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FIBER OPTIC CONTROL SYSTEM INTEGRATION

FINAL REPORT

by

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16. Abstract

A total fiber-optic, integrated propulsion/flight control system concept for advanced fighter aircraft is presented. Fiber optic technology pertaining to this system is identifed and evaluated for application readiness. A fiber optic sensor vendor survey was performed, and the results are reported. The advantages of centralized/direct architecture are reviewed, and the concept of the protocol branch is explained. Preliminary protocol branch selections are made based on the F-18/F404 application. Concepts for new optical tools are described. Propulsion system supportability and vulnerability/survivability trade study results show the presented concept is favorable. Development plans for the optical technology and the described system are included.

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In addition, evaluations of named manufacturer's products are judgements based on data supplied by the manufacturer.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Concluded)

LIST OF ILLUSTRATIONS

LIST OF TABLES

ABBREVIATIONS

A_8	Variable Exhaust Nozzle (VEN) Throat Area
AB	Afterburner
AOA	Angle of Attack
BH	Compressor Variable Geometry (CVG) Angle
BL	Fan Variable Geometry (FVG) Angle
CBP	Compressor Bleed Pressure
CVG	Compressor Variable Geometry
ECU	Electrical Control Unit
EME	Electromagnetic Effects
EMI	Electromagnetic Interference
EMP	Electromagnetic Pulse
FADEC	Full-Authority Digital Electronic Control
F/B	Feedback
FVG	Fan Variable Geometry
LED	Light-Emitting Diode
LRU	Line-Replaceable Unit
LVDT	Linear Variable Differential Transformer
NH	Compressor/High Pressure Turbine Speed
NL	Fan/Low Pressure Turbine Speed
P_0	Ambient Air Pressure
P_1	Engine Inlet Pressure
P_5	Turbine Discharge Pressure
PLA	Power Lever Angle
PLC	Power Lever Control
Ps_3	Compressor Discharge Static Pressure
RVDT	Rotary Variable Differential Transformer
T_1	Engine Inlet Temperature
T_{25}	Compressor Inlet Temperature
T_3	Compressor Discharge Temperature
T_4	Turbine Inlet Temperature
T_5	Low Pressure Turbine Discharge Temperature
T/C	Thermocouple
TM	Torque Motor
UV	Ultraviolet
VABIA	Variable-Area Bypass Injector Aft
VABIF	Variable-Area Bypass Injector Forward
VEN	Variable Exhaust Nozzle
VG	Variable Geometry
WF	Main Fuel Flow
WR	Afterburner Fuel Flow
WRM	Afterburner Main Fuel Flow
WRP	Afterburner Pilot Fuel Flow

1.0 SUMMARY

The program objectives were to define a total fiber-optic, integrated propulsion/flight control system, to determine the state of the technology of fiber optic sensors and components for use in integrated control systems, and to propose a schedule for bringing this technology to the point where it can be incorporated into future advanced fighter aircraft systems. The program effort comprised the following tasks:

I. Fiber Optic Sensor/Actuator Requirements - Control system sensor and actuator types, requirements, and environments were identified based on an advanced fighter aircraft application. The F-18/F404 application was used as an example.

II. Optical Sensor Vendor Survey - A vendor survey was conducted to assess the status of fiber optic sensor technology, available types, and level of development.

III. Fiber Optic Components - Requirements and recommendations were studied for components, such as effectors, waveguides, connectors, light sources, and detectors, needed to configure aircraft control system optical circuits.

IV. Integrated Fiber Optic System - A total fiber-optic, integrated propulsion/flight control system for an advanced fighter aircraft was conceptualized. The advantages of centralized/direct architecture were reviewed, and the concept of the protocol branch was explained. Preliminary protocol branch sensors were selected. Off-engine propulsion control issues were addressed.

V. Propulsion System Trade Studies - Supportability and vulnerability trade studies were performed to evaluate fiber optic propulsion systems relative to a baseline electrical system.

VI. Development Plan - Schedules and cost estimates to ready optical technology for advanced aircraft implementation and a milestone chart for development of the fiber optic control system through a demonstrational flight test were provided.

The benefits of relocating all aircraft electronics in a centralized bay are realized by efficiently connecting system components using optical protocol methods. Numerous optical sensors and components need development to meet aircraft requirements.

2.0 INTRODUCTION

The Fiber Optic Control System Integration program contemplated by NASA Lewis and the Tri-Services fulfills an increasing need to provide immunity to electromagnetic effects (EME) for the controls and other avionic systems of advanced military aircraft of the 1990's.

Besides providing immunity to electromagnetic effects, namely electromagnetic interference (EMI), electromagnetic pulse (EMP), nuclear radiation, and lightning, use of optical components (especially fiber optic cables for data/command transmission) is expected to reduce the weight and complexity of control systems.

Several Government and industry-funded programs are underway to develop architectures, control modes, and hardware for integrated controls, as well as fiber optic waveguides and optical devices. However, a comprehensive effort is needed to assess the optical technology readiness for making "fly by light" demonstration a reality.

3.0 CONTROL SYSTEM SENSOR/ACTUATOR REQUIREMENTS

3.1 F-18 AIRCRAFT

The F-18 application serves as an example of the kinds and numbers of control system sensors and actuators in use on a modern fighter aircraft and the environment they must operate in. In Sections 6.4 and 6.5, this control system will also serve as a model for configuring an all-optical version. Figure 1 shows an outline of the F-18 aircraft, an F-18 flight envelope, and a description of the environment in three areas where electronic units are located. Temperatures given for the engine area are for once-per-flight extreme transients.

3.1.1 F-18 Flight Control

A functional diagram of the existing F-18 flight control system is shown in Figure 2. It includes the following actuator set and sensor set:

Actuator Set	Sensor Set
Actuator, trim, longitudinal feel	Accelerometers, linear
Actuator, ratio changer	Gyroscope, rate (3 axes)
Cylinder, speed brake	Position, linear, control stick
Drive unit, wing fold	Position, linear, rudder pedals
Release, ram air door	Position, linear, servocylinders
Servocylinder, aileron	Pressure sensor, air data (AOA)
Servocylinder, rudder	Switch, FCS control panel
Servocylinder, stabilator	Switch, speed brake proximity
Servocylinder, leading-edge flap	Switch, wing fold inhibit
Servocylinder, trailing-edge flap	Switch, wing lock warning

3.1.2 F404 Propulsion Control

The complexity of the existing F404 propulsion control system is shown by the engine control system interface diagram in Figure 3. Figure 4 is a scaled rollout sketch of the engine electrical system showing the location and number of individual sensors, components, and interconnection routings. This sketch is also useful in comparing electrical versus optical cable weights, as reported in Section 7.1. The following are present:

3 Pressure Sensors	5 Torque Motors
3 Shaft Speed Sensors	5 Solenoids
9 Temperature Sensors	1 Rotary Position Sensor
1 Flow Sensor	5 Linear Position Sensors
1 Liquid Level Sensor	1 Flame Detector
5 Switches	1 Linear Accelerometer

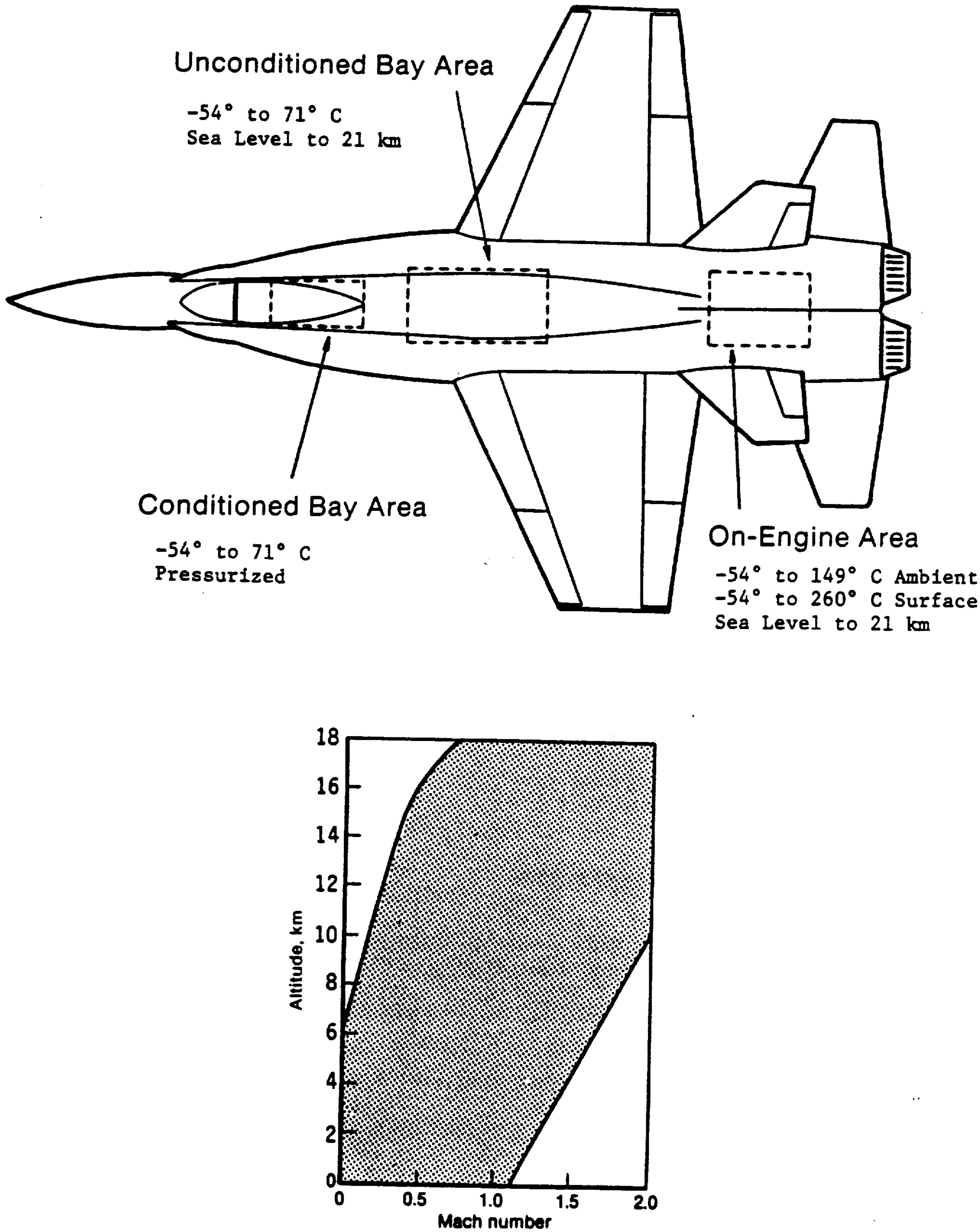

Figure 1. F-18 Flight Envelope and Bay Area Environment.

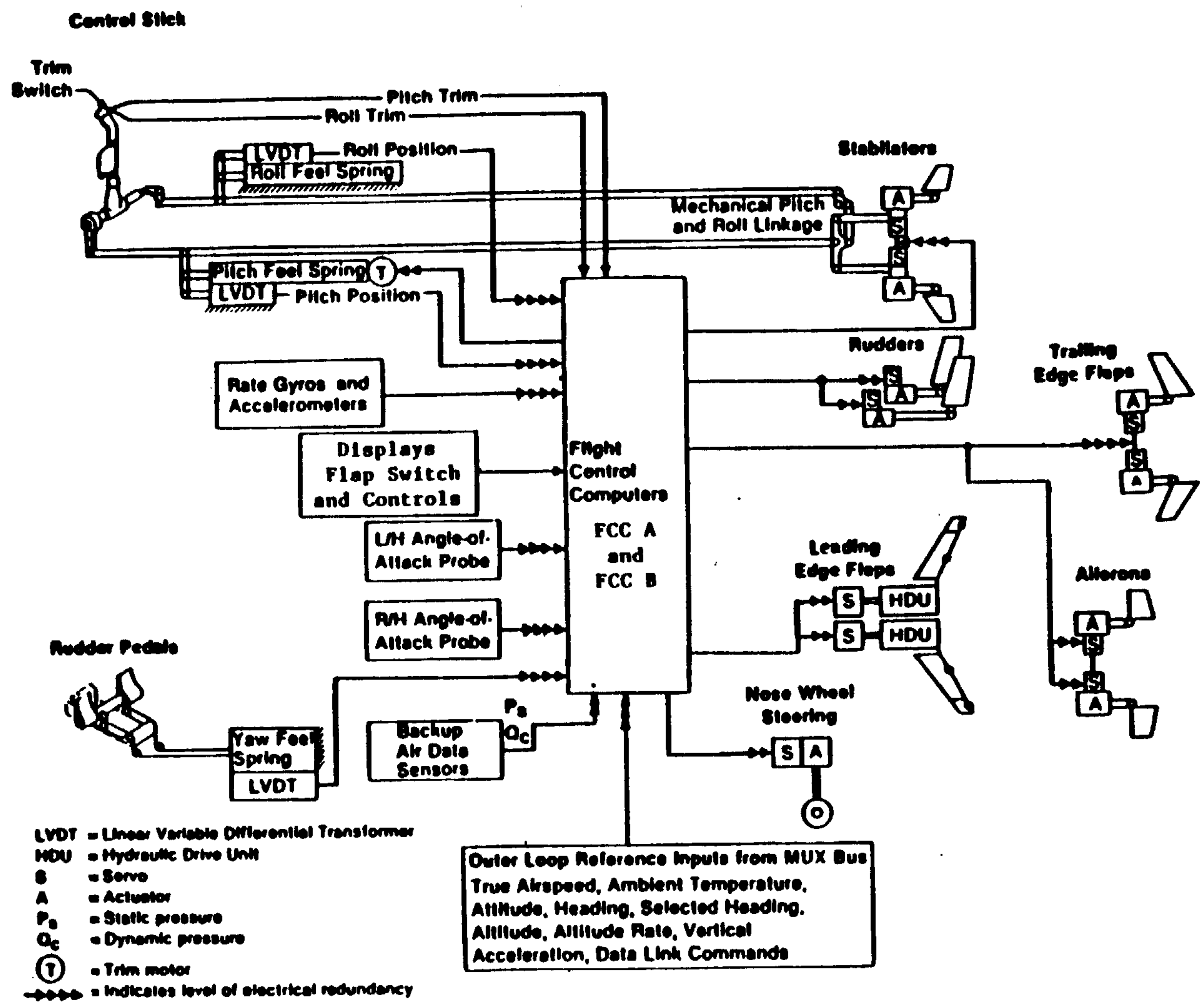

Figure 2. F-18 Flight Control System Functional Diagram.

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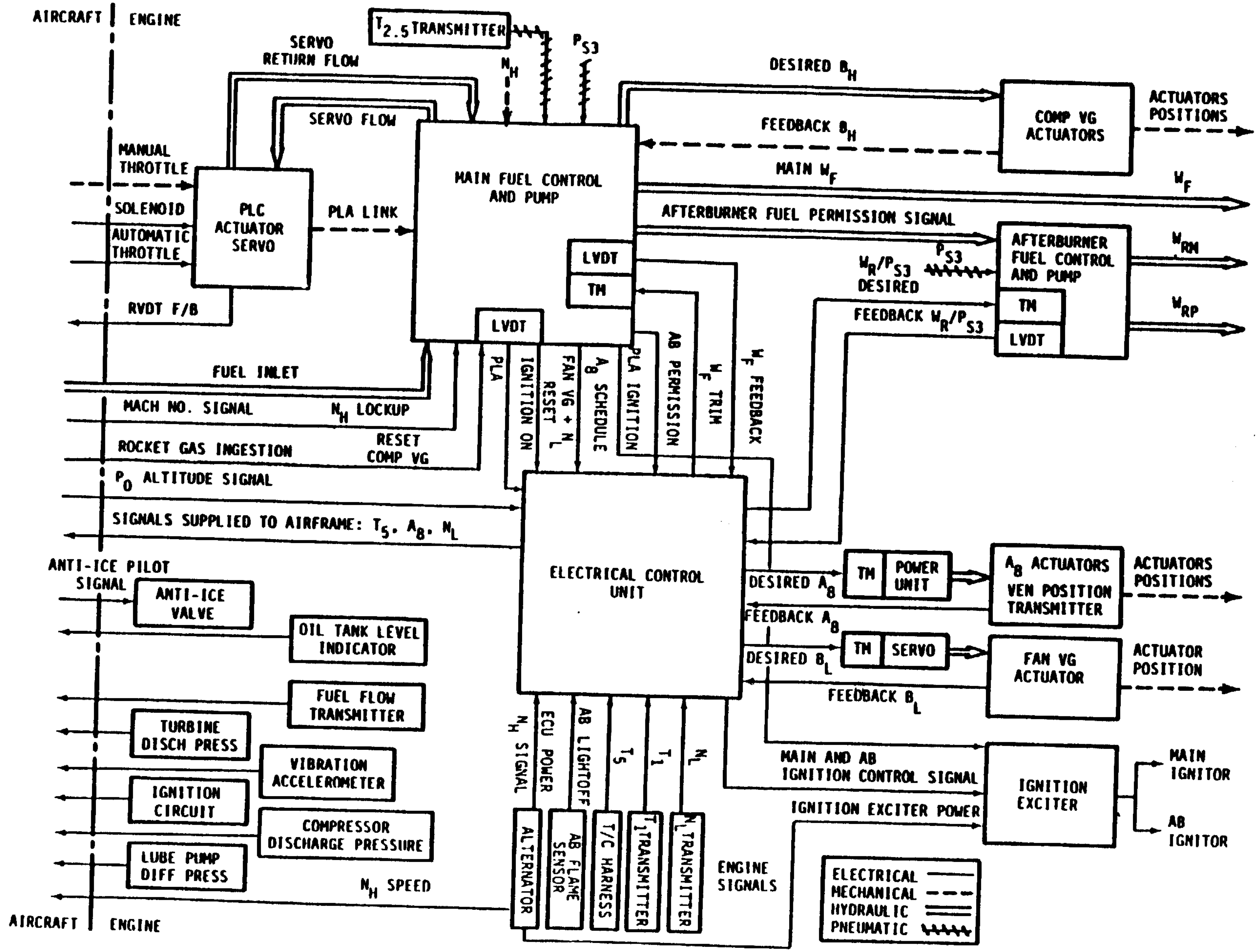
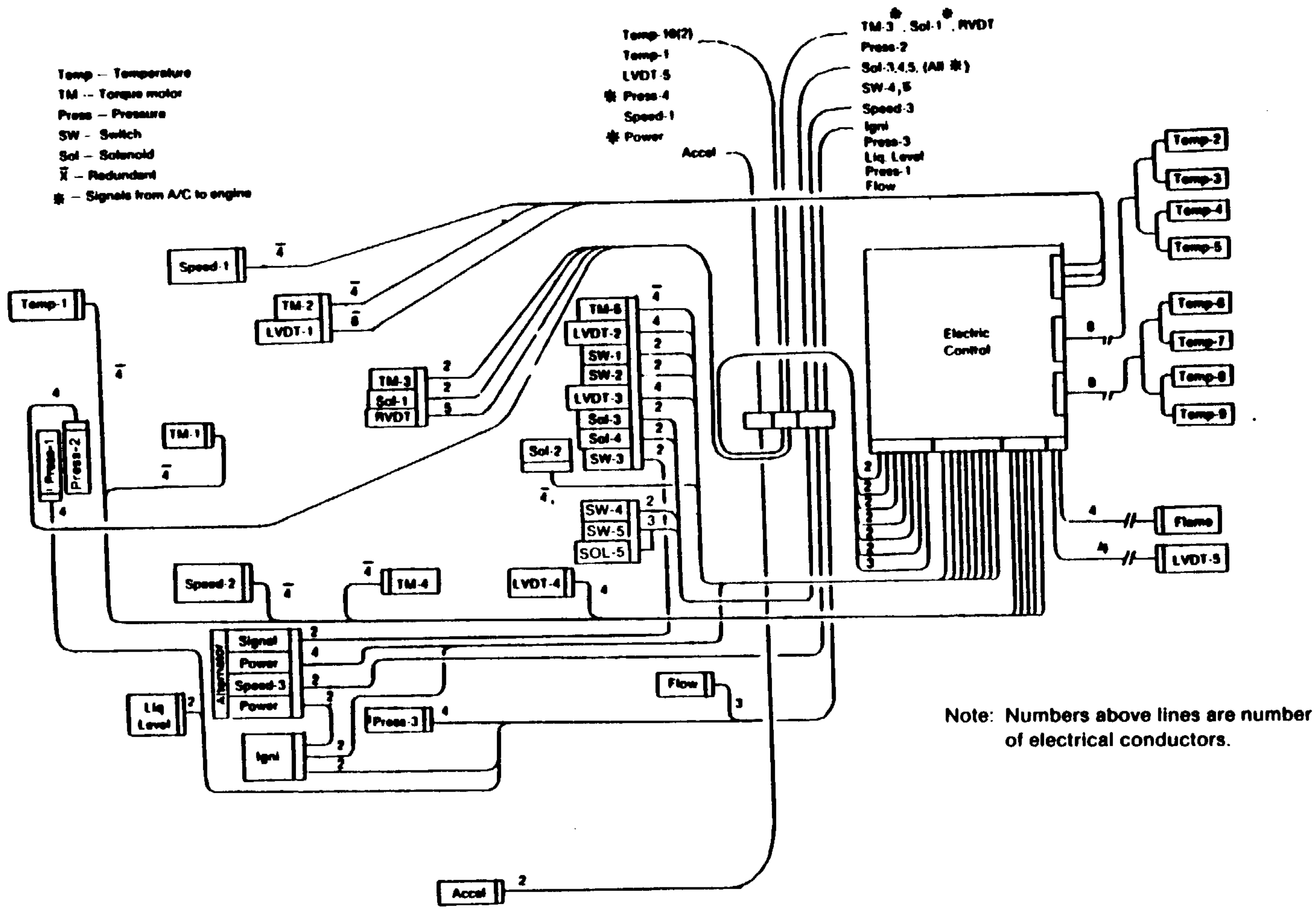


Figure 3. F404-400 Engine Control System Interface Diagram.



Note: Numbers above lines are number of electrical conductors.

Figure 4. F404 Electrical System Rollout Breakdown.

3.2 GENERIC AIRCRAFT REQUIREMENTS

The F-18 propulsion/flight control system sensors are a specific subset of sensors which may be selected for future control system designs. Having a variety of sensors available for selection provides flexibility and optimization of the control system. The optical sensor Vendor survey (Section 4.0) thus required the identification of a full set of engine/airframe sensors, including a description of the characteristics and operating environments.

Figure 5 depicts a generic set of propulsion system effectors and sensors and the approximate positions along the engine axis. Table 1 identifies the performance requirements of range, accuracy, time response, and environment for a full set of generic aircraft sensors. The rotary shaft speed sensor and pyrometer require small response times in order to follow high-speed rotating discontinuities.

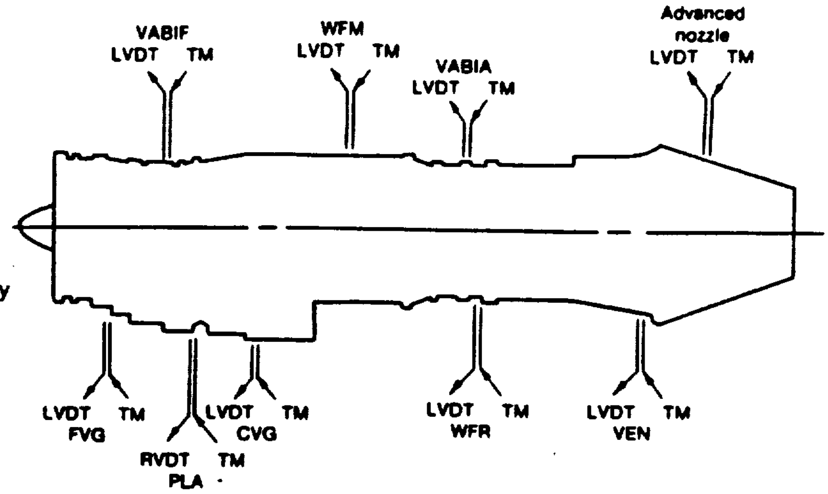
Table 1. Aircraft Fiber Optic Sensor Requirements.

Parameter (Redundancy)		Range	Accuracy	Time Response	Environment
Temperatures	T_1	-54° to 230° C	±0.21% Pt	4.3 s	200° C ↑
(Two Each)	T_{25}	-54° to 260° C	±0.21% Pt	at	200° C at
	T_3	260° to 650° C	±0.22% Pt	50 kg/m²	315° C Connector
	T_4	260° to 1650° C	±0.22% Pt	per	540° C Interface
	T_5	260° to 1095° C	±0.22% Pt	second	425° C ↓
					-54° C to max of range at probe
Pressures	ΔP/P	0-117 ΔkPa	±0.2%	10 ms	-54° to 120° C
(Two Each)	ΔP/P	1035 kPa line	Full		(Cooled)
	ΔCBP	0-690 ΔkPA	Scale		-54° to 200° C
	ΔCBP	3445 kPa line			(Uncooled)
	P_1	0-140 kPa			
	Lube	0-345 kPa			
	P_5	0-415 kPa			
	Ps_3	0-3445 kPa			
(Four Each)	P_0	0-110 kPa	±0.04% Full	10 ms	-54° to 190° C
	P_0	0-220 kPa	Scale		
Lube Level (Mil-L-7808 Oil)		0 to 0.015 m³	±2% Full Scale	1 s	690 kPa, -54° to 150° C
Fuel Flow	WF	135-9,075 kg/hr	±1.5%	2 ms	-54° to 150° C,
(Two Each)		(1-70 gpm)	Full		85 bar (Fuel)
	WR	270-18,145 kg/hr	Scale		-54° to 200° C
		(2-135 gpm)			(Air)
	WR	455-27,215 kg/hr			
		(3-200 gpm)			

Table 1. Aircraft Fiber Optic Sensor Requirements (Concluded).

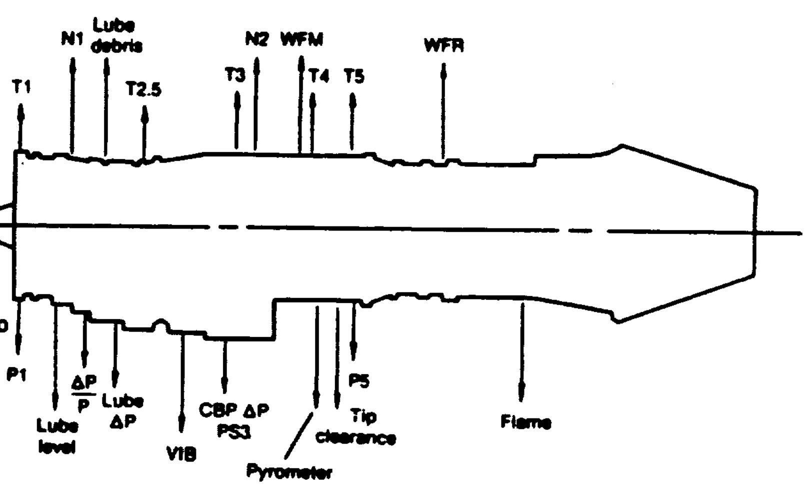
Parameter (Redundancy)	Range	Accuracy	Time Response	Environment
Linear Position WF (Two Each)	1.25 - 20 cm Stroke	±1.5% Full Scale	2 ms	-54° to 175° C, 205-550 bar Fluid Internal to Actuator; Up to 200° C at Connector
Flight Surfaces (4) (1 or 2) (4)	4 cm Stroke 15 cm Stroke 30 cm Stroke	±1% Full Scale	2 ms	-54° to 315° C
PLA (2)	0-120°	±1% F.S.	2 ms	-54° to 190° C
Linear Acceleration (8)	± 40m/s²	±0.5% F.S.	2 ms	-54° to 190° C
Shaft rpm (2) (Response is related to toothed-wheel Frequency)	1,500-15,000	±0.1% F.S.	30 µs	-54° to 315° C at Body; Up to 200° C at Connector
Angular Rate (8)	±3.5 rad/s	±0.5% F.S.	2 ms	-54° to 190° C
Vibration (1)	0-50 "G's" Peak	±5% Reading Resonance > 3 kHz, Flat Within 5% for 25 to 300 Hz	Inherent	-54° to 370° C, 500 "G's" Peak
Impending Filter Bypass Switch (1) (Fluids: Fuel, Hydraulic, Lube)	70-415 ΔkPa 690-8275 kPa Line	±5% F.S.	1 s	-54° to 150° C
Pyrometer (2) (Response is related to turbine blade-passing frequency)	540°-1095° C (Target)	±10° C 845°-980° C	10 µs	260° to 1095° C at Tip -54° to 540° C at Connector
Tip Clearance (1)	Up to 0.3 cm	± 50 µm	4 ms	As Pyrometer
Lube Debris (1) (Accuracy: capture and signal efficiency at 1100 kg/hr oil, 0.4 kg/min air, 115° C)	0.5 to 1.0 mm	95%	2 ms	-54° to 150° C
Flame Sensor (1) (Range: per commercially pure propane flame)	< 290 nm	Indication	2 ms	-54° to 370° C

- LVDT — Linear variable differential transformer
- TM — Torque motor
- VEN — Variable exhaust nozzle
- FVG — Fan variable geometry
- CVG — Compressor variable geometry
- RVDT — Rotary variable differential transformer
- PLA — Power lever angle
- VABIA — Variable bypass area
- WFM — Main fuel flow
- WFR — Augmentor fuel flow



Generic Propulsion System
Effector Set

- T1 — Fan inlet temperature
- T2.5 — Compressor inlet temperature
- T3 — Compressor discharge temperature
- T4 — Turbine inlet temperature
- T5 — Turbine discharge temperature
- P1 — Engine inlet pressure
- ΔP/P — Fan discharge pressure ratio
- PS3 - Compressor discharge pressure
- CBP ΔP - Compressor bleed pressure ratio
- P5 — Turbine discharge pressure
- N1 — Fan speed
- N2 — Compressor speed
- VIB—Vibration level
- WFM — Main fuel flow
- WFR — Augmentor fuel flow



Generic Propulsion System
Sensor Set

Figure 5. Generic Set of Propulsion Control System Sensors and Effectors.

4.0 OPTICAL SENSOR VENDOR SURVEY

The purpose of the fiber optic sensor vendor survey was to evaluate the status of fiber optic sensor technology in industry and to aid in providing a schedule and cost estimate to ready that technology for aircraft system bench testing. The survey was performed from April through September 1986.

4.1 QUESTIONNAIRE AND RESPONSES

A total of 78 vendors were surveyed. Appendix A presents a list of the vendors surveyed and a copy of the survey questionnaire form. The survey consisted of a letter explaining the purpose of the survey, the questionnaire form, and a copy of the sensor requirements as shown in Table 1.

The vendors responded in many ways. Of those actively working on fiber optic sensors, some filled out the questionnaire, some only sent literature, others only described their work over the telephone. A total of 26 vendors indicated one or more fiber optic sensors at some stage of development. A matrix of vendor versus sensor type is shown in Figure 6.

4.2 FIBER OPTIC SENSOR EVALUATIONS

Vendor survey data were used to compile evaluation charts (Table 2). Where information such as transduction technique was not available, the column is blank. Where the sensor is based on optical pyrometry, the transduction technique is described as collection. The rating methods are described below.

4.2.1 Performance Requirements

A fiber optic sensor must meet control system design needs and survive in the aircraft/engine environment. The sensor survey responses were rated in the categories of range, accuracy, environment, and response with respect to the requirement charts in Table 1 in the following manner:

3 - Meets requirements
2 - Close to meeting requirements
1 - Far short of meeting requirements or capability not determined

The performance categories are mutually exclusive. The sensor may meet the accuracy requirement but not the environment because room temperature accuracy is reported. In most cases, thermal effect on accuracy is not established.

4.2.2 Classification of Fiber Optic Sensors

Fiber optic sensors have two distinct attributes: transduction technique and transmission protocol.

	Linear Position	Angular Position	Linear Acceleration	Angular Rate	Pressure	Temperature	Shaft Speed	Mass (Volume) Flow	Pyrometer	Flame Sensor	Tip Clearance	Lube Debris	Vibration	Lube Level
Babcock and Wilcox					✓	✓		✓					✓	
MTI Instruments					✓								✓	
GE AID							✓	✓	✓	✓				
Teledyne Ryan	✓				✓	✓								
Plessy	✓	✓			✓		✓		✓	✓		✓		
GE AEBG						✓					✓			
Eldec	✓	✓												
Land Turbine									✓					
McDonnell Douglas			✓	✓	✓	✓							✓	
Focal Marine				✓	✓						✓			✓
Luxtron						✓								
Consolidated Controls		✓			✓									
Furukawa	✓	✓												✓
Aster					✓	✓								
Litton	✓													
EOTec					✓	✓								
Vanzetti									✓					
Conax	✓	✓	✓		✓	✓		✓	✓	✓	✓			
Simmonds Precision						✓	✓	✓						✓
Rosemount									✓					
Optelecom					✓									
Fujikura						✓								
Parker	✓				✓									
OPTECH					✓								✓	
Statham					✓									
Technology Dynamics	✓	✓	✓		✓	✓								

Figure 6. Aircraft Fiber Optic Sensor Requirements.

Table 2. Fiber Optic Sensor Evaluations.

	Pressure															
Performance Level	Babcock and Wilcox	Focal Marine	MTI Instruments	Consolidated Controls	Aster	EOTec	Teledyne Ryan	Teledyne Ryan	Conax	Plessy	McDonnell Douglas	Parker	Optelecom	Statham	Technology Dynamics	OPTECH
Range	All	C,D,E,	D&E	All	C	E	C,D,E	B	F	C	1	1	C,D,E	1	C,D,E	All
Accuracy	2	1	1	1	1	1	1	1	1	1	1	1	3	1	3	1
Environment	3	1	1	1	3	2	1	3	1	1	1	3	1	1	3	1
Response	3	3	1	1	3	1	1	3	3	1	1	3	1	1	3	1
Light Source																
LED	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓		✓	✓
White																
Pyrometer																
Laser												✓				
Transmission Protocol	Intensity	Intensity	Intensity	Intensity	Intensity	Intensity	Intensity	Time division multiplex	Intensity λ ratio	Wave-length coded	Interfero-metric	Time division multiplex	λ shift		λ shift	Intensity
Transduction Technique	Micro-bend	Micro-bend	Reflec-tion	Reflec-tion	Reflec-tion	Reflec-tion	Micro-bend	Bourdon tube		Diffrac-tion			Reflec-tion			Reflec-tion
Development Level	5	3	4	2	3	4	4	3	2	2	2	4	4	1	4	2

Range Code: (A) 0-117 kPad, 1035 kPa
(B) 0-690 kPad, 3445 kPa
(C) 0-140 kPa
(D) 0-415 kPa
(E) 0-3445 kPa

R.T. Room Temperature

Table 2. Fiber Optic Sensor Evaluations (Continued).

	Pyrometer						Flame Detection			Vibration				Linear Acceleration		
Performance Level	Rosemount	Land Turbine	Conax	GE AID	Plessy	Vanzetti	GE AID	Conax	Plessy	Babcock and Wilcox	MTI Instruments	McDonnell Douglas	OPTECH	Conax	McDonnell Douglas	Technology Dynamics
Range	3	3	3	3	1	3	—	—	—	3	3	1	3	1	1	3
Accuracy	3	3	3	3	3	3	—	—	—	3	3	1	1	1	1	3
Environment	1	3	1	1	1	1	3	1	1	3	1	1	1	1	1	3
Response	3	3	1	3	1	3	3	3	1	—	—	1	1	1	1	3
Light Source																
LED										√	√			√		√
White																
Pyrometer	√	√	√	√	√	√										
Laser													√			
Transmission Protocol	Intensity	Intensity or ratio	Intensity λ ratio	Intensity or ratio	Intensity ratio	Intensity	UV intensity	Intensity	Spectral shift	Intensity	Intensity	Interfer-ometric	Phase shift		Interfer-ometric	Wave-length shift
Transduction Technique	Collec-tion	Collec-tion	Collec-tion	Collec-tion	Collec-tion	Collec-tion	Collec-tion	Heated IR fiber	Raman effect	Diaph-ragm micro-bend	Reflec-tion					
Development Level	3	6	2	5	3	4	2	2		5	4	2		1	2	3

Table 2. Fiber Optic Sensor Evaluations (Continued).

	Temperature													Filter Bypass		Lube Debris
Performance Level	Babcock and Wilcox	Aster	Aster and Accufiber	Summonds Precision	GE AEBG	EOTec	Conax	Conax	Teledyne Ryan	Luxtron	McDonnell Douglas	Fujikura	Technolgy Dynamics	Conax	Consolidated Controls	Plessy
Range	C	A	D	A	D	A	D	A	C	A	1	B	A	3	3	—
Accuracy	2	2	3	1	3	2	3	3	2	3	1	1	3	3	3	—
Environment	1	1	1	1	3	1	1	1	1	1	1	1	3	1	3	1
Response	3	3	1	1	3	1	3	3	3	3	1	1	3	3	3	1
Light Source																
LED		√				√		√					√	√		√
White										√						
Pyrometer	√		√		√		√		√							
Laser												√				
Transmission Protocol	Intensity λ ratio	Intensity		Intensity ratio	Intensity	Intensity	Intensity λ ratio	Intensity λ ratio	Intensity	Pulse delay	Interfero-metric	Spectral shift	λ shift	Intensity λ ratio	Intensity	wave-length coded
Transduction Technique	Collec-tion	Reflec-tion	Collec-tion		Collec-tion	Reflection from bimetal	Collec-tion		Collec-tion	Fluores-cence decay		Raman effect			Reflec-tion	
Development Level	3	3	3	1	3	3	2	2	3	4	2	2	4	2	3	2

Range Code: (A) -54° to 260°C
(B) 260° to 650°C
(C) 260° to 1095°C
(D) 260° to 1650°C

Table 2. Fiber Optic Sensor Evaluations (Continued).

Performance Level	Linear Position									Angular Position					
	Furukawa	Conax	Litton	Teledyne Ryan	Eldec	Plessey	Plessey	Parker	Technology Dynamics	Furukawa	Conax	Consolidated Controls	Eldec	Plessey	Technology Dynamics
Range	All	All	3	5	4.5 to 6	4	8.7	All	6	3	3	3	3	1	3
Accuracy	3	3	1	3	3	2	3	3	3	3	3		3	3	3
Environment	B	A	1	1	2	1	1	1	1	3	3	1	2	2	3
Response	1	3	1	1	3	1	1	1	1	1	3	1	3	1	2
Light Source															
LED		√			√	√			√		√	√			√
White	√						√			√				√	
Pyrometer															
Laser				√				√							
Transmission Protocol	Fiber array	Intensity λ ratio	λ division multiplex	Time division multiplex	Intensity with reference	Frequency	Wavelength coded	Digital time domain multiplex	Wavelength shift	Fiber array	Intensity ratio	Fiber array	Intensity with reference	Wavelength coded	Wave-shift
Transduction Technique	Reflection		Code plate	Code plate reflection	Microbend	Interference	Diffraction	Code plate		Reflection		Transmissive code plate	Microbend	Diffraction	
Development Level	2	3	3	5	3	2	3	3	3	2	2	2	3	3	3

Environment Code: (A) to 200°C
(B) to 315°C
R T Room Temperature

Table 2. Fiber Optic Sensor Evaluations (Concluded).

Performance Level	Angular Velocity		Shaft Speed				Mass Flow				Blade Tip Clearance			Liquid Level		
	Focal Marine	McDonnell Douglas	GE AID	GE AID	Plessy	Simmonds Precision	Babcock and Wilcox	Simmonds Precision	GE AID	Conax	GE AEBG	Conax	Focal Marine	Furukawa	Focal Marine	Simmonds Precision
Range	3	1	3	3	2	1	3	1	3	3	3	1	1	3	3	1
Accuracy	3	1	1	3	1	1	3	1	3	3	3	1	1	3	3	1
Environment	1	1	1	1	1	1	3	1	3	3	3	1	1	3	3	1
Response	1	1	1	1	1	1	1	1	1	1	3	1	2	3	3	1
Light Source																
LED	√		√	√	√	√	√		√	√		√	√	√		
White															√	
Pyrometer																
Laser																
Transmission Protocol	Pulse	Interferometric	Pulse rate	Pulse rate	Pulse rate	Pulse rate	Pulse rate	Intensity	Pulse delay	Intensity λ ratio	Array		Intensity	Fiber array	Fiber array	Fiber array
Transduction Technique	Reflection		Magneto	Reflective	Reflective		Vortex shedding pressure microbend		Optical switch		Reflection		Microbend pressure	Refraction	Meniscus scattering	
Development Level	4	2	2	2	2	1	4	2	2	2	3	1		2	2	4

All sensors employing a deflecting diaphragm as the sensing element use one transduction technique, as do all sensors that use the stress-related photoelastic effect to affect the state of polarization. Generally, sensors that are extrinsic and have mechanically moving parts are more complex than those which are intrinsic and rely solely on a bulk material property.

The sensor data-transmission method, or protocol, will generally fall within one of 12 categories shown in Table 3. In many cases, a transduction technique allows the choice of several protocols. Protocol choices relate to the ability to multiplex several sensor signals together, thus affecting control system complexity and weight. Protocol is of key importance to the integrated fiber optic control system concept presented in Section 6.0.

4.2.3 Development Level

The development level indicates the remaining time and cost projected before the sensor is ready for aircraft use and the confidence level that the technical problems are solvable. Six levels of rating were used because of the wide variety of responses from the survey. It is assumed for all levels that any electronics accompanying the sensor must be redesigned for aircraft use. The levels are as follows:

Level 6 - Ready for use in an aircraft system.

Level 5 - Prototypes available in an aircraft design. Hardware is developed and has been substantially tested. Ready for users to try out.

Level 4 - Prototypes available in a nonaircraft design. Otherwise same as Level 5. The concept may not necessarily work in an aircraft environment.

Level 3 - Development phase. The concept is proven, and hardware is being made for in-house testing.

Level 2 - Research phase. Determining the viability of the concept.

Level 1 - Intention phase. Have concept in mind but work has not started.

The general absense of Levels 5 or 6 indicates general low development effort in fiber optic sensors for aircraft application.

Table 3. Optical Data-Transmission Methods.

1. Intensity Variation - Absolute returned intensity. As with microbend sensors, this is strictly the low-frequency amplitude variation of one or more wavelengths.

2. Modulated Intensity - Intensity at one carrier frequency. This is a method of shifting the low-frequency domain data into a higher frequency space. The light source is subject to constant frequency pulsing. This technique allows multiple sensor returns on one fiber by selecting the various carriers with narrow electronic band-passing, possibly at a particular wavelength.

3. Intensity Difference - Variation in amplitude of one wavelength compared to a reference wavelength within the same fiber. The two wavelengths should be close enough to allow proper correction but not so similar as to inhibit good separation.

4. Wavelength Shift - Absolute wavelength variation, as produced by rotating a grating supplied with white light for instance.

5. Modulated Wavelength - Frequency modulation. The higher frequency space equivalent of 4.

6. Pulse Rate - Period between returned pulses. Variation in frequency of a pulse train. As in speed sensors, interferometric rate sensors, Doppler devices, etc.

7. Digital Pulse Encoding - A string of pulses representing a digital value, or word. Data could be coded in binary or Gray code or represented by the number of pulses in a group.

8. Pulse Delay - Variation in pulse return time due to variation in the optical path length or velocity in the medium.

9. Pulse Duration - Pulse decay time. The variation of a pulse length as in temperature-dependent persistance of an ultraviolet-excited fluorescence.

10. Image Transmission - Transmission of position information as complete as a visual image of good resolution or as compact as the position of a shutter to three or four fiber positions.

11. Polarization Rotation - Variation in the relative magnitudes of the fast and slow modes of propagation within a polarization preserving single-mode fiber. The photoelastic effect will produce this rotation.

12. Digital Wavelength Coding - The presence of wavelength x asserts a bit within a parallel data word composed of n wavelength possibilities. Digital bits have distinct wavelengths.

5.0 FIBER OPTIC COMPONENTS

The fiber optic components needed to configure aircraft control system optical circuits include fiber cable, connectors, sources, detectors, and couplers. Effectors for actuation control and engine main and afterburner igniters are also needed. This section describes the aircraft application requirements and near-term usage recommendations for these components based on current capabilities. The information is summarized in Table 4.

5.1 FIBER OPTIC CABLE

Requirements include resistance to a wide temperature range, resistance to radiation, temperature cycling, aging, high-level vibration (50 "g's" on an engine), contamination, and handling abuse.

5.1.1 Single Fiber Versus Fiber Bundle

The majority of fiber optic lines carry data or pulses, and single-fiber paths are appropriate for these applications. Dual or even triple lines can be used for reliability, but they should be separated within the cables and connectors. Data from each can be merged at the sensor and/or detector electronics.

Fiber optic bundles are more susceptible to vibration damage and are more complicated to manufacture than single-fiber cables. Nevertheless, when raw optical energy is being transmitted, such as in the flame sensor, fiber optic bundles with a large overall diameter ($\cong$ 3 mm) allow more throughput.

5.1.2 Multi- and Single-Fiber Cable

The generic form expected for aircraft applications of a multifiber design consists of each fiber or fiber bundle, loosely buffered inside a sleeve, surrounded by a relatively soft layer for damping, and housed inside a solid tube for sealing and stiffness. A final outside layer provides abrasion resistance. For short harness assemblies, bundling single-fiber cables and splitting them off into separate cables is also possible, unless weight and bundle diameter become prohibitive.

A loose buffer tube prevents vibration energy and dimensional changes caused by temperature from being transmitted directly to the fiber. The fiber needs to be longer than the exterior cable parts to decrease tension over the temperature range. Since the buffer has a higher thermal coefficient of expansion than glass, a change in length forces the fiber into a helix shape, with losses associated with microbending and compressive forces.

A layer of loose fibrous material between the buffer tube arrangement and the outside protective layers would help absorb vibration, impact, and

Table 4. Needed Optical Component Development Status.

				Ready for use	Needs development	Not available
Fiber	Communication style-multimode (0.8 to 1.6 μm)	Up to 200° C: All applications except those given below			√	
		Up to 370° C : Aircraft position sensors, engine mid-range temperature and vibration sensors	Metal coated		√	
			All dielectric			√
		Up to 540° C: Engine upper range temperature sensors, turbine tip clearance and pyrometer	Metal coated		√	
			All dielectric			√
	Multimode UV (200nm to 300nm)	Up to 300° C: Engine flame detector			√	
Fiber cable	Single and multifiber	Up to 200° C			√	
		Above 200° C			√	
	Fiber bundle for pyrometer: up to 540° C				√	
Connectors	Up to 200° C				√	
	Above 200° C				√	
Passive MUX/DMUX couplers	Up to 70° C in A/C bay			√		
	Up to 125° C on engine with cooling				√	
	Up to 200° C on engine without cooling					√

Table 4. Needed Optical Component Development Status (Concluded).

				Ready for use	Needs development	Not available
Sources	LED 600 to 1500nm		Up to 70°C in A/C bay	√		
			Up to 125°C on engine for optical data bus	√		
	Laser Diode 800 to 1550nm		Up to 70 °C in A/C bay	√		
	Xenon Tungsten (white)			√		
Detectors	PIN Diodes	Silicon: 200 to 1000nm Germanium and Im Ga As: 800 to 1600nm	Up to 70°C in A/C bay	√		
			Up to 125°C for on-engine optical data bus	√		
	Avalanche for sensitivity		Up to 70°C	√		
	Tungsten photocathode for UV sensitivity; up to 125°C			√		
Effectors	Optically controlled, electrically powered torque motor				√	
	Optically controlled, optically powered torque motor				√	
Igniters						√

handling forces. The outer sheath or sealing tube should be lightweight and stiff but flexible enough to facilitate installation.

5.1.3 Cable to Connector Interface

The exterior layers of the cable need to be fastened to the exterior of a connector at the cable ends while the fiber and the loose tube are inside. There is currently no combination of cable and connector that is qualified for the 200° C environment. Given the changes in length described above and the limits of shear strength of adhesives so far used, axial movement of the fiber within the contact (pistoning due to temperature cycling) has been an insoluble problem. The backshell strain relief must be long and supportive of the fibers to insulate the delicate fiber/connector interface from vibration.

Techniques in fusion splicing of optical fibers are rapidly improving. A completely fusion-spliced system is recommended on the airframe. Reliability would improve by eliminating connectors, but supportability would suffer. Such a system would use fused, replaceable lengths of fiber in each cable run.

5.1.4 Qualification-Tested Cables

At least two manufacturer's fiber optic cables have been successfully tested to the requirements (-55° to 125° C and 15 "g's" from 10 to 500 Hz) of MIL-STD-1760 Aircraft/Store Interconnection Standard System (Reference 1). Use on aircraft will require formulation of new standards.

5.2 OPTICAL FIBERS

Three environmental temperature ranges can be identified, as shown in Table 4. For typical sensor data communication, single multimode fiber with a 100 to 200 μm or larger core is recommended. Many glass and quartz fibers will withstand the lower temperature range, so sensor design will probably dictate the fiber size and numerical aperture. For temperatures above 200° C, the organic coatings on current fibers are a limitation. Borosilicate or metal-clad silica fibers are high-temperature candidates currently available.

5.2.1 Mode losses

Given the use of multimode fiber, a fiber type that is either larger in core diameter or numerical aperture (NA) will allow more energy to be launched. Launch efficiency is a concern with sensors that use extrinsic techniques such as reflection from a toothed wheel. Fibers with larger NA carry more modes at higher angles, but these are the first modes lost due to vibration, microbending, index change with temperature, and other phenomena. It is better to improve launch efficiency by using larger diameter fibers. Previous work has found that modal noise and detector efficiency is improved by underfilling the modal volume of transmission fibers (Reference 2).

5.2.2 UV Transmission

Some sensor techniques require transmission to wavelengths as short as 200 nanometers. This limits the choice of materials to silica or sapphire. Sapphire optical fibers of useful quality are not yet available, and even the more developed silica technology does not transmit enough for the distances involved.

It is suggested that a flourescence technique may be useful to enable sensing of short wavelengths. There are currently available optical fibers that have an ultraviolet (UV) absorbing dye. The absorbed energy is released in photons of near 600-nm wavelength - transmissable through a much longer distance. A silica or sapphire fiber can receive UV energy in the thermally hostile area and transmit it a short distance, say one meter, to be connected to the flourescent fiber, and then to conventional fiber back to the control.

5.2.3 Single-Mode Fibers

The vast majority of fiber optic sensors reported in the vendor survey do not require single-mode fiber. A promising sensor requiring single-mode fiber would have to be traded against characteristics of this fiber which are less desirable. The core of single-mode fiber is on the order of 5 to 10 μm, making connector tolerances on the order of 1 μm. Multimode fiber connector tolerances for equivalent insertion loss are at least an order of magnitude larger. Further, some sensors that use single-mode fibers would require the use of laser diode sources which are environmentally sensitive.

5.3 FIBER OPTIC CONNECTORS

Presently, there are two styles of standard connectors which may be applicable to aircraft fiber optic systems, after some temperature-rating improvement. They are the best commercially available starting-point designs. The stainless steel SMA style, per MIL-C-83522 for single-fiber connections or small bundles, and the MIL-C-38999 style, with fiber optic inserts for multi-fiber cables, have advertised ratings to 71° and 125° C respectively. The UH-60A helicopter (Reference 3) uses a multifiber connector (Reference 4) meeting the requirements of MIL-C-28876, limited to 85° C. The materials used have the temperature resistance in themselves, but additional attention must be given to vibration, material expansivities, and oxidation resistance at temperature. Higher temperature range applications will likely require new designs.

5.4 OPTICAL SOURCES

Optical source choices include light-emitting diodes (LED's), laser diodes, tungsten, xenon, and many others. The LED offers the best combination of reliability, power usage, and efficient use of space.

5.4.1 Reliability

LED's are currently available in standard Mil-Spec packages that can operate from 25° to 125° C with 3 dB of loss, covering a broader wavelength spectrum than laser diodes. Life at 125° C is likely to be more than 10,000 hours. Operation at 180° C has been demonstrated (Reference 5).

Compared to LED's, laser diodes are the more electrically efficient but use more power and have significantly shorter life. The upper temperature limit is about 70° C without thermoelectric cooling. Tungsten sources are less efficient and less reliable than LED's but provide broadband wavelengths. Xenon sources are typically much larger and have the added complications of needing high voltages to start and creating EMI.

5.4.2 Available Spectra

LED's discontinuously cover a wavelength range from about 480 to 1550 nm. Laser diodes are commercially available from 780 to 1550 nm. Wavelengths shorter than 800 nm suffer significantly more transmission loss in optical fibers, and industry has not concentated on speed, power, and fiber coupling for existing products in that spectral range. From 800 to 1550 nm, with currently avilable devices, six spectral channels may be used on one transmission fiber with good separation. Since temperature affects the optics that presently MUX and DMUX the channels, a range of -54° to 125° C would probably require about 20 nm of buffer distance between spectral channels (edge to edge) to prevent crosstalk. This channel spacing will improve to allow more channels per fiber.

5.4.3 Optical Power

Laser diodes can launch much more power into a fiber optic system than any other source. While source outputs will continue to improve, laser diodes will always have about a 10× advantage because of the higher energy level and inherently narrow angular beam.

5.5 OPTICAL DETECTORS

Detector requirements are largely influenced by sensor design. Variables include different spectral regions, levels, sensitivities, and response times.

5.5.1 Solid State - Avalance Versus PIN Diodes

Silicon PIN photodiodes have adequate sensitivity, speed, and linearity for most applications. They are less temperature sensitive, require less surrounding circuitry, and cost less than other candidates. Avalanche photodiodes can provide 100× more sensitivity than the PIN type but require higher bias voltage levels and sacrifice linearity.

The best optically sensitive materials for solid-state detectors are silicon from 200 to about 1000 nm and germanium, indium gallium arsenide (InGaAs), or indium gallium arsenide phosphide (InGaAsP) from 800 to 1600 nm. Because optical sources have also been made in InGaAs, it will become possible to integrate sources and detectors for transmit/receive functions on the same substrate.

5.5.2 Tube Detectors

For extreme sensitivity at shorter wavelengths, a tube device may be considered. They are available in packages as small as 12-mm diameter with mechanics rugged enough to meet aircraft requirements. Tube-style detectors use a variety of photocathodes; the UV sensitive material required for flame detection is tungsten.

5.6 PASSIVE OPTICAL COMPONENTS

Passive optical components are used to direct optical energy among the various paths and are necessary for reducing control system cabling in the protocol branch architecture as described in Section 6.3. The distribution of energy can be determined by spectral content or the state of polarization, or the energy may simply be split at some ratio. Couplers can be made spectrally selective so that energy from several spectral sources is coupled to one transmission fiber to multiplex, and conversely to demultiplex, although temperature sensitivity is a limitation in aircraft applications. A coupler can combine energy between fibers in both directions. A tap can be used to monitor the energy within a fiber.

5.6.1 Coupler Types

Fused couplers place the cores of two or more fibers in proximity so that the evanescent waves couple energy between them. The distance between cores, indices of refraction, and length over which the coupling occurs control the amount of coupling and wavelength selectivity (Reference 6). One wavelength-selective device using the evanescent wave technique is made in integrated form of InGaAsP (Reference 7), offering the possibility of including spectral MUX/DMUX devices with the source and detector instead of separate components.

Couplers can also be made of bulk optic components scaled down to fiber optic compatible sizes. Taps, polarizing couplers, and spectral MUX/DMUX couplers have been made with small lenses and beam splitters. Often the lenses are of the graded index type. Another bulk optic style for spectral MUX/DMUX is made with a grating and reflective spherical surface (Reference 8). It is completely monolithic and can be made in quartz for temperature resistance. It is capable of multiplexing a large number of spectral channels with competitive efficiency.

5.6.2 Environmental Limits

The highest temperature capability available commercially is 125° C for some couplers. Reference 9 describes the design of temperature-insensitive, single-mode couplers. Multimode types, with many more modes and broader spectral range, may not have that capability. The quartz grating/reflector type mentioned above is likely to work at least to 125° C. High ambient temperatures limit the usefulness of engine-mounted passive couplers. The fused couplers and the grating/reflector types are expected to be resistant to engine vibration, but the beam-splitter/filter and graded-index lens styles will require close attention to mounting techniques.

5.7 EFFECTORS

Three options for a fiber optic effector are identified as follows:

1. Optically Controlled, Electrically Powered Torque Motor Driving a Hydraulic Actuator - Requires optic, electric, and hydraulic supply systems. Probably the best near-term approach because it uses conventional electrical torque motors and demonstrated high-temperature GaAs technology. Electrical cables/circuitry are present.

2. Optically Controlled, Optically Powered Torque Motor Driving a Hydraulic Actuator - Optic and hydraulic supply systems are required. Photovoltaic cells drive electrical torque motors. Electrical circuitry is present.

3. Optically Powered Direct Opto/Hydraulic Actuation - Candidate fluidic conversion techniques include:

   a. Photoacoustic Effect - Switching element is composed of optically active crystalline material with a large photo-acoustic coefficient; incident light energy changes the dimensions of the switching element, or pulsing incident light excites mechanical vibrations. Hydraulic energy can be switched among resonant-frequency-tuned output ports.

   b. Photothermal Shock - Very fast rise-time incident optical pulse generates a thermal shock wave that changes the state of a fluidic switch.

   c. Bimetallic Valving - Thermal energy/incident light bending of a small bimetallic switching element.

5.8 OPTICAL IGNITION

The high voltage and electrical fields associated with electric spark ignition on an aircraft engine could be produced by using optical energy to excite ignition. Required energy per spark is estimated at one millijoule. This is electrically 1000 volts at one milliamp for one millisecond. A typical infrared-emitting diode can deliver one milliwatt of power, which means one second to achieve a millijoule. However, the energy comparison is not direct because of losses in efficiency between the optical output and the spark. The following are some possible theoretical approaches.

Electical-Field-Generated Spark - Because light waves are time-varying electric fields, it is possible to create the field strength necessary to ionize air (create a spark). This has occurred as a nuisance in high-energy laser experiments. High-quality optics are required.

Thermally Generated, High-Temperature Pulse - A high-temperature source for ignition can be produced by directing a large-energy optical signal at a thermally well-isolated absorbing body. Absorption and conversion to heat can be 50% or more efficient.

Photochemically Generated, High-Temperature Pulse - An optical signal can be used to liberate chemical energy. The ignition source is the chemical reaction produced by irradiating a target of photoactive material. Also, a photoactive material could be added to the fuel or combustion chamber. A similar technique has been used for aircraft missile ignition.

Direct Photoelectrical Conversion Generated Spark - An optical signal can be converted to an electrical current with efficiencies up to 10%. High spark voltage could be transformed from a low-voltage, optically generated current. Alternatively, the current could be used to charge a capacitor until the voltage level required for a spark is reached. Circuitry near the combustor would be temperature limited, and the rate of optical energy deliverable currently falls short of requirements.

6.0 INTEGRATED FIBER OPTIC CONTROL SYSTEM

6.1 INTEGRATED AIRFRAME/PROPULSION CONTROL SYSTEM ARCHITECTURES (IAPSA) STUDY

An advanced fighter aircraft for the 1990's is postulated to require highly coupled and integrated flight and propulsion controls to achieve the needed mission performance and maneuver capability. Phase I of the IAPSA study (Reference 10) conducted by Boeing Military Airplane Company (NAS1-16942) investigated the benefits of integrated control system architectures for future high-performance aircraft. The following discussion summarizes the results of that study which influence the fiber optic control system chosen for the FOCSI study.

IAPSA examined and compared the features of six advanced architectures. Two architectures were chosen for detailed study: the distributed system (D/D) using modular construction and high-speed data buses for intersystem communication and the centralized/direct-connected system (C/D) using high-speed computers and optical technology to concentrate the electronics in centralized locations.

The IAPSA evaluation selected C/D architecture as having the greatest payoff in meeting 1990's supersonic military aircraft system requirements, as shown in Table 5. System maintainability and vulnerability were the most important factors. Low line-replaceable unit (LRU) count, due to integration and centralization of flight, engine, and inlet controllers, promoted high maintainability. Vulnerability to combat damage and EMI/EMP was minimized by low LRU count and optical technology. Low LRU count was also beneficial to reliability and life-cycle cost. C/D architecture posed a higher technical risk in the areas of fiber optics and fault-detection schemes; however, it was reported that sufficient lead time should resolve these issues.

Table 5. IAPSA Analysis Results (from Reference 10, p 6-23).

Grading Area (Weighting)	Baseline		Distributed		Centralized	
	Grade	Weighted Grade	Grade	Weighted Grade	Grade	Weighted Grade
Reliability (3)	1	3	2	6	3	9
Maintainability (2)	2	4	1	2	3	6
Availability (2)	2	4	2	4	3	6
Life-Cycle Cost (3)	1	3	2	6	3	9
Flexibility (1)	1	1	3	3	2	2
Computing Requirements (1)	3	3	3	3	2	2
Complexity (2)	2	4	3	6	2	4
Vulnerability (2)	2	4	1	2	3	6
1990 Technical Risk (1)	3	3	3	3	2	2
Thermal Immunity (1)	2	2	1	1	3	3
Weighted Total	31/18 = 1.72		36/18 = 2.00		49/18 = 2.72	

The many benefits of low LRU count in a centralized system would be negated without the use of fiber optic sensing. In a centralized electrical system, sensors distributed throughout the aircraft would require long wiring harnesses that are unacceptable from a weight and (in composite aircraft) EMI/EMP standpoint. Fiber optic sensing is an enabling technology for a centralized system, especially if the protocol branch method of connecting the components is employed, as described in Section 6.3.

6.2 CENTRALIZED/DIRECT ARCHITECTURE

The total fiber-optic, integrated propulsion/flight control architecture concept chosen for FOCSI study is the centralized-computing/direct-connected or centralized/direct system, echoing IAPSA. A schematic of the architecture is shown in Figure 7. All of the electronic components are located in two central, cooled bays. All of the sensors and actuators are interfaced with optical fibers. Engine and airframe control surface actuators are optically controlled and hydraulically powered. A detailed discussion of the off-engine propulsion control is presented in Section 6.5.

In addition to the advantages described in the preceding general IAPSA conclusions, C/D architecture also provides the following benefits:

- Order of magnitude better electronics reliability.
- Maintenance interval determined by optical device reliability.
- Life-cycle cost driven by optical components and highly reliable electronics.
- Simpler environmental control system.
- Simplified electrical power distribution and interrupt protection.

6.3 PROTOCOL BRANCH METHOD

The variety of fiber optic sensor transmission protocols was described in Section 4.2.2. The multitude of options in specification of a complete fiber optic C/D system requires an efficient methodology to connect the optical protocol fibers directly from optical termination cards in the centralized bays to the sensors and/or actuators. By grouping the sensors on the aircraft into branch groups, the task of evaluating all the possible combinations is greatly reduced. Appendix B includes a description of how the protocol branch method relates to sensor selection.

The protocol method of optical system configuration begins with selection of candidate protocols that have the necessary robustness to survive the aircraft environment without loss of data integrity. Next, sensor/actuator functional groups are defined by location or task similarity; the issues of

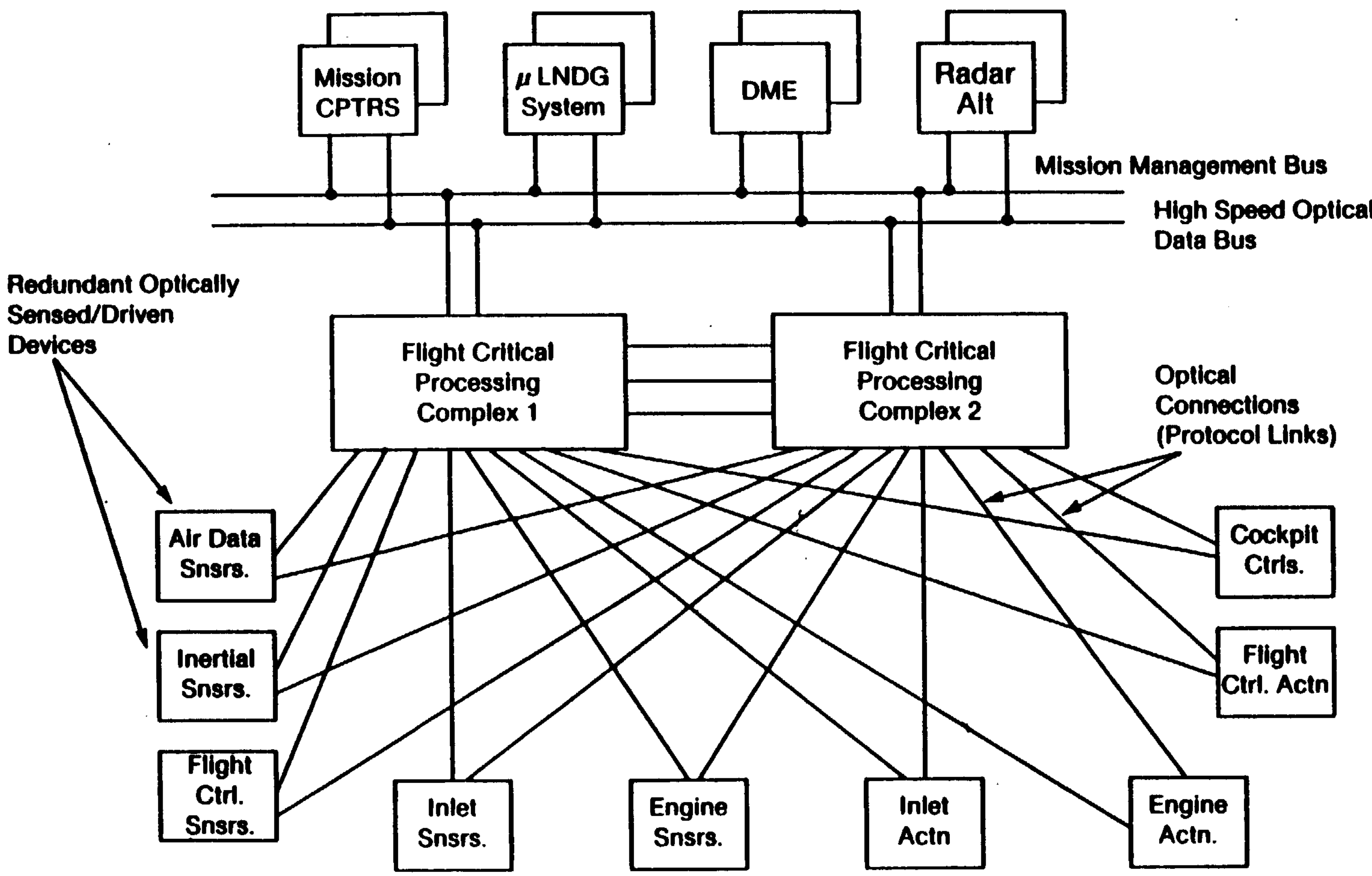


Figure 7. FOCSI Centralized/Direct Architecture.

reliability and redundancy may also be addressed. Functional groups are then assigned to candidate protocols, defining protocol branches, and tradeoffs among protocol and device characteristics are evaluated. Reference 11 gives a step-by-step example of the protocol branch method as applied to the wing of an advanced fighter aircraft.

Each optical termination card in the centralized bays will support a single protocol and communicate with between 1 and 16 groups of devices, or branches, as shown in Figure 8. Each card converts the multiplexed optical protocol information coming in on the fiber into meaningful, compensated, linearized data going out on the computing system backplane.

6.3.1 Preliminary Protocol Branch Selections

The following chart shows protocol branch selections that have robustness necessary to survive in an aircraft environment and are currently supported by enough devices to make them feasible.

Protocol	Pros	Cons
Wavelength-Referenced Intensity	• Good MUX-ability • Many Device Types • F-P Devices Very Accurate	• Limited Update Rate (Presently 10-200 kHz)
TDM Code	• Fast Update Rate • Excellent MUX-ability	• Delay Coil Bulky • 1% Accuracy
WDM Code	• Very Fast Update • Small Devices	• Uses Broad Spectrum
Pulse Rate	• Simple Devices • Rapid Update	• Limited Device Types
Pulse Length	• Supports Midrange Temperature Sensor	• Limited Device Types

The wavelength-referenced-intensity protocol is an example that is highly multiplexable and supported by many devices. Figure 9 shows two examples of optical position sensor concepts using the wavelength-referenced-intensity protocol. Example A employs multiple wavelengths while example B uses only a single wavelength referenced to a constant wavelength. Appendix B describes in detail the most suitable decoding for optical sensors in the recommended far-term architecture. The optics of the receiver card may be implemented in a very general way with the use of a dispersive element, such as a corrected

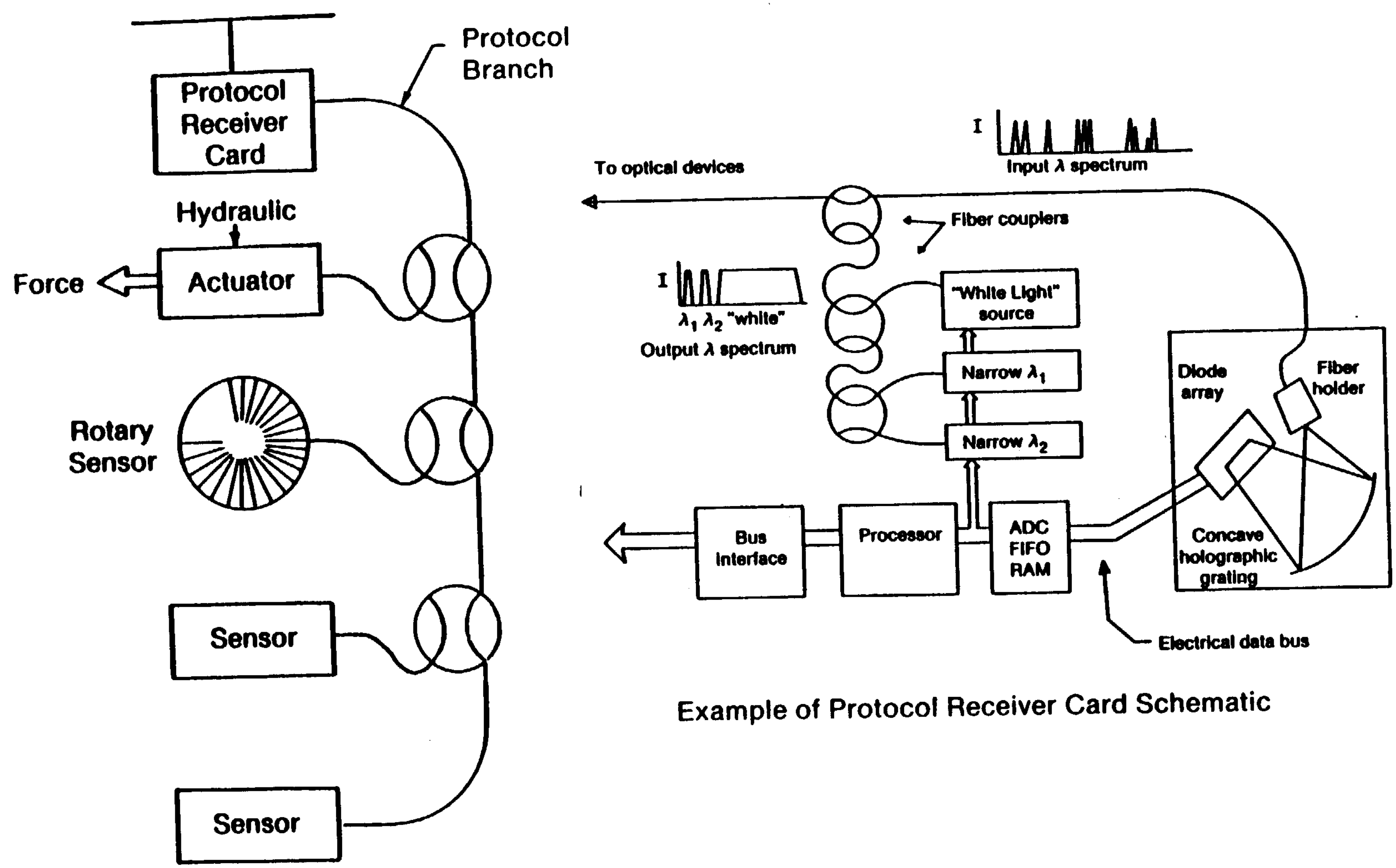
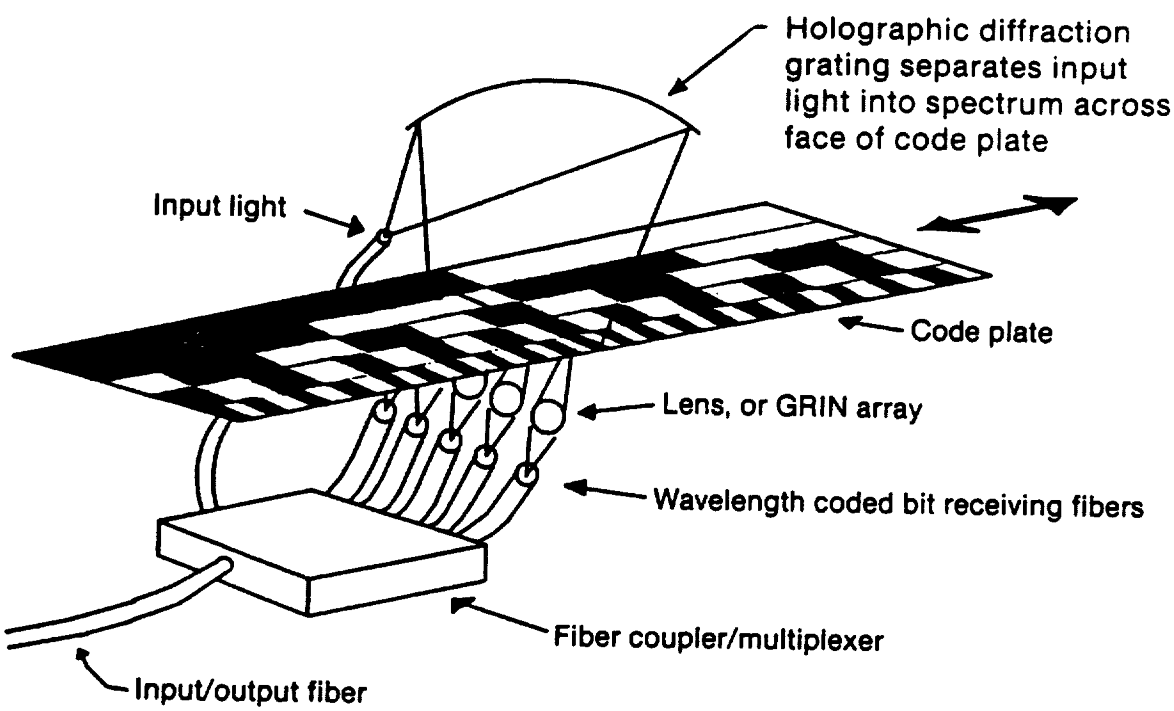
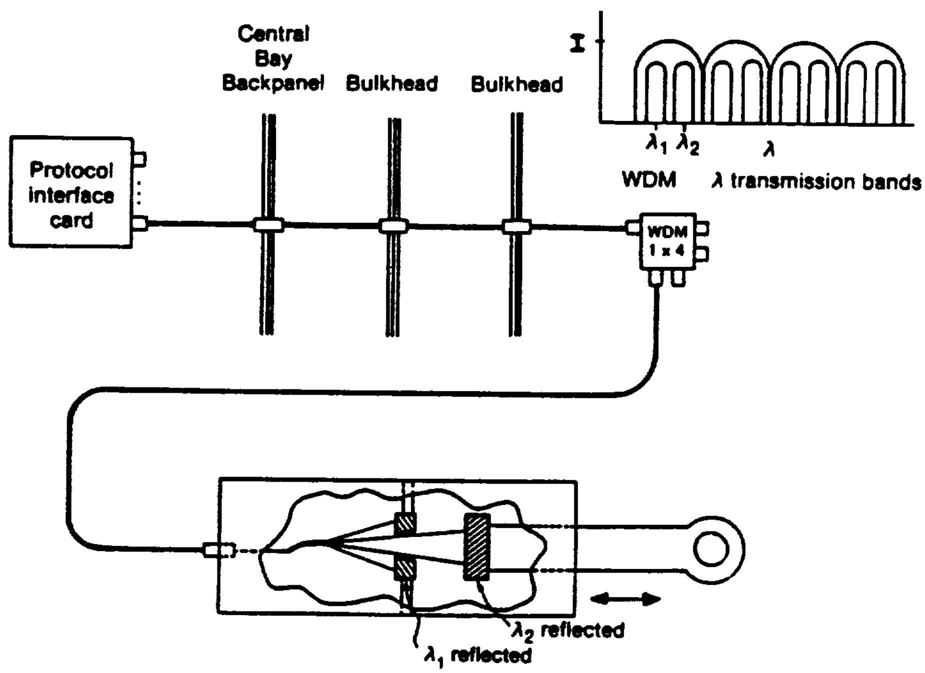


Figure 8. Protocol Branch Configuration Example.



a) Position Sensor Using Wavelength Division Code Plate Decoding



b) Position Sensor Using the Difference of Two Wavelengths Decoding

Figure 9. Examples of Sensors Using Wavelength-Referenced-Intensity Protocol.

holographic grating, and a dense linear array of photodiodes. These two components form an optical spectrum analyzer and provide information on the complete spectral content. This analyzer will support the following decoding capabilities:

- Fabry-Perot Decoding: Multiplexing is possible by differences in finesse. Many accurate sensor types are possible.
- Wavelength 1 - Wavelength 2 Decoding: Allows tracking spectral drift and broadening; capable of multiplexing 10 to 50 devices.
- Wavelength Resonance Decoding: Spectral gap shift; possible integrated optic sensor.
- Peak Wavelength Shift/FM Decoding: Grating distortion, birefringence.
- Pyrometer Blackbody Temperature Decoding: Possible to multiplex pyrometers by selecting pairs of infrared wavelengths for each, with each pair being separated by a µm of wavelengths.
- Wavelength Division Code Plate Decoding

6.3.2 Optical Tools for Protocol Branch

Optical systems and networks require different tools than those needed by electrical systems. Several general tools are already available: optical multimeters contain an LED and a detector to enable power, attenuation, and continuity measurements; optical spectrum analyzers reveal frequency content; fiber fusion splicers produce solder-like joints.

The protocol system requires specific tools currently not available. A sensor simulator attached to the optical fiber in place of any sensor could analyze sensor input light characteristics and provide sensor return light to evaluate conditions of the fiber branch and receiver card. A tool attaching to the fiber in place of a protocol receiver card could provide light to stimulate a sensor and to drive and analyze aircraft protocols including sensor output characteristics. A slot usage meter mounted in-line between the receiver card and the branch could analyze the occupancy of possible protocol ports, or slots. A fault simulator attaching at any optical port, or in-line with devices, would aid system checkout and verification by fault injection.

6.4 FLIGHT CONTROL SYSTEM DESCRIPTION

Using the protocol branch method, the F-18 flight control system can be configured into the following preliminary functional groups for a fiber optic control system:

Group	Redundancy	Members	Protocol
Rudder	2	Servocylinder, Rudder	$\lambda_1 - \lambda_2$
	4	Pedals, Rudder, Position	
	4	Stick, Control, Pitch Position	
	4	Stick, Control, Roll Position	
Controls	1	Switches, Panel, Stick, Speed Brake, Wing Lock, Fold	$\lambda_1 - \lambda_2$
	2	Actuator, Trim, Longitudinal Feel	
	2	Release, Ram Air Door	
Sensors	4	Gyroscope, Rate	Pulse Rate, Width
	4	Accelerometer, Linear	
	4	Angle of Attack	
Aileron	2	Servocylinder, Aileron	WDM Digital
	2	Servocylinder, Leading-Edge Flaps	
Stabilator	4	Servocylinder, Stabilator	WDM Digital
	4	Servocylinder, Trailing-Edge Flaps	

6.5 PROPULSION CONTROL SYSTEM DESCRIPTION

6.5.1 Near Term

The near-term propulsion control system approach is directed toward aircraft implementation in the 1995 time frame, using technology that must be frozen by 1988-1989. The configuration for this study was defined to include an engine-mounted Full-Authority Digital Electrical Control (FADEC) with all engine-mounted sensors and cables remaining electrical. Possible exceptions are the pyrometer and/or light-off detector using fiber optics to eliminate the need for fuel-cooled sensor electronics. In addition, near-term optical position or speed sensors could be introduced to acquire engine-mounted experience.

The main difference from the present advanced engine configuration is communication between the engine and airframe through an optical data bus. This reduces the electromagnetic interference threat on the relatively long electrical cables and allows compatibility with an all-optic airframe but requires addition of an electrical/optic data bus coupler. Figure 10 shows this near-term approach applied to the F404 control system.

It may be possible to develop some optical sensors for near-term application, with the benefits of reduced cable weight and possibly reduced sensor complexity. However, since many of the sensors will not be ready, the full

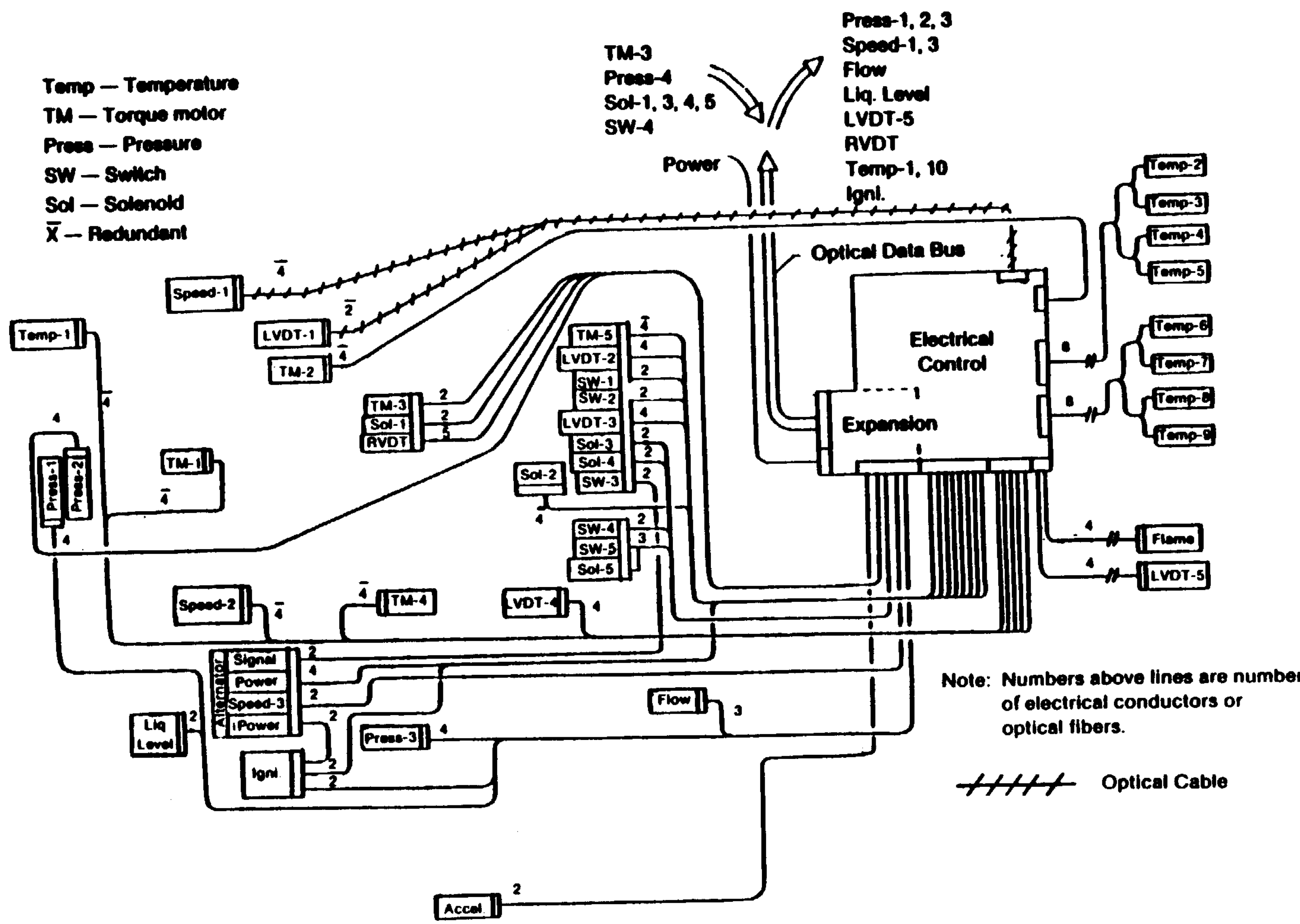


Figure 10. F404 System Rollout for Near Term Fiber Optic Aircraft.

benefits of a total fiber-optic, integrated C/D aircraft system will not be realized. Also, moving the FADEC to the aircraft bay is too drastic a change to occur in the next two to three years, since engine-mounted controls are predominant. Additionally, the mixture of supportability tools and addition of optical/electrical interfaces to the engine control make a part-electrical/part-optical system less favorable. The described near-term approach could serve as a test-bed for propulsion system optical components.

6.5.2 Far Term

The far-term propulsion system approach is directed at aircraft implementation and flight qualification in the year 2000 time frame and later. It takes advantage of airframe all-optical protocol branch architecture by moving the FADEC to the aircraft bay. Communication with the engine optical sensors is through engine-mounted optical couplers that must be developed to permit operation in high-temperature environments. Some possible protocol branch groupings for the F404 sensor set are as follows:

- Digital-pulse-coding branch: positions, liquid level
- Pulse-rate branch: speeds, flow, inlet temperature (pulse delay based on fluorescence decay)
- Wavelength-coded branch: pressures and switches
- Amplitude-variation branch: turbine temperature, flame detector, accelerometer
- Pulse-duration branch: torque motors and solenoids

Figure 11 shows the far-term approach applied to the F404 control system, with all sensors becoming optical. To demonstrate this kind of system on the F404 engine would require replacing all sensors, using the fuel control as only a fuel valve, reconfiguring the cable set with protocol couplers, and redesigning all computation for mounting in the aircraft bay.

The engine electronic control could now be conceived of as consisting of processor cards and protocol cards, mounted in an enclosed chassis or pod. It would be adjacent to and interface with the same power and data connections as other flight control cards through backplane electrical and optical connectors. It would be accessed only by an engine manufacturer technician.

6.5.3 Off-Engine FADEC Accountability

An engine-mounted propulsion control provides a complete propulsion system with a fully assembled and tested control system prior to aircraft installation. This assures fault isolation and accountability, thus avoiding airframer and engine manufacturer logistics problems. This has been the traditional approach throughout the propulsion industry.

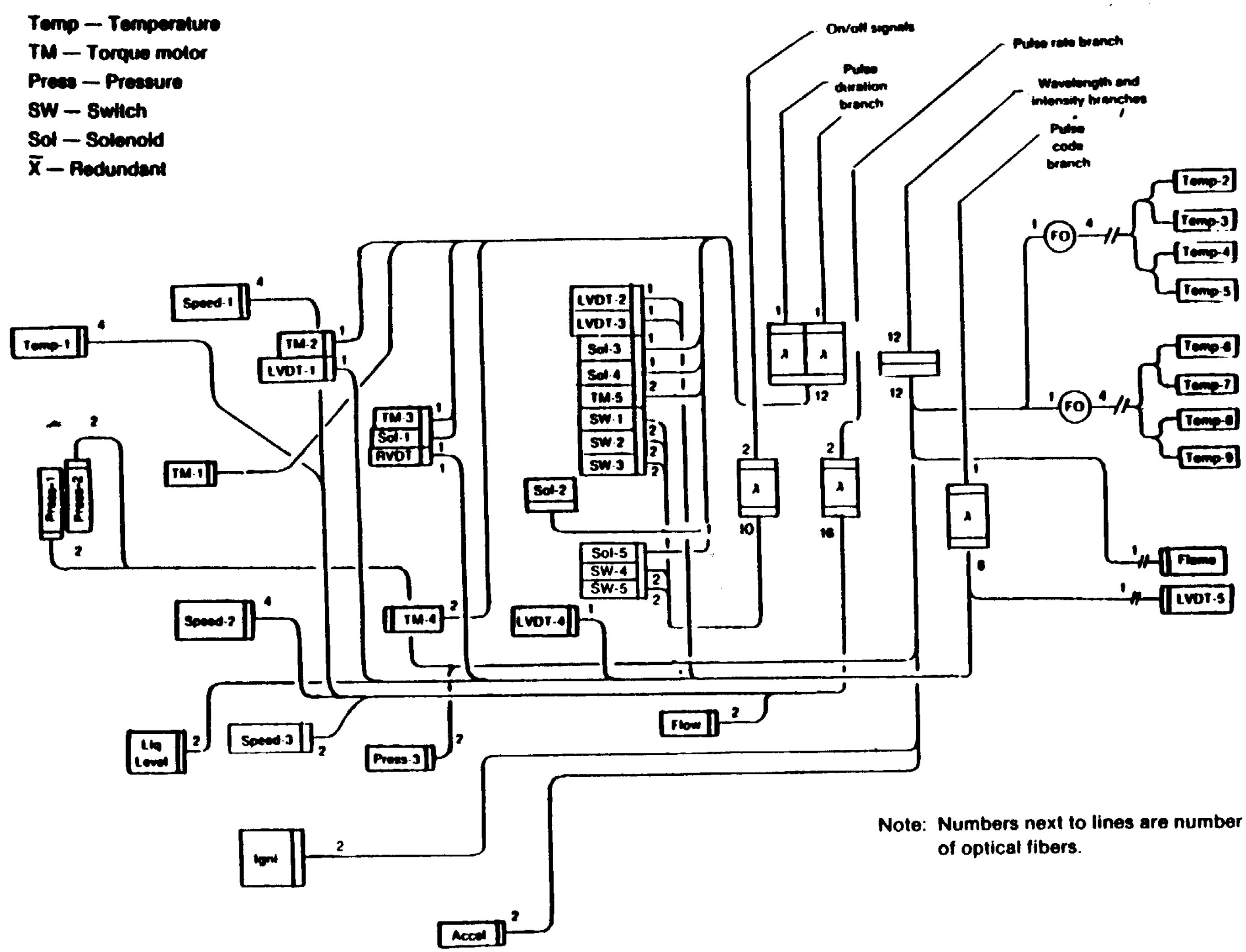


Figure 11. F404 System Rollout for Far Term Fiber Optic Aircraft.

Moving the propulsion control to the aircraft bay as a separate entity, in order to eliminate engine-mounted electronics, should not open up new approaches to control responsibility. The engine control and interface connections should remain essentially parts of the propulsion system, even though separated from the engine by fiber optics and integrated with the flight control computer. The propulsion system could still be independently tested using a flight control computer simulator.

Fully hardware-integrated fiber optic propulsion/flight control system concepts are described as embedding engine electronic control computation within the overall flight control. If justified by trade study results, a new approach to accountability must be formulated.

6.5.4 Pressure Transducer Location

A fully fiber optic integrated control system assumes moving the engine electrical control to the aircraft bay. Electrical pressure sensors are usually mounted in the on-engine control and connected with pneumatic tubing to the sensing site. The control chassis provides vibration isolation and a reduced-temperature environment. Time delay of the pressure signals precludes moving the sensors to the bay with the control electronics.

Engine mounting of the pressure transducers in a separate chassis that must be separately cooled increases life-cycle cost and decreases reliability by increasing system complexity. However, this is just the approach being strongly considered for advanced FADEC systems, even though the FADEC remains on the engine. With the number of pressure transducers on advanced engines, say 10 per channel, it is advantageous for allocation of computer time to provide them with a separate processor. In fact, they may turn out to be "smart" transducers. Also, a separate box for pressure transducers may more efficiently assign the roles of controls component designers and control computer designers.

Fiber optic pressure transducers, in a fully optical system, would not contain electronics. Normally, for electrical transducers, electronic compensation is performed within each transducer. It should not be assumed that fiber optic transducers need as much compensation as electrical transducers. A considerable part of electrical transducer nonlinearity is from temperature effects in the electronics themselves. In low-accuracy applications such as the F404, pressure transducers are mounted directly on the engine casing. It seems reasonable that fiber optic transducers without electronics may achieve acceptable performance. It remains to be seen, however, whether materials can be chosen for fiber optic pressure transducers to minimize temperature and other effects.

6.5.5 Addressing Off-Engine FADEC Issues

Studies have been performed to assess the advantages and disadvantages of on/off engine-mounted control locations (Reference 12). Results have shown that engine-mounted control configurations are preferable. The emergence of optical technology is likely to impact control system design in the 1990's. This impact will justify reevaluation of the following on-engine versus off-engine control issues:

Issue: Reliability - Failures of aircraft supplied power and cooling to an off-engine control would cause loss of all engines.

Response - Present aircraft flight controls use highly redundant power and cooling supply configurations. Engine-generated power could be a secondary source. Failure of an on-engine control due to cooling loss would be more rapid.

Issue: Reliability - Reliability through multiple engines is compromised if engine control systems are combined in any way.

Response - The centralized aircraft control could be housed in at least two redundant, physically separated areas, each capable of controlling both engines.

Comment - Reliability of electronics mounted in the centralized, less hostile temperature and vibrational environment is significantly improved.

Issue: Vulnerability - A single localized aircraft control is vulnerable to a single battle-damage occurence and loss of the total aircraft.

Response - Redundant central bays can be physically separated and located strategically.

Issue: Vulnerability - Longer control cables and additional connectors between the engine and bay are more vulnerable.

Response - The weight advantage of fiber optics can be translated to increased redundancy.

Comment - Optical cables should eliminate potential signal interference occurrences.

Issue: Life-Cycle Cost - On-engine control location shows significant reduction in recurring and acquisition cost of the control.

Response - From a total aircraft viewpoint, elimination of many LRU's in a centralized system should reduce LCC. The bay provides commonality and simpler cooling.

Comment - Lack of need for EMI shielding and lighter weight of optical fibers greatly reduces the weight penalty of sensor cables in a centralized system. Use of protocol branch method to multiplex signals further reduces weight.

7.0 PROPULSION SYSTEM TRADE STUDIES

7.1 TRADE STUDY PROPULSION SYSTEMS

Figure 12 shows five propulsion control systems for the trade study evaluation. They are intended to allow assessment of the major electrical/optical components as a system. They are not intended to imply a specific connection configuration. System A is the all-electrical baseline; systems B through E are alternate concepts to integrate with an all-optical airframe. Table 6 lists normalized weight/area estimates for each system based on an F404 on-engine cable set (six multibranched harnesses), present advanced FADEC programs, and recent fiber optic component design estimates.

Table 6. Normalized Weight/Area Estimates for Trade Study Propulsion Systems.

	A *		B		C		D		E	
System	Weight	Area	Weight	Area	Weight	Area	Weight	Area	Weight	Area
	* 1.0 is baseline									
Engine-Mounted Control; Triplex Cable Set	1.0	1.0	1.0	1.0	1.0	1.0	0.5	0.9	0.5	0.9
Engine-Mounted Triplex FADEC (A, C, and D) or Triplex Protocol Couplers (E)	1.0	1.0	0	0	1.0	1.0	1.2	1.2	1.0	1.0
Data Bus Couplers (A, C, and D)	1.0	1.0	0	0	1.0	1.0	1.0	1.0	0	0
Data Bus (A, C, D) or Interface Cables (B) or Protocol Cables (E)	1.0	1.0	20.0	6.4	0.5	0.9	0.5	0.9	2.0	2.0
Flight Control Module (Including FADEC in B and E)	1.0	1.0	1.3	1.3	1.1	1.1	1.1	1.1	1.0	1.0

System A is a baseline present FADEC system. The aircraft is assumed to be electrical. Data bus couplers are mounted on the thrust frame.

System B is the same as A except the FADEC is moved to the aircraft bay. FADEC is now in a less hostile environment. There is a large increase in cable area and weight between the engine and the aircraft bay.

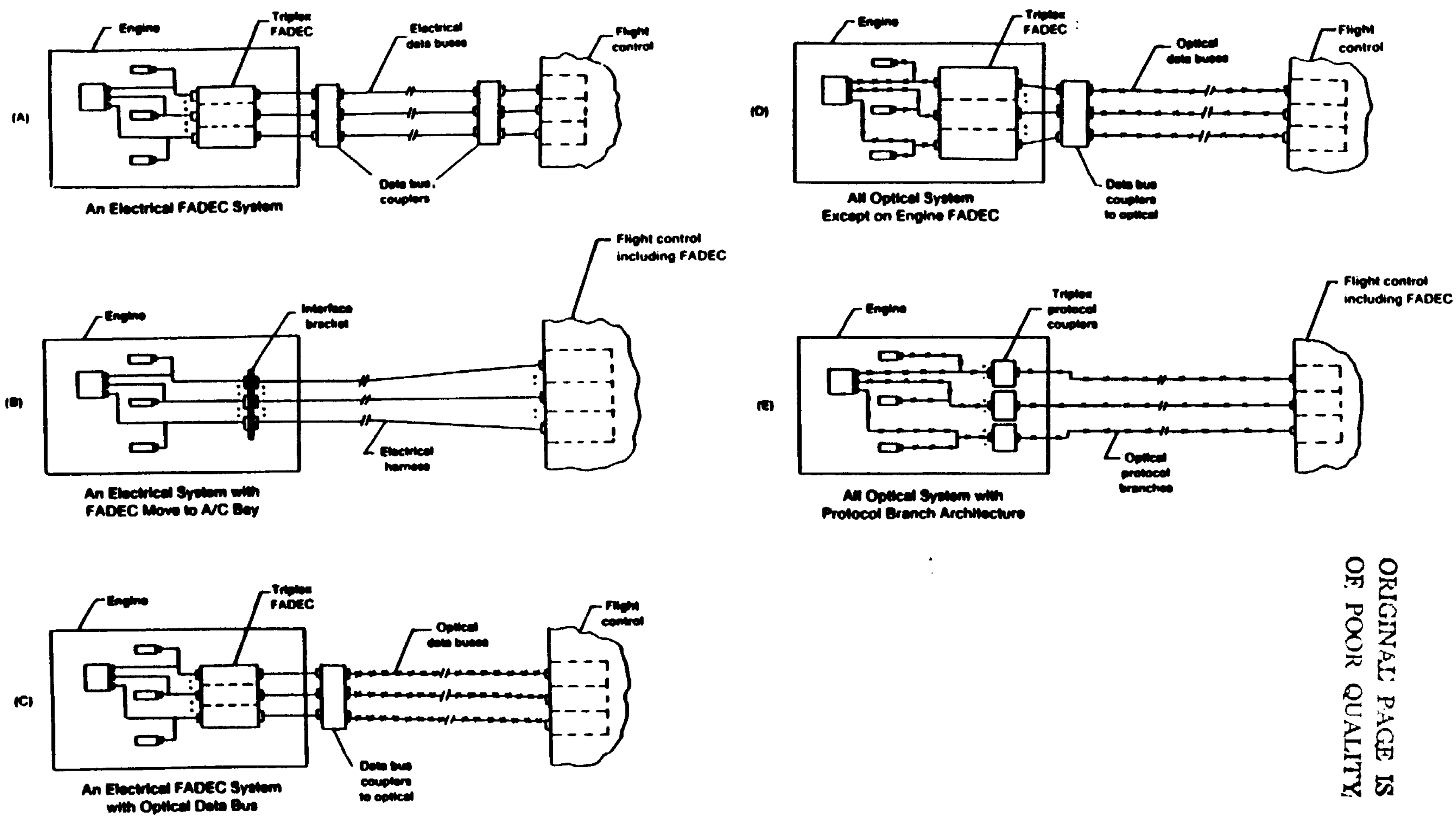


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Figure 12. Propulsion Control Systems For Trade Study.

System C is the same as A except there is an optical data bus between the engine and the aircraft bay. The long cables are now compatible with the optical airframe and weigh less.

System D is the same as C except all sensors/components/cables on the engine are optical. FADEC must grow to incorporate the optical/electrical conversion. On-engine cables are configured to take advantage of optical protocols and will weigh less.

System E is the all-optical approach with FADEC in the aircraft bay. Fiber optic protocol branches run between the engine and aircraft. Although similar in weight to the baseline FADEC, the three coupler channels do not intercommunicate and are easily separated to decrease vulnerability.

7.2 SUPPORTABILITY STUDY

7.2.1 Approach and Assumptions

Each system was evaluated relative to System A, the electronic baseline, in four major areas. The baseline system was assigned a nominal rating of 5 in all categories. For each proposed alternative system, a qualitative judgement in each category was made in comparison to the baseline. A higher value (>5) indicates a better evaluation; a lower value (<5) is worse.

One key assumption was that costs for fiber optic sensors, effectors, components, cables, and support equipment and reliability of fiber optic sensors, effectors, components and cable will eventually be comparable to those of current electronic items. Another assumption was that the aircraft bay is significantly less hostile in terms of temperature, vibration, and contamination and allows a lower weight design for the electronics than an on-engine location.

The results are shown in Table 7. A definition of each evaluated area and a discussion for each system evaluation versus System A follows.

7.2.2 Reliability

Operational reliability is relative capability of a system to function in terms of mean time between system inoperability. The Mean Time Between Maintenance Actions (MTBMA) was used to evaluate overall system reliability.

For System B, operational reliability is improved, but redundancy will already have driven the failure rate into the 10^{-7} to 10^{-6} events per flight hour regime, so improvement is negligible. The MTBMA for the FADEC will improve substantially, but additional cable complexity and length may degrade this somewhat.

Operational reliability is essentially the same for System C. The MTBMA will be reduced due to the addition of the data bus optical coupler. Optical

Table 7. Propulsion System Supportability Trade Study Results.

	System				
	A	B	C	D	E
Reliability					
Operational	5	5	5	5	5
MTBMA	5	6	4	3	7
Maintainability					
Tooling/Support Equipment	5	5	3	3	5
Skill Levels	5	5	3	3	4
Repair Level	5	5	5	5	5
Mean Time To Repair	5	6	5	5	7
Life-Cycle Cost					
Acquisition	5	6	4	4	6
Operation and Support	5	6	4	3	7
Availability	5	6	4	3	7

cables to the flight control will be similar to electrical cables in terms of reliability.

System D has negligible impact on operational reliability. The MTBMA will be degraded because of the double optical conversion required in the FADEC and coupler. Additional circuitry is needed. Increased heat load will result from the larger power supplies required.

Negligible impact on operational reliability results from System E, but the MTBMA should be improved due to relocation of FADEC as in System B.

7.2.3 Maintainability

Areas evaluated include impact on tooling/support equipment, impact on required skill levels, impact on component repair level, and impact on Mean Time To Repair (MTTR). Base level engine repairs include removal and replacement of parts (down to, say, board level electronics) at the organizational level (outside) and intermediate level (inside), but no parts testing. The electronic controls parts testing and repair are done at the depot level.

System B presents no impact on tooling, support equipment, or skill levels required at the organizational level of maintenance. Component repair level will remain the same. The MTTR will improve since there are fewer cable connectors, and fault-isolation time will be reduced.

Additional support equipment and tooling are needed for flight line fault isolation for System C due to the optical cables and data bus to optical coupler. Also, optical test equipment will be required at the depot level. Additional skills will be required at all levels of maintenance to support both optical and electronic components. There will be no impact on component repair level. The MTTR will remain the same based on the assumption that trouble shooting time will be similar.

For System D, support equipment and tooling requirements are greater due to the use of a mix of electrical and optical components. Additional skills will be required to maintain optical components at all levels of maintenance. No impact will occur on component repair level or MTTR. Fault-isolation capability and timing are similar to System A.

System E tooling and support equipment will be similar to System A except that they are optical. Depot will still require electrical and optical repair skills, while base level will only require optical skills. Use of protocol branches will reduce cable/connector requirements which will reduce trouble shooting time. Repair levels for all components will remain the same.

7.2.4 Life-Cycle Cost (LCC)

Acquisition and Operation and Support (O&S) costs were evaluated for each system.

The incorporation of the FADEC into the flight control in System B will significantly reduce the acquisition cost due to commonality with the flight control in aspects such as cooling, power, and hardware. The increase in flight control costs will be small. Increase in cable costs due to additional length will be minimal in comparison with FADEC cost reduction. O&S cost will be lower due to reduction in MTBMA and MTTR.

System C acquisition cost will be impacted by the need for new support equipment to test optical cables and data bus optical couplers. Costs for the coupler and optical cables are assumed to be similar for the comparable electrical devices. O&S costs will increase due to reduced MTBMA.

The acquisition cost of System D will be similar to System C since additional tooling and support equipment will be required at each base. O&S cost will increase due to a significant increase in maintenance action rate.

System E incorporates the FADEC into the flight control system, reducing acquisition cost significantly. O&S costs will also be lower due to reduced maintenance event rate and MTTR.

7.2.5 Availability

The impact on engine availability was evaluated based on the MTBMA and MTTR evaluations. This is a qualitative estimate of the system impact on the frequency and elapsed time of engine flight line maintenance actions. The increased maintenance action rate for Systems C and D will have a negative impact on engine availability. The reduction in maintenance action rate and MTTR for Systems B and E will improve engine availability.

7.3 SURVIVABILITY/VULNERABILITY STUDY

7.3.1 Combat Effectiveness Potential

Survivability is part of the overall combat capability posture of a given weapon system; other factors include performance, lethality, and availability. The survivability of a weapon system is a function of the mission, threats, susceptibility, and vulnerability of the particular aircraft. By definition, survivability (P_S) is determined by the susceptibility (P_H) of being hit by a threat mechanism and vulnerability ($P_{K/H}$) as in the following relationship:

$$P_S = 1 - (P_H \times P_{K/H})$$

For this study, susceptibility and vulnerability are specifically defined as follows (MIL-STD-2089):

Susceptibility is the probability of being hit by a threat damage mechanism and is the sum of the threat density, target signature, and threat effectiveness.

Vulnerability is the probability that, given a single-shot hit on the engine by a damage mechanism, the engine will be damaged to a level which causes sufficient performance degradation to classify the engine as killed. Implicit with engine vulnerability is the probability that the aircraft will abort due to engine failure resulting from a threat mechanism hit.

7.3.2 Susceptibility

The means of reducing susceptibility by the use of fiber optics falls into three categories as follows:

1. Reducing EMI - Electromagnetic-interference-disturbed components may result in aborted missions and reduced aircraft availability. Inherently immune to EMI, fiber optics enhances aircraft operability, especially in the normally heavy EMI environment on carrier decks and in flight.

2. Reducing Susceptability to EMP - The effects of electromagnetic pulse threats (directed-energy weapons or high-altitude nuclear events) are reduced because there is little internal coupling of EMP energy to critical electronic components.

3. Reducing EM Radiation Signature for Detection or Homing - The primary source of EM radiation useable for missile detection and homing comes from radio, radar equipment, and other powered sources. Fiber optic reduction of EM radiation sources would be small assuming a baseline of properly shielded and maintained electrical wiring.

7.3.3 Vulnerability

The primary survivability benefit of using fiber optics is in reducing overall aircraft vulnerability to threat damage. While the probability of hit is a function of the susceptibility factors, the probability that a kill mechanism (such as a gun projectile, warhead fragment, or blast) hits the engine or any critical component is a function of the location and protection of the components and the distribution of hits over the aircraft surface.

Fiber optics permits more latitude in engine control location on the aircraft. Additional vulnerability protection may be afforded by strategic placement of critical components. The effect of adding redundancy to engine control components enhances survivability by effectively eliminating critical components. Fiber optic weight savings can be traded for redundancy. Also, fiber optic cables can be routed through areas previously avoided, because of electrical hazards, resulting in shorter cable lengths.

Changes in presented area and resulting changed vulnerable area provided by study Systems A through E were small compared to the overall aircraft and made no significant change in vulnerability.

8.0 DEVELOPMENT PLAN

8.1 OPTICAL TECHNOLOGY

Figures 13 and 14 show schedules and cost estimates to ready optical sensor and component technology for implementation in advanced aircraft on a demonstrational basis. Costs shown are on a per sensor/component basis; components, once developed, can be used with any applicable sensor. The result would be flight-quality hardware. Admittedly, some sensors will be easier to develop than others, so the charts are meant to show typical values.

Present status within the six-year development plan for the various sensors/components is shown along the top of each chart. In general, it is based on the vendor survey responses. For example, there are many optical linear position sensor concepts under development, one of which has been packaged in an aircraft design (Reference 3). Optical lube debris sensors have received little attention. Unknown factors are those vendors who did not report their status, vendors who did not respond to the survey, and vendors who were not sent a survey.

8.2 OPTICAL SYSTEM

Figure 15 is a chart projecting milestones and cost for development of the integrated fiber optic control system described in Section 6.0. It covers the following steps towards completion of a flight test:

- Sensor/component development covers the work shown in Figures 13 and 14. Interdependent sensors and components must be developed in parallel.
- Protocol branch sensor/actuator networks should be constructed and evaluated. Protocol branch tools will assist the system development.
- Optical system update studies are needed to review technology status and current control system requirements.
- To evaluate aircraft/engine worthiness, each sensor and component should be placed in a test-bed demonstration. This would take the form of piggybacking on ground and flight tests.
- For eventual flight test implementation, an integrated control system must be designed in detail for a particular application. For the far-term approach described in Section 6.5.2, the engine-mounted control must be redesigned for protocol inputs and airframe mounting. This would include specifications, drawings, sets of hardware, special test items, procedures, and training.

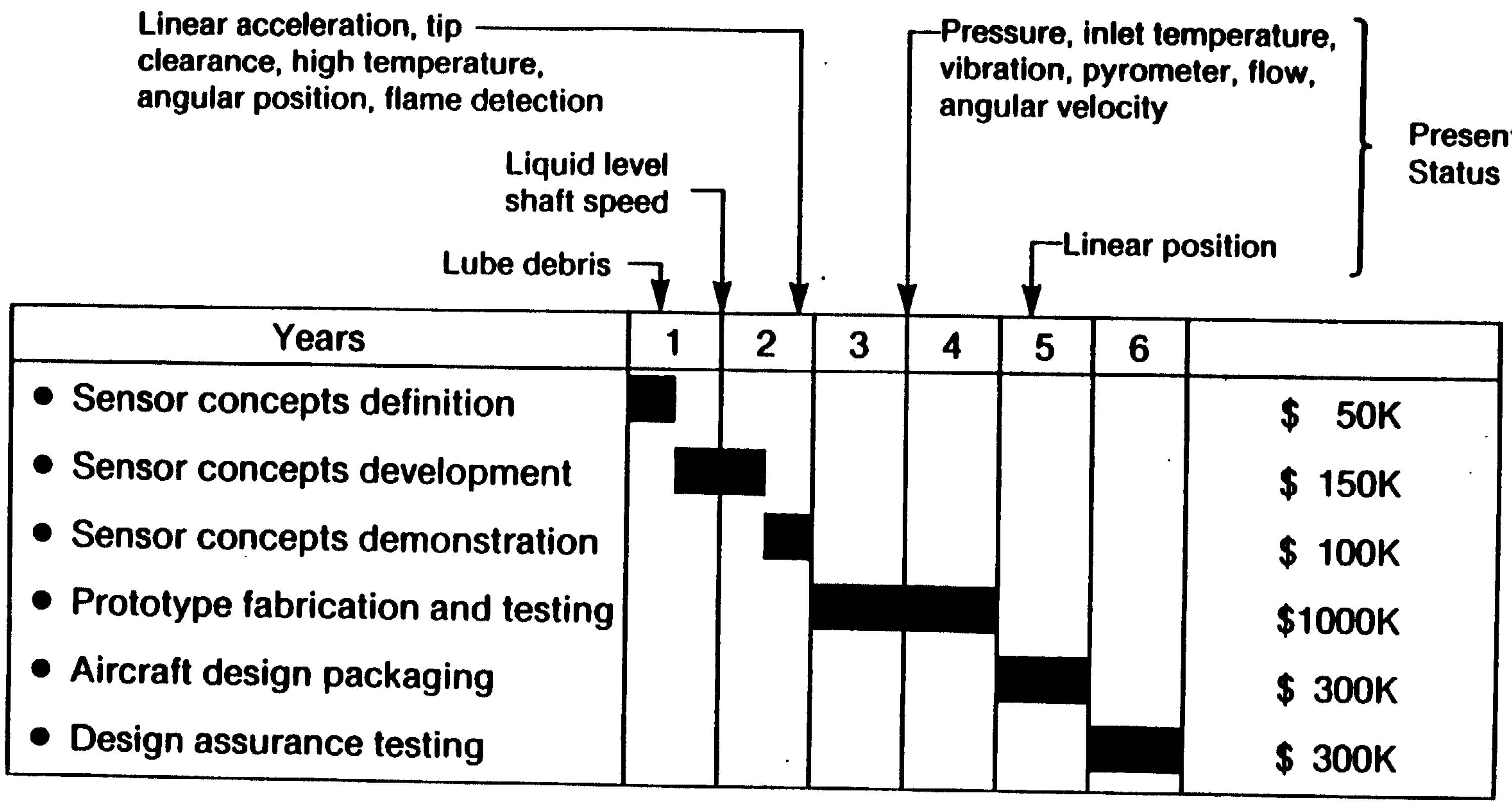

Figure 13. Optical Sensor Development Schedule To Achieve Flight-Quality Hardware.

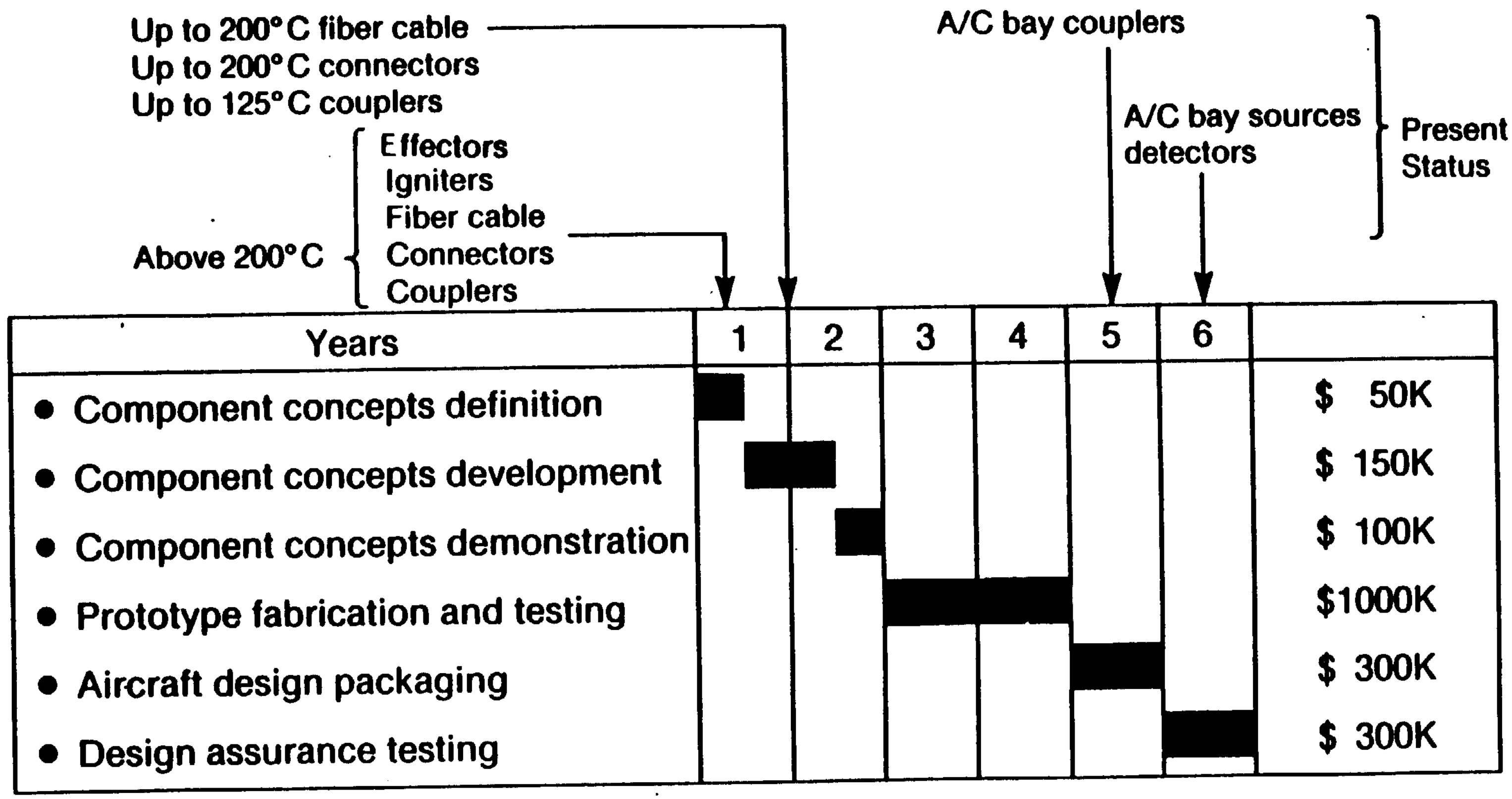

Figure 14. Optical Component Development Schedule To Achieve Flight-Quality Hardware.

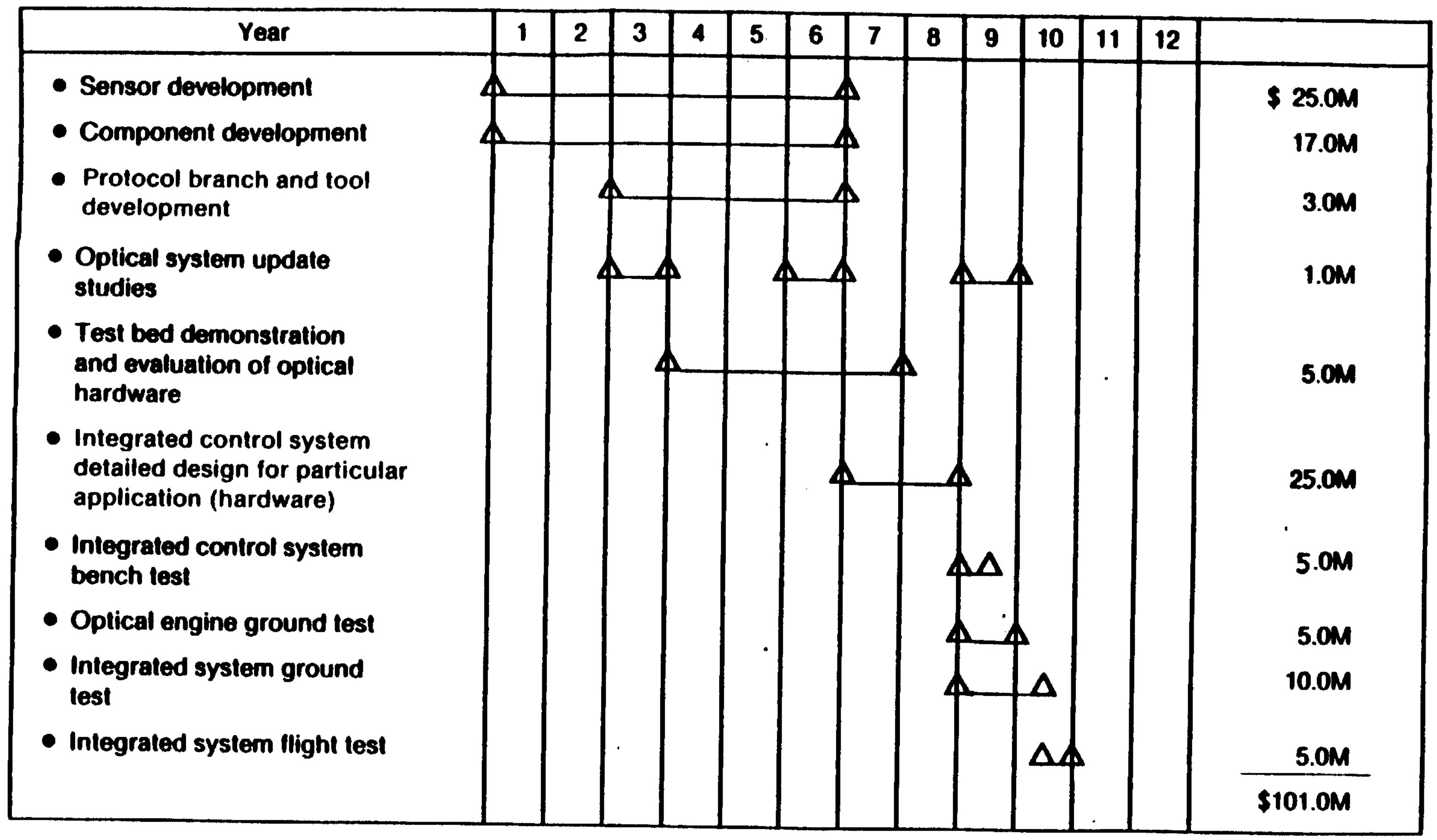

Figure 15. Far-Term Integrated Optical System Milestone Chart.

- An integrated control system bench test is used to operate all the designed hardware in the laboratory under simulated aircraft inputs.

- The optically configured engine must be ground tested before being assembled to the airframe. Airframe communication would be simulated.

- The selected airframe must be configured with the integrated optical flight/propulsion control system and ground tested.

- Integrated optical flight/propulsion control system flight test.

9.0 CONCLUDING REMARKS

The subject of this report concerned the definition and evaluation of a total fiber-optic, integrated propulsion/flight control system, the component parts of such a system along with development status, and plans to implement the system on future advanced fighter aircraft.

A wide variety of sensors was shown to compose the propulsion and flight control system measurement set. The requirements comprise many ranges, high accuracy, and harsh environment. A fiber optic sensor survey indicated that, while all sensor categories received responses, almost all are in some need of development. Classification of fiber optic sensors by transmission method (communication protocol) was introduced as an aid to system design.

Requirements and recommendations were given for fiber optic circuit components. All-dielectric, high-temperature fiber (if needed), passive couplers, and high-temperature cable-to-connector interfaces most need development for the high-temperature engine environment.

A total fiber-optic, integrated propulsion/flight control system was described based on previous integrated architecture studies as well as the protocol method of efficiently connecting system components to centralized bay electronics. In terms of propulsion system supportability and vulnerability, study results show that fiber optics enable the favorable relocation of the engine electronic control in the aircraft bay. Considerable weight savings are expected on the airframe, but these were not specifically addressed.

Up to six years of development is forecast to ready fiber optic sensors and components for aircraft application. Another four years is projected to design and build an integrated control system and complete a flight test.

APPENDIX A

FIBER OPTIC VENDOR QUESTIONNAIRE

AND

VENDORS SURVEYED

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Fiber Optic Sensor Vendor Survey Questionnaire Form

Please copy this form for each device or version of devices.

Name of device ____________________

Parameter sensed:
___ Temperature
___ Pressure
___ Flow, Mass
___ Flow, Volume
___ Liquid Level
___ Position, Linear
___ Position, Angular
___ Velocity, Linear
___ Velocity, Angular
___ Acceleration, Linear
___ Lube Debris
___ Pyrometer
___ Blade Tip Clearance
___ Flame
___ Other ________

Device Status: (estimated year)
Research ________ Development ________
Prototypes Available ________ Mil-Qualified ________

Device Specifications
- Range, operational ________
- Range, damage limits ________
- Accuracy, % full scale ________
- Linearity ________
- Drift ________
- Hysteresis ________
- Precision, % full scale ________
- Time constant (63.2%) ________
- Size and Mass
  - Sensor head ________
  - Conditioning E/O ________
- Electrical power required ________
- Optical power required ________
  - ___ LED ___ LASER ___ White Light

Environmental Limits:	Operationally accurate	Max.	Damage
Temperature			
Range	________	________	________
Thermal shock	________	________	________
Sensitivity	________	________	________
Pressure			
Range	________	________	________
Acoustic shock	________	________	________
Sensitivity	________	________	________
Vibration (duration)			
Random freq., 6 g's	________	________	________
Sinusoidal, 20 g's, 2000Hz	________	________	________
Acceleration shock, level	________	________	________
Resonant freqs.	________	________	________

Sensitivity to aerospace fluids (list)
- Vapor ________
- Condensation ________
- Immersion ________

Interfacing technique, or protocol (wavelength shift, analog level, etc.)

____

Please attach a basic schematic of device and interface: (block diagram)

Contact: Name ________ Phone ________

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Vendors Surveyed for Fiber Optic Sensor Development

Accufiber Co.
Vancouver, WA

Amphenol Products,
Lisle, IL

Aster
Medfield, MA

AT&T Technologies
Holmdel, NJ

Babcock and Wilcox
Alliance, OH

Brandenburger and Co.
Palo Alto, CA

Collimated Holes, Inc.
Campbell, CA

Comar, Inc.
Richardson, TX

Computer Genetics Corp.
Wakefield, MA

Consolidated Controls
Bethel, CT

Conax Buffalo Corp.
Buffalo, NY

Corning Glass Works
Corning, NY

Cuda Products Corp.
Jacksonville, FL

Cutler-Hammer Products
Milwaukee, WI

Develco
San Jose, CA

Diaguide, Inc.
Fort Lee, NJ

EG&G
Salem, MA

Electro Corp.
Sarasota, FL

ELDEC Corp.
Bothell, WA

EOTEC Corp.
West Haven, CT

Ericcson Lightwave Cable
Overland Park, KS

Fiberoptic Systems, Inc.
Simi Valley, CA

Force, Inc.
Christiansburg, VA

Fort Fiber Optics
Newport Beach, CA

FSI
Lombard, IL

Fujikura Ltd.
Pittsburg, PA

Furukawa Electric Co.
New York, NY

Galileo Electro-Optics
Sturbridge, MA

General Electric Co. AEBG
Cincinnati, OH

General Electric Co. AID
Wilmington, MA

General Electric Co. CR&D
Schenectady, NY

GE Electronics Lab
Syracuse, NY

General Fiber Optics, Inc.
Cedar Grove, NJ

General Motors Res. Labs
Warren, MI

Gould Research Center
Rolling Meadows, IL

Gulton Industries
Costa Mesa, CA

Hewlett Packard
Palo Alto, CA

Honeywell, Inc.
Plymouth, MN

Hughes Research Lab
Malibu, CA

Infrared Fiber Systems
Silverspring, MD

ITT Electrooptical Prod.
Roanoke, VA

Kaptron, Inc.
Palo Alto, CA

Land Turbine Sensors, Inc.
Tullytown, PA

Litton Fiber Optic Products
Blacksburg, VA

Luxtron Corp.
Mountain View, CA

McDonnell Douglas Astron. Co.
Huntington Beach, CA

Mechanical Technology, Inc.
Latham, NY

Omron Electronics, Inc.
Schaumburg, IL

OPCOA, Inc.
Santa Anna, CA

Optech, Inc.
Herndon, VA

Optelecom, Inc.
Gaithersburg, MD

Optical Sensors Inc.
Colchester, VT

Parker Bertea
Irvine, CA

Paroscientific, Inc.
Redmond, WA

Rosemount, Inc.
Egan, MN

Scientific Technology
Mountain View, CA

Simmonds Precision
Norwich, NY

Skan-A-Matic
Elbridge, NY

Square D
Pinellas Park, FL

Stathem
Oxnard, CA

Teledyne Gurley
Troy, NY

Teledyne Ryan Electronics
San Diego, CA

Vanzetti Systems, Inc.
Stoughton, MA

Vibrometer Corp.
Billerica, MA

Welch Allyn, Inc.
Skaneateles Falls, NY

York Technology
Princeton, NJ

Outside USA

Arel Control Ltd.
Yavne, Israel

British Marine Tech. Ltd.
London, England

Canadian Instr. & Res. Ltd.
Mississauga Ont., Canada

Canstar Communications
Ontario, Canada

Delta Controls Ltd.
E. Molesey, Surrey, England

Focal Marine Ltd.
Bedfor, Nova Scotia, Canada

Fugitsu Laboritories
Kawasaki, Japan

Optronics Ltd.
Cambridge, England

Plessy
Kingsthorpe, Northampton, England

Polytech GmbH
Kalsruhe, West Germany

Rolls Royce
Derby, England

Sumitomo
Tokyo, Japan

APPENDIX B

PROTOCOL AND SENSOR SELECTION

The Protocol Branch Method and Sensor Selection

The protocol branch innovation is a concept, or method, that allows the efficient creation of multiplexed analog systems of fiber optic sensors and actuators. Central to the method is the distinction, in any real sensing device, between the transduction technique and the data transmission technique, or protocol. Ideal availability of a completely filled selection matrix of sensors supporting all combinations of the two would allow the most flexible sensing system architecture definition.

Every optical sensor type, such as pressure, temperature, or vibration, will employ one or several possible techniques to transduce the measured parameter into an analog optical signal. This signal will be transmitted along an optical fiber using 1 of approximately 12 data-transmission techniques or protocols. In many actual sensing devices, the selection of transduction technique absolutely determines the transmission method, but in others several options are available. Conversely, the selection of transmission technique does not rigidly constrain the transduction options. The protocol branch method exploits the possibility of independent selection of each quality for each device in the system. At present, the matrix of devices indexed by these two parameters is rather sparsely populated, so the method is of limited usefulness. However, as the available devices increase in number and flexibility, the matrix will fill, and use of an optimization procedure like the protocol branch method will become essential.

Consider the play of variables in the definition of a fiber optic sensing system: givens include the parameters that will be sensed, the length of the fiber runs, the required update rates, necessary accuracy , and environmental limitations. For example, there are currently several different fiber sensors for temperature, all with good accuracy and robustness. The selection of one over the others will then depend primarily on whether it is data compatible on a multiplexed network of other sensors. All other things being equal, sensor types that are easily multiplexable will be preferred over those that require dedicated fibers. Those that will multiplex with other types of sensors, say pressure, will be even more preferable. But now, which pressure sensors to choose? There are, again, several options of transduction technique and transmission protocol. Adding the position sensors, the limit switches, the vibration sensors, and others will increase the complexity of the selection process to the point of impossibility for the unaided human to arrive at an optimum solution. The protocol branch method provides a procedure to obtain a near ideal combination of variables.

One of the important benefits of adopting the protocol branch method is that it will drive sensor design in the direction of filling the matrix of device types. The holes, or missing pieces in the complete family, will become more apparent. When the sensor designers and inventors have a clear understanding of this matrix, the separability of the two qualities, and an appreciation of the protocol branch benefits, a significant change in their design philosophy may take place. This will result in greater acceptance and use of the fiber optic technology due in part to the improved ability to tailor a new fiber optic sensor system to exact requirements.

FOCSI Protocol Branch Selection

Of the 12 identified techniques for transferring analog optical data from a sensor to the interface card, or from the card to an effector, only a few are currently suitable for serious use in aircraft systems of sensors and effectors, or actuators.

The preferred protocol is the two-wavelength-referenced analog level. In this technique, one wavelength carries the information in analog intensity level, referenced not to absolute light or dark levels but to an accompanying reference wavelength intensity level. These two wavelengths travel the same fiber path, encounter the same connectors, experience the same random loss mechanisms, and arrive at the optical terminal card equally attenuated. The ratio of the two levels will contain the information while the absolute levels may vary at random. This decoding technique is capable of handling several existing sensors, including linear- and angular-displacement devices, as well as pyrometric temperature sensors which take a ratio of two wavelengths for a blackbody calculation.

This multiwavelength protocol is feasible because of the development of the diode array photodetector and is greatly improved with the use of a holographic diffraction grating. These two elements very handily combine with fiber optics to allow easy spectral analysis of the guided light. An optical-to-electrical conversion card built with these two elements will have an unusually broad range of sensor communication protocol capability.

Previous implementation of this technique employed two photodetectors with wavelength filters to perform the discrimination. This approach, while simple, has several significant flaws including errors due to source wavelength drift and filter center wavelength shift, from age or temperature effects, and sheer number of optical components needed to multiplex several devices. Each channel requires a beamsplitter, two optical filters, and two detectors, as well as a means to tap some power off the multiplexed fiber. Each channel detection set steals optical power from all the other channels because the power division, or distribution, takes place prior to the wavelength separation.

Our approach is to perform the wavelength pair separation first with an optically dispersive element, preferably a holgraphic diffraction grating. Detection will be by an array of photodetectors on a single substrate. This grating-array (GA) technique offers several advantages including: improved distribution of individual-channel optical energy to the correct channel detectors, greater energy efficiency, simpler optical arrangement, ability to compensate for wavelength shifts, and ability to decode several sensor types.

The multiwavelength GA protocol decoding technique is one of the most capable, robust, and straightforward to implement. It is recommended as the optical-to-electronic interface for virtually all optical sensors in the FOCSI architecture. The principal drawback of the technique is the 10 to 200 kHz response rate, making it possibly unsuitable for turbine-speed sensing by pulse counting. The technique is capable of interpreting and converting several different optical data-transference protocols, making it one of the most flexible techniques available, and requires a simple optical arrangement, making it feasible for development for use in a harsh environment.

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