. Combining the ratio of image size/object size, $B/G = b/g$ with Eq. (A.1) yields

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$$f = \frac{gB}{G+B} \approx \frac{gB}{G} \tag{A.2}$$

with the approximation valid for our case of large distances $g >> f \approx b$. If we cover 190° visual angle towards the runway by five high resolution HD cameras with portrait orientation (design for the DLR–DFS validation experiments, see chapters "Remote Tower Prototype System and Automation Perspectives," "Which Metrics Provide the Insight Needed? A Selection of Remote Tower Evaluation Metrics to Support a Remote Tower Operation Concept Validation"), each one covers a horizontal visual angle $2\theta = 38°$. With portrait orientation of a ¾″ CCD chip [1080×1920 pixel on (horizontal H × vertical $V = 5.9$ mm × 10.6 mm) active image size] we get for the required focal width ($B = H/2$):

$$f = \frac{0.5H}{\tan(\theta)} = 8.6\,\mathrm{mm} \tag{A.3}$$

The standard zoom camera used in the DLR system (zoom factor $Z_{\max} = 26\times$) covered a focal width of $f = 3.5$ mm (wide angle 42°) to $f = 91$ mm (tele visual angle 1.7°). From Eq. (A.2), we obtain at a distance of 500 m a section of 343 m orthogonal to the optical axis covered by the visual angle 2θ.

In the same way, we obtain for the video pixel resolution (pixel width $p = 5.5$ μm $>> g$)

$$g\alpha_V = G_{\min} \geq g\, p/f = 0.64\, m \tag{A.4}$$

as estimate for minimum video resolution and object size at distance $g = 1$ km, respectively, that covers at least 1 pixel. That is, under ideal illumination and foreground/background contrast conditions, it should be possible for an operator viewing a HD display with well-adjusted Gamma correction (see below) to detect at this distance the wheel of a small aircraft. 60 cm at 1 km distance corresponds to $\alpha_V = 0.6$ mrad $= 2.1$ arcmin ($= 1/30°$) $\approx 2\, \alpha_E$, i.e., only half of the typical angular resolution of the human eye (see above).

In chapter "Remote Tower Experimental System with Augmented Vision Videopanorama," we used the approximation (A.3) to estimate the field of view and pixel resolution for given focal width as dependent on the chip size H or pixel distance $B = H/2$ from the optical axis:

$$\theta(B) = \arctan\left(\frac{B}{f}\right) \tag{A.5}$$

This FOV angle (FOV $= 2\theta$) is plotted in Fig. 5 of chapter "Remote Tower Experimental System with Augmented Vision Videopanorama" as function of focal width for the panorama and PTZ CCD chip size. Differentiation yields the corresponding dependence of pixel FOV $\Delta\theta$ on distance B from the axis ($p = \Delta B = 7.5$ μm):

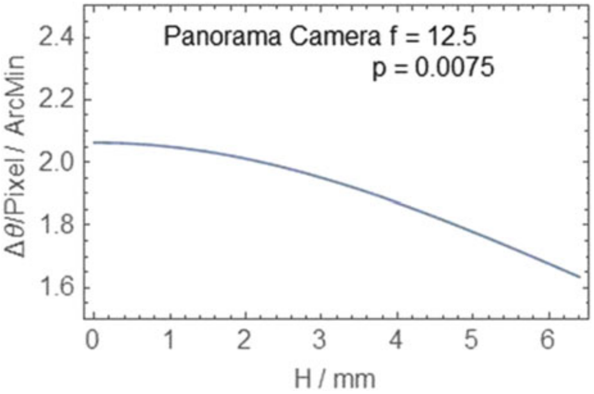

Fig. A.1 Decrease of pixel FOV with distance H from optical axis for thin lens with $f = 12.5$ mm and image chip pixel width $p = 7.5$ μm

$$\Delta\theta_p = \frac{p}{f}\left[\frac{1}{1 + (H/f)^2}\right] \tag{A.6}$$

which for our initial experimental system yields near the optical axis ($H = 0$) $\Delta\theta_{\min} = 7.5$ μm/12.5 mm = 2.1 arcmin, corresponding to the above-mentioned minimum resolvable object size. The decrease of $\Delta\theta_{\min}$ with distance H from the optical axis is depicted in Fig. A.1:

For large distance, lim $\Delta\theta(H \to \infty) = 0$ and, moreover, the paraxial approximation loses its validity with increasing H. Due to the decrease of $\Delta\theta_p$ with H, the received light power per pixel from the corresponding object area decreases accordingly which reduces the contrast towards the chip boundaries. This is only one simple example for (nonlinear) dependencies of image properties on viewing angle, and it underlines the necessity to carefully specify, test, and characterize the selected electronic (image chip and pixel type and size, signal-to-noise ratio, etc.) and optical camera components [lens system, quality of corrections for image distortions, MTF (see below)].

In reality, the ideal pixel resolution is hardly achieved anywhere on the whole image area due to limited contrast as quantified by the modulation transfer function (MTF, see below). It corresponds to the Nyquist limit of black–white line pair resolution, with line width = pixel size. The realistic value depends on several additional camera and digital processing parameters. One important camera parameter is the *f* number *f#* (the aperture-stop number, typically 1.4–22), defined as ratio of focal length to aperture stop diameter D (Hecht and Zajac 1974):

$$f\# = f/D \tag{A.7}$$

Minimum and maximum for $f = 8.6$ mm are $f\# = 1.4$ and 22 corresponding to aperture diameters $D_{\max} = 6.1$ mm and 0.4 mm, respectively. In practice, the camera requires motor driven automatic iris control to adjust for (rapid) illumination changes (bright sun, clouds, shadow, etc.). If under bright illumination conditions, D becomes small, the depth of focus becomes larger so that sharpness of image details increases. On the other hand, a resolution problem may arise due to diffraction effects originating from the wave character of the light.

The above, first order paraxial approximation neglects all lens distortions [chromatic and monochromatic aberrations, e.g., (Hecht and Zajac 1974)] which influence the imaging quality of the optical system. From a systems point of view, the design task also includes an optimal combination of electronic and optical camera component, i.e., chip technology including size and signal/noise level, and type of objective (including automatic aperture control for quick adaptation to changing illumination).

Diffraction Limit and Resolution

With decreasing aperture diameter D, the wave character of light (wavelength λ) plays an increasing role so that diffraction effects may begin to limit resolution. The (Fraunhofer or farfield) diffraction limited angular resolution $\Delta\alpha$ and corresponding "Airy disk" blur radius q_1 depend on λ and is defined via the "Airy" or point-spread function (focal image of a distant light source via a well corrected (aberration free) optical system) (Hecht and Zajac 1974)

$$q_1 = f\Delta\alpha = 1.22\lambda f/D = 1.22\lambda f\# \tag{A.8}$$

It describes the spread of the distant point light source (blurring) as distance between intensity maximum at the optical axis and the minimum between the axis and the first of a series of circular diffraction fringes (first minimum of dark ring) of a circular aperture. The resolution improves ($\Delta\alpha$ decreases) with shorter wavelength and with decreasing $f\#$. This means that for the visible spectrum ($\lambda \approx 0.4$–0.7 μm) with green light (0.6 μm), we get an Airy disk (blur diameter) of the order of $f\#$ μm, i.e., between 1 and 20 μm. For $f\# >$ ca. 6, the spread is larger than the pixel size (for $\lambda > 0.7$ mm = green) so that for small aperture diameter (bright light conditions) with constant exposure time the image quality decreases. Of course with slow movement scenarios, longer exposure times may be selected with smaller $f\#$ in order to keep illumination constant and improve resolution.

Contrast and MTF

Contrast is defined via the object (foreground) and background intensity or brightness which for human perception has to be transferred into the subjective luminance value (see below). The classical contrast measurement is based on alternating black–white line pairs of different widths (spatial frequency) where contrast c is defined as

$$c = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} \tag{A.9}$$

with maximum value $c_{\max} = 1$ for $I_{\min} = 0$ (ideal black) and $c_{\min} = 0$ for equal max/min luminance $I_{\max} = I_{\min}$. In real systems, c may vary across the image diameter (see above), i.e., it is a function of the image coordinates $c = c(x, y)$. A contrast measurement of black–white line targets over a range of spatial frequencies yields the modulation transfer function (MTF) that quantifies the optical system with regard to contrast. Because a line pair requires at least two pixels of the image chip to be resolved, the pixel width as minimum resolvable line width defines the Nyquist limit of the system for object detection under ideal luminance conditions.

Figure A.1 depicts an example measurement with one of the HD cameras used in the validation experiments (Mahmoudzadeh Vaziri 2013). Shown is the horizontal resolution. The MTF calculation is based on the Fourier transformation of the image into the spatial frequency domain using a commercial software (Quick MTF: 2013). One recognizes the typical decrease of contrast down to ca. 20 % of maximum at the Nyquist limit of 0.5 cycles/pixel (1 pixel/line).

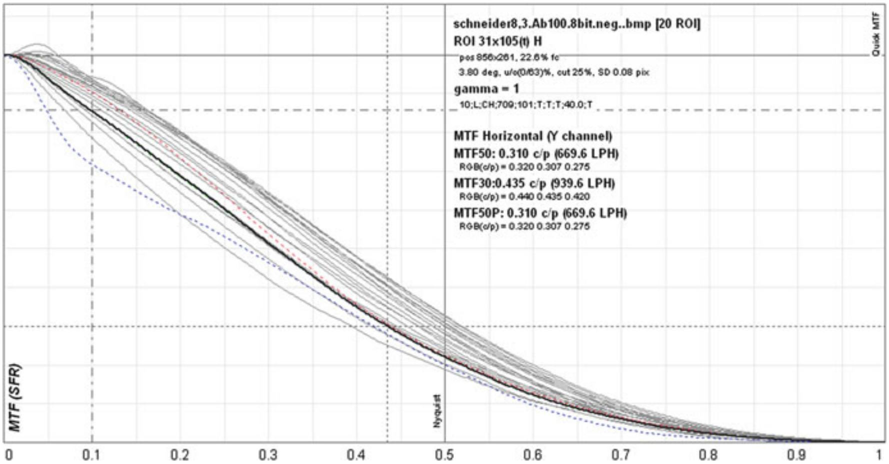

Fig. A.2 Repeated measurements of modulation transfer function of one of the HD cameras used in the prototype setup of the DLR–DFS validation experiment. MTF50 = 0.31 cycles/pixel derived from 939.6 line pairs over the analyzed image range

For the characterization of the system, typically MTF50 (spatial frequency at 50 % of maximum contrast) and MTF30 values are used as indicated in the figure legend: MTF50 at 0.31 c/p and MTF30 at 0.435 c/p.

Determining Effective Resolution by Detectability Experiments

The initial experimental DLR videopanorama system was used for determining the effective video resolution under realistic conditions (see chapter "Remote Tower Experimental System with Augmented Vision Videopanorama"), i.e., the difference between real detectability of small objects in the airport environment from the ideal Nyquist limit (pixel resolution) of the camera system. Different predetermined flight situations or events during airport circling of a DLR aircraft were used to measure time-of-detection by human observers (e.g., first *A/C* detection during approach, determination of landing gear up/down). For this purpose, based on Eq. (A.4) for idealized pixel resolution $\alpha^{\mathrm{V}}/\alpha^{\mathrm{E}} \approx 2$, we derived a relationship for the difference of object (or event i) detection distance under video replay and under direct visual observation, respectively, $\Delta x_i = = x_i^{\mathrm{E}} - x_i^{\mathrm{V}}$, as function of object/event distance x_i, with eye resolution/video resolution ratio ($\alpha_{\mathrm{E}}/\alpha_{\mathrm{V}}$) as constant system parameter. This procedure allows for an averaging of observations with different detectability distances via linear regression. The initial measurement was performed via time differences $\Delta t = t^{\mathrm{V}} - t^{\mathrm{E}}$, with a common time base for observers and aircraft, and aircraft GPS-position x^{E} correlated with observation time t^{E}. The corresponding video-observation position $x^{\mathrm{V}} \leq x^{\mathrm{E}}$ was obtained via *A/C* speed v through $x^{V} = x^{\mathrm{E}} - v\Delta t$, yielding:

$$\alpha^{V} = G \,/\, \left(x^{\mathrm{E}} - v\Delta t\right) = \alpha^{E}\left(1 - \alpha^{E} v\Delta t \,/\, G\right)^{-1} \tag{A.10}$$

With $\Delta x = v\Delta t$, we get for object (event) i at distance x_i

$$\Delta x_i = \left(1 - \alpha^{E}/\alpha^{\mathrm{V}}\right) x_i^{E} = \beta x_i^{\mathrm{E}} \tag{A.11}$$

so that an average effective video resolution as obtained from observers' detection distances x_i^{E}, x_i^{V} during airport circling may be derived from the slope β as:

$$\widehat{\alpha}^{\mathrm{V}} = \frac{\alpha^{\mathrm{E}}}{1 - \beta} \tag{A.12}$$

Basics of Physiological Optics for Detectability

The subjectively perceived resolution and contrast determining the detectability of static and moving objects depend on the physiological and psychophysical perceptual properties of the human observer. This is taken account of by a transformation of the radiation optics magnitudes (light power, irradiation power, etc.) into corresponding technical optics magnitudes and a number of psychophysical laws. The transformation is based on the spectral sensitivity distribution $V(\lambda)$ of the human eye with a maximum in the green range at $\lambda = 550$ nm, and lower/upper sensitivity boundary between 400 and 800 nm for the bright light adapted eye. It is shifted into the blue range by ca. 50 nm for the darkness adapted eye [e.g., (Gobrecht 1978)]. This contrasts to the camera's CCD image sensor with a significant sensitivity in the near infrared spectral range which provides an advantage under low brightness conditions.

The proportionality constant for the transformation is derived by integrating $V(\lambda)$ with Planck's famous black body radiation law [spectral radiant density: radiant energy per wavelength or frequency interval (dl), per second (s), per m^2 per spacial angle (sterad, sr)], yielding for the ratio of technical optics magnitude (X_v) units/ radiation physics magnitude (X_e) units:

$$K_m = 673\,\frac{\text{candela steradian (cd sr)}}{\text{Watt (W)}} = 673\,\frac{\text{lumen (lm)}}{\text{W}} \tag{A.13}$$

for bright light adaptation, e.g., 1 W of radiant power corresponds to 673 lm of perceived power at maximum sensitivity ($V(\lambda) = 1$). For night vision, the darkness adapted eye is much more sensitive: $K'_m = 1725$. Several correspondences between the technical optics (physiologically relevant) and radiation physics magnitudes are established via K_m and K'_m:

- radiant intensity I_e/W/sr—luminous intensity I_v/Candela cd
- radiation power Φ /W—luminous flux Φ_v/lumen (lm)
- radiation density L_e/W/(sr m^2)—luminous density L_v/cd/m^2
- emittance M_e/W/m^2—radiance M/lm/m^2
- irradiance (intensity)/E_e/W/m^2—illumination E/lm/m^2 = Lux (lx)
- irradiation H/Ws/m^2—exposure H/l× s

Luminance Sensitivity and Gamma Correction

Individual γ-values quantify the nonlinear luminance sensitivity characteristic of camera, display, and human observer which classically is described by the Weber–Fechner law as logarithmic stimulus (S)–(subjective) response (E) function:

$$E = \log S \tag{A.14}$$

An improved version of the nonlinear functional relationship between stimulus strength S and luminance sensitivity E which better matches the empirical findings is given by the Stevens function (Birbaumer and Schmidt 2010):

$$E = k\,S^{\gamma} \tag{A.15}$$

A most natural video reconstruction of the real scenery should realize a linear relationship between system input and visual output. For the display with digital input signal I_{in} and output intensity I_{out}, the corresponding overall relationship is

$$I_{\text{out}}^{\text{Display}} = kI_{\text{in}}^{\gamma(\text{Display})} = kI_{\text{out}}^{\gamma(\text{Display})}(\text{Camera}) = kI_{\text{in}}^{\gamma(\text{Camera})\gamma(\text{Display})} \tag{A.16}$$

The human observer exhibits a typical value of $\gamma = 0.45$ which should be realized by the camera sensor in order to obtain a natural reconstruction. This results in the typical display γ-setting of

$$\gamma(\text{Display}) = 1/\gamma(\text{Camera}) \tag{A.17}$$

which yields a good matching of display-γ to human perception, if γ(Display) is selected in the range $1.8 < \gamma < 3$, with a typical average value of 2.4. Decrease of display-γ increases the contrast for dark objects in low light level areas, while at the same time keeping small luminance differences in light areas in an acceptable level. An example is depicted in chapter "Remote Tower Prototype System and Automation Perspectives," Fig. 14.

Appendix B: Signal Detection Theory and Bayes Inference

Appendix B provides some additional basics of signal detection theory and Bayes inference. Based on experimental data with operational experts, these methods are employed in chapters “Videopanorama Frame Rate Requirements Derived from Visual Discrimination of Deceleration during Simulated Aircra” and “Model Based Analysis of Two-Alternative Decision Errors in a Videopanorama-Based Remote Tower Work Position” for quantifying requirements and performance characteristics of the RTO system via analysis of two-alternative decision experiments. More details may be obtained from the references, for our purpose, in particular from (Robert 2001; Green and Swets 1988; MacMillan and Creelman 2005; Zhang and Mueller 2005). Practical examples are taken from the corresponding previous chapters (prediction errors with RTO video frame rate experiments: chapter “Videopanorama Frame Rate Requirements Derived from Visual Discrimination of Deceleration during Simulated Aircraft Landing”; discrimination errors with validation trials: chapter “Model Based Analysis of Two-Alternative Decision Errors in a Videopanorama-Based Remote Tower Work Position”) and the related original publications, respectively, referenced therein.

Bayes Inference

Bayes inference was used in preceding chapters to quantify the risk of inferring from an observation with limited evidence for one of two possible world states (e.g., a specific observable aircraft maneuver in the control zone taking place or not) on a false cause which does not correspond to the actual situation. Generally, it allows for quantifying the probability of a random event *A* acting as a cause for another,

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dependent random event B (an observation) by means of inverting the measured conditional probability using Bayes theorem. According to this fundamental statistical law, the compound probability of two interdependent random variables is given by

$$p(A,B) = p(A \wedge B) = p(A|B)p(B) = p(B|A)p(A) \tag{B.1}$$

which yields for the conditional probability of A given B, i.e., the conclusion from effect B to probability of the cause A, via inversion of probabilities

$$p(A|B) = \frac{p(B|A)}{p(B)}p(A) \tag{B.2}$$

as classical version of Bayes theorem for two interdependent random variables. For statistically independent variables, Bayes formula reduces to the well-known product of independent probabilities $p(A,B) = p(A)\ p(B)$. For our purpose of analyzing two-alternative decision experiments, this most simple version of Bayes theorem is sufficient. It is worth mentioning, however, that extensions allow for generating complex Bayesian networks, e.g., for analyzing the performance of complex sociotechnical systems such as delay propagation in air traffic networks. For this purpose, convenient software tools are available [e.g., the Bayesian belief network tool NETICA (https://www.norsys.com/2999)].

For our purpose, we are interested in the probability of a certain world state (situation S_i) given the probability of an observers' response R_j, based on her perceived evidence in support of a corresponding hypothesis. We start with the measured estimate of an observers' decision making within the context of an observation task. For a two-alternative decision task, the response alternatives to two world states, prepared for the experiment as independent (random) situations S_1, S_2 (e.g., landing aircraft with gear up or down) are quantified as estimates of conditional probabilities, abbreviated as Hit rate H, rate of Misses M, correct rejections CR, and False Alarms FA. They are typically defined within a response matrix as follows:

$$\begin{array}{llll} p(R_1|S_1) := H & & p(R_1|S_2) := \mathrm{FA} \\ p(R_2|S_1) := M & & p(R_2|S_2) := \mathrm{CR} \end{array} \tag{B.3}$$

with normalization $H + M = 1$ and $\mathrm{CR} + \mathrm{FA} = 1$ for two-alternative decision experiments due to the independence of events S_1, S_2 (Green and Swets 1988; MacMillan and Creelman 2005). R_1, R_2 are the two possible alternative subjective responses based on the subjects hypothesis due to the perceived evidence. It is quite convenient to visualize this matrix within a Venn diagram:

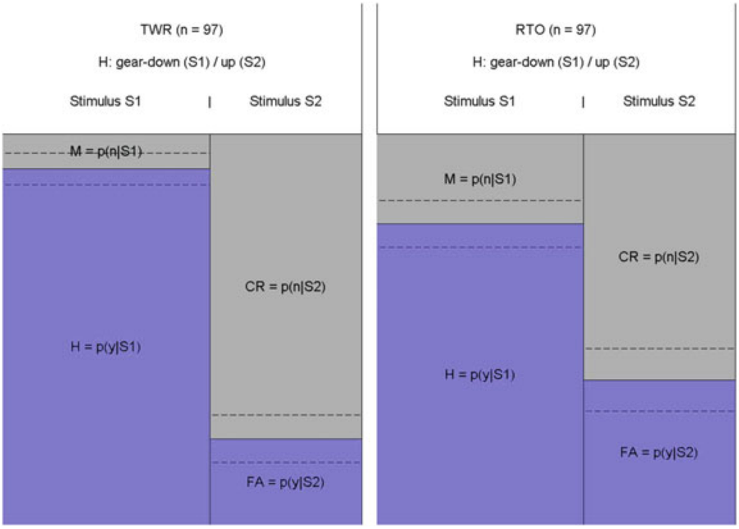

Fig. B.1 Measured response matrices (probabilities) visualized within Venn diagrams as relative size of respective areas. Here, a concrete example is shown, taken from the experimental results of chapter "Model Based Analysis of Two-Alternative Decision Errors in a Videopanorama-Based Remote Tower Work Position" (visual discrimination task: gear up or down of approaching aircraft) for quantifying RTO performance. Areas correspond to probabilities of Eq. (B.3). Dotted lines indicate standard errors of mean

Corresponding to Eq. (B.2), the probability of causating world state S_i for response R_j is obtained as inversion of the conditional response probability $p(R_j|S_i)$ due to an event observation (e.g., observers response probability approximated by the hit rate H of a decision experiment), given a certain precondition, e.g., the a priori knowledge of one of the two possible world states (situations) S_1, S_2. This a priori knowledge on S_i is known through the experimental design (relative number N_1, N_2 of situations S_1, S_2). The corresponding a priori probability $p(S_i)$ is multiplied with the likelihood of the observed evidence $p(R_j|S_i)/p(R_i)$, e.g., for calculating via the Bayes theorem the risk of an unexpected situation S_i (false conclusion on the world state) as cause for the subjective observation (erroneous perception) R_j if $i \neq j$:

$$p(S_i|R_j) = \frac{p(R_j|S_i)}{p(R_j)} p(S_i) \tag{B.4}$$

with situations and responses S_i, R_j; i, $j = 1$, 2. We may choose $R_1 =$ signal detected (or alternative 1), $R_2 =$ noise detected: no signal (or alternative 2). Subjects' response probability is $p(R_j) = p(R_j|S_i) \cdot p(S_i) + p(R_j|S_j)\ p(S_j)$ and $p(R_i|S_i) + p(R_j|S_i) = H + M = \mathrm{CR} + \mathrm{FA} = 1$ (i.e., for a given experimentally determined world state (situation), the subjects decision is either correct or incorrect). The design of the experiment with $N(S_1) = N_1$, $N(S_2) = N_2$, $N = N_1 + N_2$ yields for the prior probabilities $p(S_1) + p(S_2) = 1$.

For practical purpose, it is quite often convenient to use Bayes odds as relative measure instead of probabilities. For this purpose, Eq. (B.4) may be written with the likelihood ratio (e.g., ratio of Hit rate to False Alarm rate) defined by

$$\mathrm{LR}_{ji}(R_j) = p(R_j|S_j) \,/\, p(R_j|S_i) \tag{B.5}$$

The Bayes inference of Eq. (B.4) can then be expressed using LR

$$p(S_i|R_j) = \frac{p(R_j|S_i)}{p(R_j|S_i)\,\mathrm{p}(S_i) + p(R_j|S_j)\,p(S_j)}p(S_i) = \frac{1}{1 + LR_{ji}(R_j)\,\frac{p(S_j)}{p(S_i)}}p(S_i) \tag{B.6}$$

With the prior odds for a two-state world (derived from the known world states with our experimental ratio N_1/N_2) given by

$$\mathrm{Opr}_{ji} = p(S_j) \,/\, p(S_i) = p(S_j) \,/\, (1 - p(S_j) \tag{B.7}$$

Analogously, the posterior odds (ratio of world state probabilities as modified by the hypothesis due to observed evidence based response R_j) is given by

$$\mathrm{OPo}(R_j)_{ij} = p(S_i|\, R_j) \,/\, p(S_j|\, R_j) \tag{B.8}$$

With Eq. (B.6), we obtain from Eq. (B.8), the posterior odds for the world state i contrary to prediction (unexpected situation due to the decision derived from perceived evidence) as:

$$\mathrm{OPo}(R_j)_{ij} = \frac{p(R_j|S_i)p(S_i)p(R_j)}{p(R_j)\,p(R_j|S_j)p(S_j)} = LR_{ij}(R_j)\mathrm{OPr}_{ij} \tag{B.9}$$

Signal Detection Theory

Within psychophysics, signal detection theory (SDT) plays an important role in quantifying decision making, in particular for two-alternative experiments. The standard paradigm is to discriminate a signal embedded in a noisy background from the noise without a signal. In the RTO context (see main chapters), we have used this method to discriminate aircraft landing with sufficient braking deceleration (signal case) from landing with too weak braking, leading to runway overrun (noise). Another example was the discriminability of flight maneuvers for quantifying the RTO performance as compared to the standard tower work condition. The unique feature of SDT is its capability to separate the intrinsic "detector" sensitivity or system discriminability of the observer from his subjective preference to judge more conservative (avoiding false alarms at the cost of missing some correct ones, i.e., increasing the number of misses) or more liberal (preference for identifying as much as possible signals at the cost of increasing the FA rate).

Parametric Discriminability d′ *and Subjective Criterion* c

For this purpose, it has to be assumed that the observers' internal response or familiarity with the two alternative signals (S_2 or noise, S_1 or stimulus + noise) is distributed according to a Gaussian density. Discriminability d' and decision criterion c are then defined by means of the z scores (integration limits) of the inverse cumulative densities. This is visualized with the two density functions in Fig. A.2. The subjective criterion at the position c of the familiarity axis of the two possible random events depicts the integration limits, separating the H and M areas of S_1 (right density function) on the one hand and CR and FA for the S_2 density on the other.

The inverse of the normalized cumulative Gaussian densities $f_1(x)$ for S_1 (situation 1 or signal + noise) and $f_2(x)$ for S_2 (situation 2 noise), i.e., z scores of hit (H) and false alarm (FA) rates, defines a linear relationship with discriminability $d' = (\mu_1 – \mu_2)/\sigma$ as intersection with the $z(H)$ axis:

$$z(H) = \frac{\mu_1 - \mu_2}{\sigma} + z(\mathrm{FA}) \tag{B.10}$$

H and FA are taken as estimates of the indicated areas in the density functions of Fig. B.2, with respective integration limits or z scores (inverse Φ^{-1} of the cumulative normalized probability density $f(x)$) defined by criterion c. If a sufficient number of data (hit rate H, false alarm rate FA) are given, e.g., between subjects with different confidence ratings, a linear regression may be performed in order to

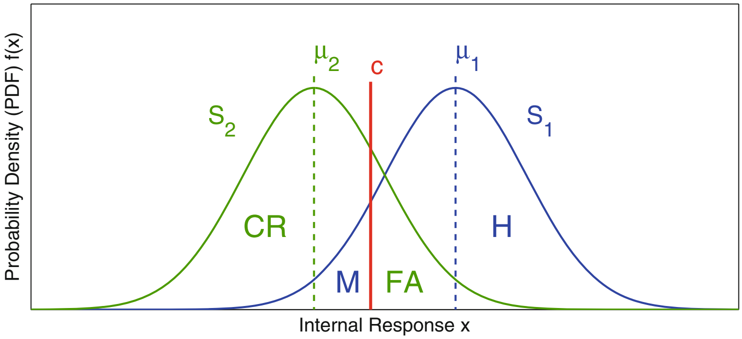

Fig. B.2 Gaussian density assumption of observers' internal random response (or familiarity) x to noise (S^2) and noise + signal (S^1) stimulus determine the distance between the means μ_1, μ_2 of the two densities f_1, f_2 as intersection with the $z(H)$ axis.

If the variances of the two Gaussian densities cannot be assumed equal as precondition, e.g., $\sigma_{\text{Signal}} = \sigma_1 \neq \sigma_2 = \sigma_{\text{Noise}}$, Eq. (B.10) can be shown to change as follows [e.g., (Metz et al. 1998)]:

$$z(H) = \frac{\mu_1 - \mu_2}{\sigma_1} + \frac{\sigma_2}{\sigma_1} z(\text{FA}) \tag{B.11}$$

From (B.10), it follows that with two equal variance, Gaussian densities for the subjective (internal) response or familiarity with situations S_1, S_2, the discriminability d' is defined as difference between normalized mean values:

$$d' := (\mu_1 - \mu_2)/s = F^{-1}(H) - F^{-1}(\text{FA}) = z(H) - z(\text{FA}) \tag{B.12}$$

measured in units of standard deviations between signal means. Φ is the Gaussian probability integral (cumulative density) of density $f(x)$ (x = subjective response or familiarity with situations S_1 (signal + noise), S_2 (noise)).

Correspondingly, the criterion value c is obtained as

$$c := 0.5\,(z(H) + z(\text{FA})) \tag{B.13}$$

In Fig. B.2, c separates the M from H area and CR from FA area in Fig. B.2. Due to the independence of the two alternative events S_1, S_2 (with independently normalized densities $f(S_1)$, $f(S_2)$), the results of the response matrix are unambiguously represented by the (FA, H) data pair.

As a standard graph of SDT, the so-called receiver operating characteristic (ROC) unambiguously characterizes the observer in this experiment via his discriminability d' and decision criterion c. A single data point in (FA, H) ROC space, typically as average over many runs and/or participants of an experiment (representing the average of, e.g., 100 decisions), is unambiguously characterized by a pair of (isosensitivity d', isobias c) parametrized ROC curves. In this way, the same conditional probabilities $p(R_1|S_1) = H$, $p(R_1|S_2) = \text{FA}$ that were used with the Bayes inference for calculation of the risk of world state contrary to expectation ($S_i \neq R_j$) can be employed for deriving an unbiased discriminability value for the observer/decision maker. Examples of ROC curves calculated with the above equations for concrete experimental data are presented in chapters "Videopanorama Frame Rate Requirements Derived from Visual Discrimination of Deceleration during Simulated Aircraft Landing" and "Model Based Analysis of Two-Alternative Decision Errors in a Videopanorama-based Remote Tower Work Position." Each point (H, FA) on an ROC curve is unambiguously determined by the criterion c, separating the subjective yes/no, signal/noise, and world state 1/2 decision threshold. It follows that c is unambiguously characterized by the ROC curve slope that decreases with more liberal decisions, i.e., gathering more hits H at the cost of allowing for more false alarms FA when c shifts to the right (decreases). Because the criterion corresponds to the integration boundary c of the two densities $f(S_1), f(S_2)$ in Fig. B.2, it can be expressed through the likelihood ratio [see Eq. (B.5) for the discrete case] via the probability densities

$$l(c) = \frac{-f(c|S_1)}{-f(c|S_2)} \tag{B.14}$$

that in fact equals the slope of the ROC curve at c. For details, see Green and Swets (1988).

If sufficient data are available, they may be used for deriving optimum d' and c via data fitting. Quite often, however, the amount of data is limited, and a single average pair (<FA>, <H>) is used for deriving an unambiguous pair of d' and c parameterized ROC curve crossing at this (FA, H) coordinate. Figure B.3 depicts a series of d' parametrized ROC curves that shows how different discriminability values can be attributed to three series of measurements (red, green, blue (H, FA) datapoints from frame rate experiments described in chapter "Videopanorama Frame Rate Requirements Derived from Visual Discrimination of Deceleration during Simulated Aircraft Landing") in this case by using the average of each set of four points.

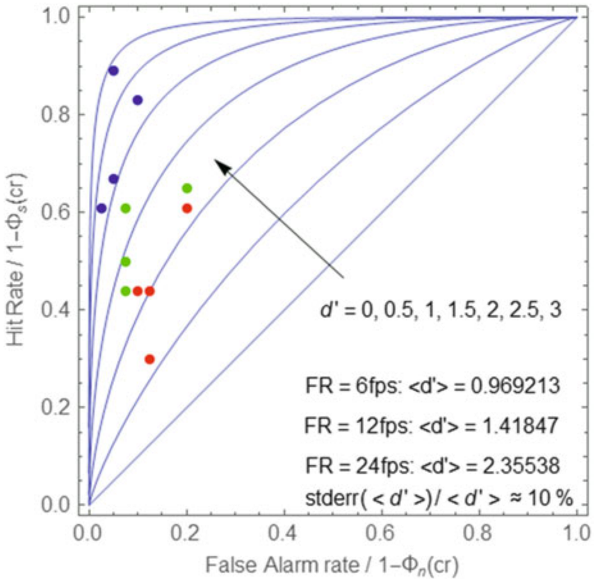

Fig. B.3 Series of d' parametrized ROC curves with three sets of example data points (*red*: 6, *green*: 12, *blue*: 24 Hz) from chapter "Videopanorama Frame Rate Requirements Derived from Visual Discrimination of Deceleration during Simulated Aircraft Landing" (frame rate experiments). Unambiguous discriminability parameter <d'> for each set via average <H, FA> for each set. Axes titles indicate calculation of ROC curves via the cumulative probability densities of noise and signal ($n = S_2$, $s = S^1$), with criterion cr ($\equiv c$) as integration boundary

In chapter “Videopanorama Frame Rate Requirements Derived from Visual Discrimination of Deceleration during Simulated Aircraft Landing,” in Fig. 11 the unambiguously ($<d'>$, $<c>$) parametrized curve pairs are plotted, intersecting at the single average data point of each data set, represented by the crosses with error bars (standard errors). They correspond to three groups of subjects with three different experimental conditions (in that case different frame rates) used for generating three average pairs (<FA>, $<H>$). In this way, within the experimental uncertainty, three different pairs of isosensitivity/isobias curves are attributed to the measured average responses.

Quite often, the limited set of measured data is not sufficient for verifying the Gaussian density precondition with regard to the familiarity or subjective response to the signal and noise vs. noise without signal. In this case, a nonparametric variant may be advantageous for calculating discriminability and decision bias. Such a method based on the area under the ROC curve is described in the next section.

Nonparametric Discriminability A *and Subjective Bias* b

This method is based on an estimate of the average area under ROC curves. For the estimate, the possible areas for the sets of straight lines enclosing all proper ROC curves (with non-negative slope) for any specific (FA, H) point are determined as depicted in Fig. B.4. Proper ROC curves must lie within areas A_1, A_2. Different formulas for average area A as discriminability index and a corresponding index b as nonparametric subjective bias were derived in the literature, but only recently a final correct version was published by Zhang and Mueller (2005).

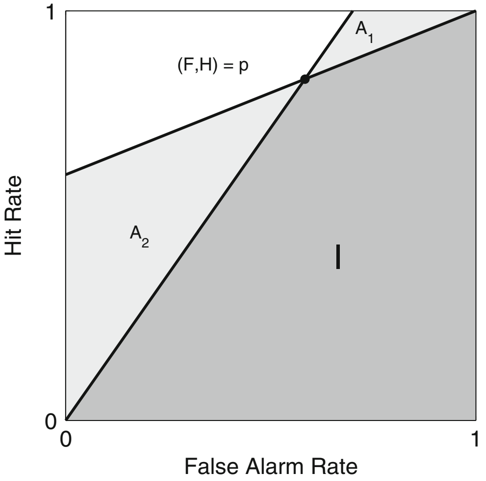

Fig. B.4 Proper ROC curves must lie within areas A_1, A_2. Redrawn after Zhang and Mueller (2005)

The isosensitivity and isobias curves are calculated directly from the measured conditional probabilities H, FA, and are given by the Zhang and Mueller formulas as follows for the A isopleth:

$$A = \begin{cases} \dfrac{3}{4} + \dfrac{H - \mathrm{FA}}{4} - \mathrm{FA}(1 - H) & \text{if} \quad \mathrm{FA} \le 0.5 \le H \\ \dfrac{3}{4} + \dfrac{H - \mathrm{FA}}{4} - \dfrac{\mathrm{FA}}{4H} & \text{if} \quad \mathrm{FA} \le H \le 0.5 \\ \dfrac{3}{4} + \dfrac{H - \mathrm{FA}}{4} - \dfrac{1 - H}{4(1 - \mathrm{FA})} & \text{if} \quad 0.5 < \mathrm{FA} \le H \end{cases} \tag{B.15}$$

and for the associated measure of decision bias which is based on the slope of the constant discriminability A isopleths, and which corresponds to the likelihood ratio:

$$b = \begin{cases} \dfrac{5 - 4H}{1 + 4\mathrm{FA}} & \text{if} \quad \mathrm{FA} \le 0.5 \le H \\ \dfrac{H^2 + H}{H^2 + \mathrm{FA}} & \text{if} \quad \mathrm{FA} \le H < 0.5 \\ \dfrac{(1 - \mathrm{FA})^2 + (1 - H)}{(1 - \mathrm{FA})^2 + (1 - \mathrm{FA})} & \text{if} \quad 0.5 < \mathrm{FA} \le H \end{cases} \tag{B.16}$$

A further advantage of the discriminability index A is its limited range of values $0.5 \le A \le 1$ as compared to the parametric index with $0.5 \le d' \le \infty$. Figure 14 (chapter "Videopanorama Frame Rate Requirements Derived from Visual Discrimination of Deceleration during Simulated Aircraft Landing") and Fig. 8 (chapter "Model Based Analysis of Two-Alternative Decision Errors in a Videopanorama-based Remote Tower Work Position") illustrate the application of this method with the example of increase of discriminability of moving objects on a videopanorama with video frame rate. The position of the group average (H, FA) results (large crosses) on the A isopleth determines the corresponding decision bias b which in this case indicates conservative decision making, i.e., avoiding false alarms.

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