TECHNOLOGY ASSESSMENT OF AUTONOMOUS INTELLIGENT BIPEDAL AND OTHER LEGGED ROBOTS

FINAL REPORT

Contract Number MDA972-02-M-0025

Submitted To:

Dr. Alan Rudolph
Defense Sciences Office
Defense Advanced Research Projects Agency
3701 North Fairfax Drive
Arlington, Virginia 22203-1714
Phone: (703)-696-2240
Fax: (703)-696-3999
arudolph@darpa.mil

Submitted By:

Dr. Robert Finkelstein, President
Robotic Technology Inc.
11424 Palatine Drive
Potomac, Maryland 20854-1451
Phone: (301)-983-4194
Fax: (301)-983-3921
RobertFinkelstein@compuserve.com

And

Dr. James Albus, Senior NIST Fellow
Intelligent Systems Division
National Institute of Standards and Technology
Building 220, Room B124
Gaithersburg, Maryland 20899-0001
Phone: (301)-975-3418
Fax: (301)-990-9688
james.albus@nist.gov

Revised
13 May 2003 & 21 November 2004

CONTENTS

Section **Page**

I. EXECUTIVE SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

I.1 Purpose

The **purpose** of this project is to perform a **technology assessment** of *supervised autonomous intelligent humanoid robots*, to examine current technology and systems to determine the feasibility of humanoid robots, and other legged robots, for *militarily useful behavior* in the near to far term (e.g., years 2002 - 2030) and to provide a technology roadmap for developing and demonstrating a humanoid robot for a selected military mission. The expectation is that DARPA will support the **development and demonstration** of militarily useful humanoid robots.

I.2 Background

There are a number of ongoing programs in the Department of Defense (DOD) for the development of **combat robotics**, but they emphasize the development wheeled or tracked vehicle platforms, not humanoid robots. But the world of **artifacts** is designed by humans for humans – such as tools, buildings, and vehicles. A humanoid robot, with biped legs, dexterous arms and hands, and sufficient intelligence, could function smoothly in that world: moving about in buildings, climbing stairs or ladders, opening doors with doorknobs instead of force, using existing tools, operating existing machinery, driving existing vehicles - and firing existing weapons. In the **natural environment**, military wheeled vehicles can operate on about 30% of the earth's land surface, and military tracked vehicles can travel on about 50%. Legged organisms and machines, including bipedal humanoids, can travel over nearly the entire land surface. Also, humans will **interact** most easily with robots that appear to be human. While programs in several countries are focused on developing **humanoid robots**, Japanese companies, in general, have expended the most effort in developing humanoid robots. Although these robots have advanced sensing and control for autonomic effector movement (such as walking), they are limited in their autonomous interaction with the environment. Because the U.S. is more advanced in autonomous intelligent control (albeit, for vehicles), an interesting project would be to **integrate a U.S. control system** (such as the NIST hybrid 4D/RCS) with a suitable humanoid robot. The resulting autonomous, intelligent, robots will have widespread **military** and **civil** applications.

I.3 Expert Panel

We assembled technology data from in-house RTI databases, Japanese and other industrial humanoid robot developers, and U.S. government and university laboratories. For technology and program guidance, we formed an **advisory panel** of U.S. humanoid robot experts. The panel provided insight into several **key issues**: the U.S. is rapidly falling behind the Japanese (and perhaps even the Europeans) in developing humanoid robots; hexapod robots are inappropriate as large legged robots; quadruped and hybrid robots, such as a Centaur-type robot, can be militarily useful; rapidly advancing technology will make militarily valuable humanoid robots feasible on the battlefield by 2015 (and as capable, efficient, and reliable as human soldiers by 2035); the 4D/RCS control architecture can be used to achieve supervised, intelligent autonomous humanoid robots; and the advent of humanoid robots will have major civilian societal impacts and advance the scientific understanding of human physiology and psychology.

I.4 Expert Survey

A **survey** of robotics experts provides insights in the form of comments, opinions, and scoring of the survey forms. The experts judge the current state of technology for developing militarily useful robots as generally poor because of the lack of enabling technologies (such as adaptable bipedal leg control). The experts foresee **2012** as the expected year in which the technology will be at least satisfactory, although there are some optimists forecasting a year sooner than 2007 (depending primarily on funding). They expect humanoid robots to be used for at least some military missions by 2020. The most promising humanoid robot **mission** is deemed to be reconnaissance, surveillance, and target acquisition (RSTA), followed by military operations in urban terrain (MOUT). They expect humanoid robots to have a **significant impact** on military operations by **2024**. The experts deem **hybrid legged robots** to be more useful for the military than pure bipedal humanoids (with the humanoid second in importance). They judge the biped to be the most technically difficult legged robot to develop. The experts judge **propulsion** (suitable energy source) to be the most pressing humanoid R&D need, followed by **bipedal leg control**. The experts think that **semi-autonomy** (about half teleoperation and half autonomy) is sufficient for most missions.

The **expected unit cost** of a military humanoid robot, forecast by the experts, is about **$1 million**. {**Note:** This is comparable to the unit manufacturing cost of the Honda Asimo humanoid, reported to be $1 million (after a development cost of $100 million), with an annual leasing cost to the user of about $150,000 [Washington Post, 3 Aug. 02, P.C01], and a possible sales price of $100,000 [Economist, Vol. 357, Issue 8202, P.102)]. But another source reports that the Asimo production cost is about $80,000 [The Industrial Robot, V. 28, Issue 3, P.186]. By comparison, the Sony Aibo quadruped dog robot costs about $1,500, selling more than 100,000 units [Economist, Vol. 357, Issue 8202, P.102)]. The Sony HOAP-1 humanoid robot is expected to sell for $41,000 [PC Magazine, 13 Nov. 01, P.67], while the Sony SDR-3X humanoid manufacturing cost is about $24,000 [The Industrial Robot, V. 28, Issue 3, P.186]. A security humanoid robot, to be manufactured by a Sanyo Electric Co. team, is to sell for about $86,000 [Hara, Yoshika, CMP Media, 16 Sep. 03, P.A157].}

I.5 User Survey

A survey of prospective humanoid and legged robot users judges **countermine** and **explosive ordnance disposal** (EOD) missions as the primary way they would likely employ the robots (with RSTA a close second). The users predict that humanoid robots will have significant military worth, but that they will not be ubiquitous throughout the military in the 21st century. The users tended to be more pessimistic than the experts about the promising missions for humanoid robots, but while the experts selected RSTA as the most promising mission, the users selected countermine/EOD operations. The users favored **quadruped robots** as their legged choice over bipedal humanoids. While the experts expect a unit cost of $1 million for military humanoid robots, the users predict a cost of about $400,000. The major issue for users is **technology**, followed closely by **safety**. The users favor somewhat **greater autonomy** for humanoid robots than the experts. And they think that humanoid robots should be fielded *the sooner the better*.

I.6 Metrics for Humanoid and Legged Robots

We defined, weighted, and scored metrics and submetrics against which to evaluate prospective humanoid and legged robots, as they are designed and proposed. The **four main metrics** are: effectiveness, efficiency, life cycle cost, and development risk.

I.7 Functional Analysis

We **decomposed** the major functions (sensing, processing, etc.) of any legged robot in terms of the corresponding subsystems and described various approaches for the subsystems to function as part of an autonomous legged robot.

I.8 State of Humanoid and Legged Robot Technology

After examining the literature, we concluded that in recent years there has been **significant progress** in the technology of bipedal humanoid and other legged robots (primarily hexapods and quadrupeds). Teleoperation (and telepresence) of legged robots is feasible in the near-term and militarily useful. A number of tools, including genetic algorithms, neural networks, expert systems, vision-based walking, and various kinds of control algorithms, are being developed for optimal gait control. Many of these techniques will enable humanoid robots to learn complex tasks in uncertain environments without the need for programmers to foresee every contingency. Methods for robot cognition are improving and humanoid robots are becoming more lifelike in their movement and ability to interact with humans. Nevertheless, more progress is needed for humanoid robots to achieve **military worth**.

I.9 Roadmap

The U.S. Army's EOD Technical Detachment issued the U.S. military's first known **Mission Needs Statement for a humanoid robot** and are eager to cooperate in the development of humanoid robots for EOD missions. As we show, the Technology Readiness Levels of humanoid robot subsystems for the EOD mission must be elevated. The **short-term roadmap** proposes a **demonstration project** to include: monitoring and assessing humanoid robot technology and applying risk mitigation methodology; working with the EOD users and using the **Quality Function Deployment** (QFD) method to map their functional requirements into potential technology solutions; employing **Multifunctional/Multidisciplinary Design Optimization** (MDO), preferably with an available humanoid platform, to integrate sensors, a power source, and intelligent control in the development and demonstration (in computer **simulations** and a **physical field test facility**) of a militarily useful humanoid robot. The **long-term roadmap** shows that it is feasible – and sensible – to begin a humanoid (and other legged) robot program for military applications immediately, where products with great military (and civilian) worth will become available within this decade; and where fully autonomous humanoid robots, with human-like physical strength and agility and advanced cognitive abilities, will be operational in a little more than two decades.

1.0 PURPOSE

The purpose of this project is to perform a **technology assessment** of *supervised autonomous intelligent humanoid robots*, to examine current technology and systems to determine the feasibility of humanoid robots for *militarily useful behavior* in the near to far term (e.g., years 2002 - 2030) and to provide a technology roadmap for developing and demonstrating a humanoid robot for a selected military mission. In addition, our sponsor, the Defense Advanced Research projects Agency (DARPA), requested that we examine the feasibility of other legged robots in addition to bipeds, especially hexapods.

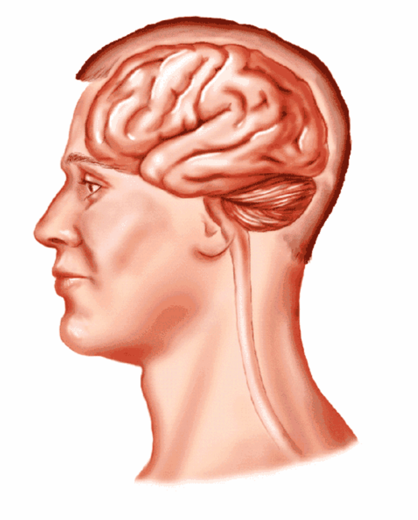
The expectation is that DARPA will support a subsequent system development and demonstration phase, for militarily useful legged and humanoid robots.

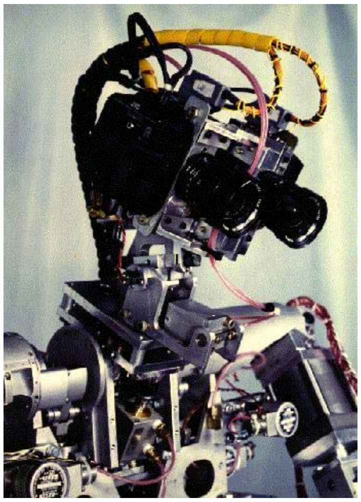
2.0 BACKGROUND

There are a number of ongoing programs in the Department of Defense (DOD) for the development of combat robotics, but they emphasize the development wheeled or tracked vehicle platforms, not humanoid robots. But the world of **artifacts** is designed by humans for humans – such as tools, buildings, and vehicles. A humanoid robot, with biped legs, dexterous arms and hands, and sufficient intelligence, could function smoothly in that world: moving about in buildings, climbing stairs or ladders, opening doors with doorknobs instead of force, using existing tools, operating existing machinery, driving existing vehicles - and firing existing weapons. In the **natural environment**, military wheeled vehicles can operate on about 30% of the earth's land surface, and military tracked vehicles can travel on about 50%. Legged organisms and machines, including bipedal humanoids, can travel over nearly the entire land surface. Bipedal motion is also more efficient for long distance travel (albeit, computationally more difficult) than multi-legged systems, and bipeds can traverse steep slopes that are beyond the ability of tracked or wheeled vehicles. In conjunction with arms and hands, a humanoid can rappel down vertical surfaces and climb sheer cliffs. Also, humans will interact most easily with robots that appear to be human.

While programs in several countries are focused on developing humanoid robots, Japanese companies, in general, have expended the most effort in developing humanoid robots. For example, the Fujitsu Company is developing the HOAP-1 (Humanoid for Open Architecture Platform) humanoid robot, the Sony Corporation is developing the SDR-3X humanoid robot, Kawada Industries, Inc. is developing the HRP-2P humanoid robot, and the Honda Corporation is developing the Asimo humanoid robot. While these robots have advanced sensing and control for autonomic effector movement (such as walking), they are limited in their autonomous interaction with the environment.

Because the U.S. is more advanced in autonomous intelligent control (albeit, for vehicles), an interesting project would be to **integrate a U.S. control system** (such as the hybrid 4D/RCS developed by the Intelligent Systems Division of the National Institute of Standards and Technology (NIST) **with a suitable humanoid robot**. However, before undertaking such a project, it is prudent to perform a **technology assessment** of supervised autonomous intelligent humanoid robots, to determine their prospective military worth and the feasibility of humanoid robots for militarily useful behavior in the near to far term (e.g., years 2002 - 2030), and, if humanoid robots are worthwhile, to provide a technology roadmap for reducing developmental risk and eliminating technology gaps. The resulting autonomous, intelligent, robots will have widespread **military** and **civil** applications.





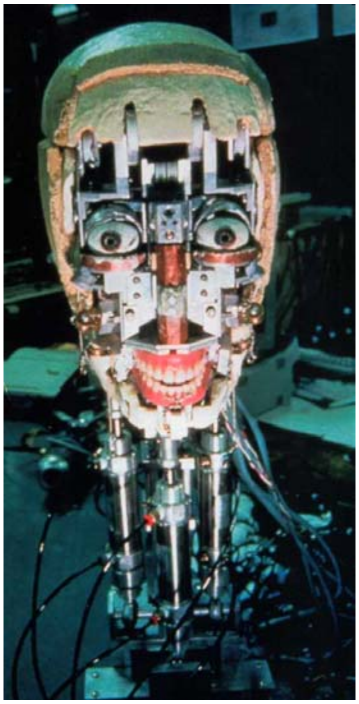


Figure 2-1: Human to Humanoid Head Evolution

2.1 Exemplar Humanoid Robots

While the Japanese humanoid robots are generally the most advanced in terms of autonomic functional movement, such as walking or stair climbing, they are without situational awareness. An early humanoid developed by the Honda Motor Co., the P2 (**Figure 2-2**), resembles an astronaut in a spacesuit. With a height of six feet (1.8 m) and a weight of about 460 pounds (209 kg), P2 is an obvious candidate for the NFL. In development for 10 years, and requiring an effort of at least 200 person-years, the P2 was introduced in Tokyo on 20 December 1996. Following the development of the P2, Honda developed the prototype P3 Humanoid Robot, which was completed in September of 1997. The P3 was smaller than the P2, with a height of 5.25 ft. (1.6 m) and a weight of 286 lb (130 kg). Honda followed the P3 with the smaller, now commercially-available humanoid robot called *Asimo* (while the name is an acronym for *Advanced Step in Innovative Mobility*, it is also evocative of *Isaac Asimov*, the scientist and science fiction author who wrote "I Robot" and conceived the "Three Laws of Robotics"). Asimo is 3.9 ft. (1.2m) tall, 1.5 ft. (0.45m) wide, 1.4 ft. (0.44m) deep, and weighs 95 lb (43 kg). According to Honda, Asimo was made intentionally smaller than previous humanoids in order to appear less threatening to future users, which Honda sees primarily as families, where it will provide maid type services, or disabled and geriatric patients, where it will provide nursing aide type services. Honda has reportedly spent more than **$100 million** developing humanoid robots.

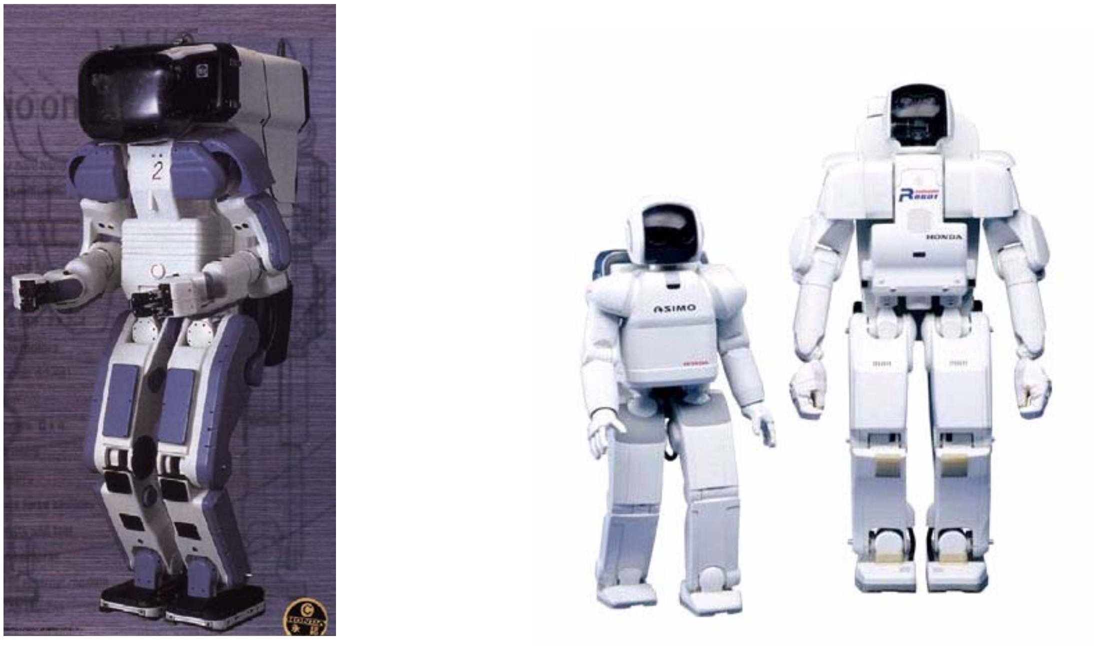


Figure 2-2: The Honda P2 (left), ASIMO (middle), and P3 (right) Humanoid Robots

In addition to Asimo, a number of other humanoid robots have been developed and are commercially available or nearing commercialization. Sony of Tokyo, for example, built a prototype of a small walking humanoid robot, called the *SDR-3X,* that was announced on 21 November 2000. The SDR-3X (**Figure 2-3**) is only about 1.7 ft. (0.52 m) tall and about 0.75 ft. (0.23 m) wide. Four of these robots were on display at Robodex 2000 in Yokohama the weekend of 24 November 2000, dancing like Broadway professionals.

Yoshikazu Tsuno / AFP

Figure 2-3: The Sony SDR-3X: A Robotic Chorus Line

The Aircraft and Mechanical Systems Division of Kawada Industries Inc. built the *H7* humanoid robot (**Figure 2-4**) for the University of Tokyo. Kawada subsequently used some of the same technology to develop the *Isamu* humanoid robot, which is about 5 ft. (1.5 m) tall, about 2 ft. (0.6 m) wide, and weighs about 120 lb. (55 kg). Isamu has 32 degrees of freedom (DOF), with a more anthropomorphic head than the earlier H7 humanoid.

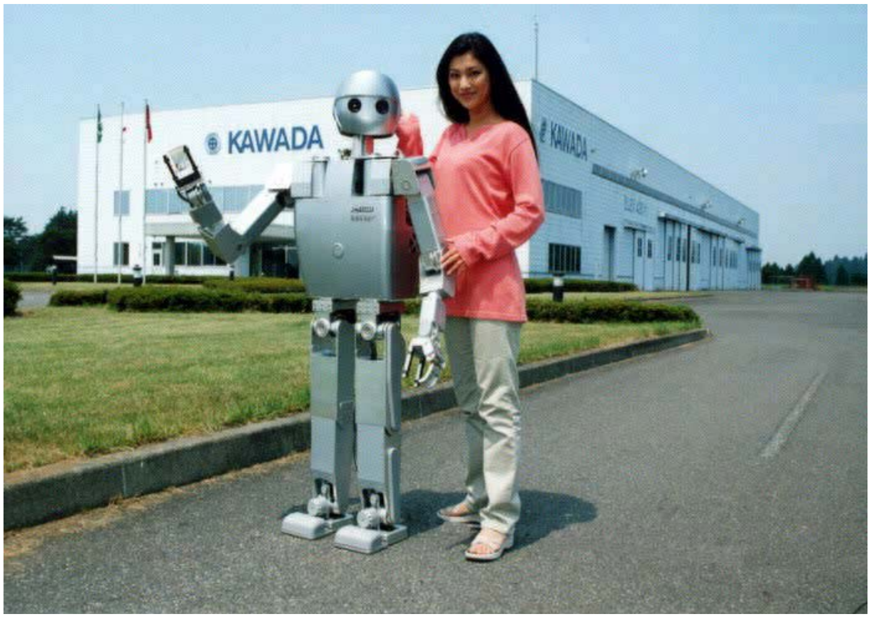


Figure 2-4: The Kawada H7 Humanoid Robot

The most advanced Kawada humanoid robot is the prototype *HRP-2P,* which was introduced at Robodex 2002 (**Figure 2-5**). It is 5 ft. (1.5 m) tall and weighs 127 lb. (58 kg), with 30 DOF. The HRP-2P is unusual in that it (unlike other current humanoid robots) has upper body strength sufficient, for example, to lift a desk with a human partner (**Figure 2-6**).

Figure 2-5: The Advanced Kawada HRP-2P

Figure 2-6: The Kawada Humanoid Robot Lifting a Desk

Fujitsu and Yamaha have also produced humanoid robot prototypes; and groups (mostly in university laboratories) in the U.K., Germany, China, Thailand, and other countries, are developing humanoid robots as well. There are a number of projects in the U.S., such as at MIT and the NASA RoboNaut, shown in **Figure 2-7**, which is designed to move on a track and so does not have legs and is not bipedal. But in general, the U.S. is lagging behind Japan in humanoid robot technology.

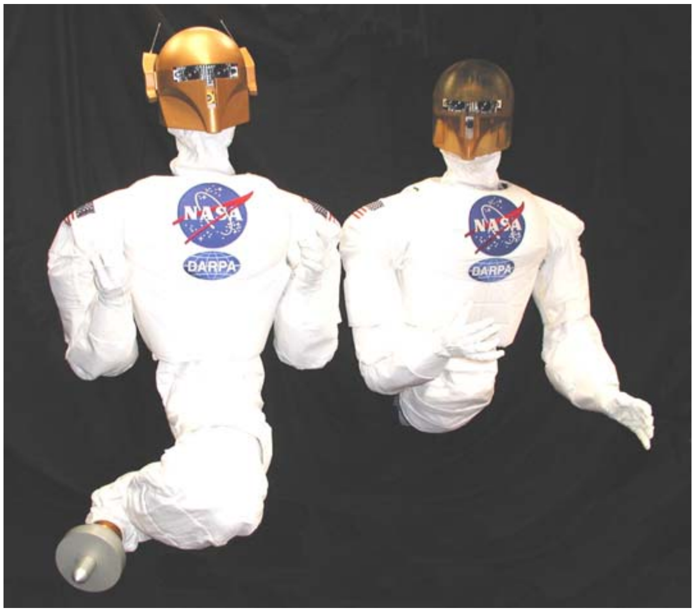


Figure 2-7: RoboNaut Units A & B

3.0 EXPERT PANEL

Our first task was to perform an Environmental Scan by assembling technology data and forming an **Expert Panel**. We assembled the technology data from in-house RTI databases, Japanese and other industrial humanoid robot developers, and U.S. government and university laboratories. (Please see **Appendix D** for the list of references). We formed an advisory panel of U.S. humanoid robot experts, including one member who is also a retired Army Colonel and is an expert in military operations as well. The panel, which convened on 1 November 2002 at the Intelligent Systems Division (ISD) of the National Institute of Standards and Technology (NIST), provided information and guidance for the project. The expert panel consisted of:

- Dr. James Albus, Senior NIST Fellow and former Chief of the Intelligent Systems Division of the National Institute of Standards and Technology. Dr. Albus is an expert on the design of intelligent control systems for robots and large complex systems.
- Dr. Robert Ambrose, Program Director at the NASA Johnson Space Center of the NASA RoboNaut project. Dr. Ambrose has developed one of the most advanced upper body robotic devices in the world.
- Dr. Robert Finkelstein, President, Robotic Technology Inc. and adjunct Associate Professor at the University of Maryland Clark School of Engineering and University of Maryland University College. Dr. Finkelstein, an expert on military applications for robotic vehicles and machine intelligence, is Principal Investigator for the project.
- Dr. Oussama Khatib, Professor of Computer Science, Robotics Lab, Stanford University, is an expert in the dynamics of humanoid robotic systems including systems that run, jump, tumble, and bounce.
- Dr. Mark Swinson, Deputy Director, Intelligent Systems and Robotics Center, Sandia National Laboratories, a Colonel in the U.S. Army (Ret.), and former Deputy Director of the DARPA Information Technology Office.

The contact information for the **expert panel** follows:

NAME	PHONE	EMAIL
Dr. James Albus	301-975-3418	james.albus@nist.gov
Dr. Robert Ambrose	281-244-5561	rambrose@ems.jsc.nasa.gov
Dr. Robert Finkelstein	301-983-4194	RobertFinkelstein@compuserve.com
Dr. Oussama Khatib	650-723-9753	khatib@cs.stanford.edu
Dr. Mark Swinson	505-845-9642	mlswins@sandia.gov

3.1 Panel Discussion

The **panel provided insight** into several key issues. The project was initially to be focused on humanoid robots, but was tasked by DARPA to include consideration of hexapod robots. J. Albus opined (and the panel subsequently concurred) that the hexapod design is flawed for macro-sized legged robots, and that there are good reasons why there are no large animals with six (or more) legs. For insects, spiders, and millipedes, the mass of the legs is small, and the mechanical stability advantage (of six or more legs) for small brains (with limited intelligence) is large. However, if the brain has sufficient computing capacity to control perception, gait, and balance, there is a big advantage in not carrying around an extra pair of legs (and nature does not like to waste structure and energy). As Albus noted, even the dinosaurs did not have six legs; many of them were bipedal and carried a large tail for balance, as do today's kangaroos. All pack animals have four legs, and the fastest running animals also have four legs – although bipeds have greater endurance at cruising speed than quadrupeds (perhaps benefiting from not having an extra pair of legs). All of this presupposes sufficient control for legged motion; with insufficient control the greater stability of hexapods becomes an advantage. Six (or more) legs are best for creatures that weigh less than a few grams – or in the case of lobsters, crabs, and octopi, spend most of their time underwater. Six-legged machines became popular in robotics laboratories with people that were working with computers having limited abilities. There are good reasons why evolution, with practical wisdom learned over billions of years, has never favored large animals with six legs.

The panel noted that the small U.S. humanoid robot community is at risk at being overwhelmed by foreign research, development, and commercialization of humanoid robots. However, the increased increase in humanoid robots in the U.S., as exemplified by a new journal dedicated to humanoid robot research, is encouraging. As an example of the international state of humanoid robotics, the IEEE Robotics and Automation Society is holding the Third IEEE International Conference on Humanoid Robots (*Humanoids 2003*) in Munich, Germany. Most of the chairmen and program committee members are from Germany or Japan (it is co-sponsored by the Robotics Society of Japan). Out of 30 key conference positions, only 6 are from the U.S.; while 12 are from Germany/Switzerland, as might be expected from the conference location, and 12 are from Japan.

The aims and scope of the conference are instructive: "Unlike autonomous service robots that perform a more or less limited range of special tasks without human supervision, the autonomous humanoid robot combines advanced manipulation skills with human-like cognitive processes embodied in (approximate) human shapes so as to be able to operate in unchanged man-made environments. It receives its tasks by carrying on a dialogue with human instructors involving speech, gestures as well as facial expressions, and it can use the same tools and appliances as human beings. The papers accepted for this conference will identify current research trends, present and review recent work and, possibly, speculate about the future of humanoids. They should address the general question of what the roadblocks towards full humanoid autonomy are and how they can be removed. They must also be clearly related to the general theme of the conference, i.e., how and why the work presented may be applied to present or future autonomous humanoids."

Major topics for the *Humanoids 2003* conference include:

- ☐ Brains, Mind and Robot Epistemology
    - Philosophical implications of artificial embodied minds
    - Embodiment as the basis for intelligence: co-evolution of cognitive and manipulative skills along with internal representations
    - Autonomous construction of categories and concepts through interaction
    - Grounding of behaviors and reasoning in sensory patterns
    - Higher-level representations and consciousness
    - Mental simulation, emulation and planning
    - Anticipation as a hallmark of intelligence
    - Learning and sequencing of high-level behaviors
    - Coupling of sensing, behavior and reasoning (situated perception action cycle)
    - Fault tolerance through multi-sensor perception and compensation
    - Issues of self-reproduction
    - Neurophysiological findings as a guide to artificial brain design

- ☐ Interaction with Humans and the Environment
    - Control and instruction through dialogues: recognition, production and integration of natural language, gestures, facial expressions
    - Development of language and gestures through observation and imitation
    - Desires, intentions and emotions and their expression
    - Simulation and rendering of face expressions
    - Keeping the focus of attention; recognizing specific situations
    - Body motion as an aid for the humanoid to express its internal state (of mind)
    - Communication between humanoids (human-understandable vs. proprietary)
    - Human psychology, social acceptance of humanoids and culture/country-related issues
    - Intermediate applications and habitats (toys, help for the elderly, deep space missions, ...)

- ☐ Structure and Purpose of Body and Limb Movement
    - Body gross and fine motion and its learning through demonstration
    - Learning of grasping and sensory-motor control for complex manipulation tasks; adaptation to structurally new tasks
    - Physical interaction with human-beings or with other humanoids for cooperative tasks (with or without explicit instruction/communication)
    - Navigation, planning of movement and collision avoidance
    - Body-centered behaviors (limb coordination), posture stability
    - Locomotion, gait and foot-placement
    - Simulation of all aspects of body and limb dynamics

- ☐ System and Components Design
    - Mechatronics of hands, feet, legs, arms, heads; new types of actuators
    - Materials for actuators and skin
    - Sensor design (articulated vision, tactile, directional ears, new sensors)

- Evolutionary hardware and control software
- High level programming
- Architectures for component coordination and distributed control (multi-agent-systems, distributed control, organizing internal multi-processor systems)
- Power-supply
- Building an international infrastructure for humanoids research (simulation software, shared use of components or full robots, ...)
- Humanoids for entertainment, artistic systems or educational robots including contests

Our panel also provided information on a new International Journal of Humanoid Robotics (IJHR), which will begin publication in 2003 and initiate a website by July 2003 (http://www.worldscinet.com/ijhr/editorial/submitpaper.shtml). Prof. Khatib, our panel member, is on the Advisory Board of the IJHR. The new journal has a stated aim as follows:

In recent years, we have witnessed a rapid growth in not only the theory, but also the development and application of advanced robots, such as the humanoid robot. Traditionally, "Robotics R&D" focused first on mechanics, modeling, planning, and control. Today, however, it is necessary to study both the artificial body and artificial mind at the same time. Thus, the humanoid robot seems an adroit platform to investigate mind-body interaction, or psychosomatic engineering which also includes artificial psychology, and the science of learning. Hence, the first objective of this journal is for researchers to publish timely, high-quality, original work dealing with theoretical, experimental, computational, integrative, and applied studies in Advanced Robotics. In particular, this journal seeks to foster and promote discussion which addresses various issues that are important to the mental and physical development of advanced robots, such as humanoid robots or biologically-inspired robots. The second goal of this journal is to promote an awareness of humanoid robots and their promising applications (to the general public, corporate executives, and educators). This journal would suit all researchers in the areas of Robotics, Mechatronics, Machine Learning, Cognitive Engineering, Artificial Psychology, and Artificial Intelligence. In particular, the areas it would cover include, but are not limited to:

- ☐ **MIND**
  - Mental Architecture
  - Development
  - Learning
  - Adaptation
  - Perception
  - Decision-making
  - Cognition and Knowledge
  - Robot Vision
  - Audition and Speech
  - Taction
  - Multi-Modal Interactions
  - Natural Language Understanding
  - Belief and Value Systems

  - Emotion
  - Imagination
  - Inference
  - Linguistic Programming
  - Coordination and Cooperation
  - Autonomous Behaviors
  - Educable Robots
  - Sociable Robots

- ☐ **BODY**
  - Mechanism and Design Kinematics and Dynamics Simulation
  - Planning
  - Control
  - Manipulation
  - Grasping
  - Positioning
  - Locomotion
  - Energy Sources Actuators
  - Sensors Telecommunication
  - Man-Machine Interaction
  - Tele-operation
  - Virtual Reality
  - Real-time Systems
  - Embedded Systems
  - Distributed Systems
  - Reliability
  - Long-lasting Operations

- ☐ **APPLICATIONS**
  - Neuroscience Research Tools
  - Smart Toys or Robot Buddies
  - Mechanized Drivers or Pilots
  - Mechanized Warriors
  - Assistance to Elderly
  - Office Assistance
  - Household Assistance
  - Health Care
  - Rehabilitation
  - Robot Game Players
  - Robot Tutors or Guides
  - Entertainment
  - Tele-existence
  - Tele-presence
  - Rescue
  - Surveillance
  - Security

  - Explosive Disposal
  - Exploration
  - Industrial Services
  - Manufacturing

The expert panel emphasized that the rationale for humanoid robots was to enable human-centered robotics, to have robots which function best in a human environment. Robots with non-humanoid forms are likely to function better in other environments, so humanoids should not be sub-optimized or wasted performing tasks better performed by other kinds of robots.

Given the energy and dynamic limitations of humanoid robot technology compared with humans, the panel noted, research is needed to improve the dynamics – and dexterity – of the robot. And robot design and dynamics can best be explored with high-resolution engineering and applications simulations. One approach to improving robot dynamics is to model natural human motion in terms of energy expenditure and apply the results to humanoid robots. For example, humanoid robot motion should be task-oriented, not trajectory-generated, with the task generating postures related to energy requirements. The humanoid robot's motion should be subject to the minimization of the forces on joints (also a good strategy for humans, especially aging ones). And the trajectories body parts (e.g., limbs, head) should not be generic, but based on the specific environment (as discerned by the humanoid's sensors). The real-time computational power needed for a humanoid robot can be available in a commercial notebook computer.

Near-term compelling applications, according to the panel, include performing maintenance and repair tasks aboard the space station, as well as other space missions (albeit, the space station's RoboNaut is not bipedal, but uniquely unipedal) and missions for Army MOUT (Military Operations in Urban Terrain).

Considering the spectrum of **legged robot body forms**, the panel noted the following:

- ☐ **Nilpedal:** No-legged, crawling, snake-type robots are very useful for moving through pipes and tight spaces (such as found in nuclear power plants) for the purpose of inspection or tactical maneuver. Commercial crawling telerobots are available. And this body form was deemed not in our purview.
- ☐ **Unipedal:** Single-legged robots, such as the pogo-stick type robot developed at MIT, have been used to explore mobility control. NASA's RoboNaut is a kind of single legged robot that is typically attached to a track or rail for mobility on the space station (it also uses hand-over-hand mobility). A robot that moves on a pseudopod, like a snail, would also qualify as unipedal. In addition to performing military missions aboard satellites and space vehicles, this body form can be used for (earth) military applications if it were attached, for example, to a robotic wheeled or tracked vehicle platform to provide the platform with the ability to interact with and manipulate the environment as a human would.
- ☐ **Bipedal:** Two-legged robots may be humanoid in having an overall body form similar to that of a human; or they may be non-humanoid, with many possible body forms. Non

humanoid bipeds may resemble birds or dinosaurs or other animal forms, or they may forms resembling science fiction notions of aliens (e.g., having tentacles, or multiple heads, or interesting placements of eyes and other sensors). Both humanoid and non-humanoid bipeds can have military worth, but the non-humanoid bipeds must have compelling advantages over humanoids, at least for particular missions, in order to merit development. In any event, the development of humanoid bipeds should take priority over non-humanoid bipeds.

- **Tripedal:** Three-legged robots might have utility for certain applications (where the third leg can serve to provide stability, as a tail does in some animals), but we did not consider them further.
- **Quadrupedal:** Four-legged robots will be useful for a variety of military applications; potentially, they can carry significant loads with speed and dexterity.
- **Quintrupedal:** Five-legged robots do not seem to offer any significant advantage (in the animal kingdom, most starfish have five legs, although some have more).
- **Hexapods and Beyond:** Organisms with six or eight or more legs are successful in nature (e.g., insects, crabs, octopuses, spiders, centipedes and millipedes), especially where stability and movement are controlled by tiny brains (although the octopus seems to be relatively intelligent and its legs (tentacles) are also used as dexterous arms and end effectors). Robots with six – or more – legs may likewise be useful, but not generally for the larger, relatively intelligent robots that we are considering.
- **Centaurs and Other Hybrids:** Robots that do not resemble Earth-type organisms may have significant military worth. For example, a Centaur-type robot, with a four-legged lower body and a human-type upper torso, with arms and end effectors and a head, might be very useful for military operations. It could carry a heavy load, move rapidly over all sorts of terrain, yet manipulate and perceive the environment as a human would. Other kinds of hybrid robots might also be valuable (e.g., a Hydra-type multiple-headed robot, a humanoid robot with tentacles in addition to arms and hands, a humanoid robot with flexible eye and sensor stalks on the head, cormorant-type zoomorphic robots that can fly and swim as well as walk on land, etc.).

Contemplating current and future technology, the panel forecast **behavioral clusters**, for a humanoid robot, that would be useful for military applications. These include:

Within 5 years (of the start a suitable development program) a humanoid robot will be able to**:**

- **Manipulation:** load, aim, and shoot a rifle; unlock a door with a key; collect environmental samples; disable explosives; cut the pant leg of a wounded soldier and apply appropriate pressure to a wound;
- **Perception and cognition:** locate and map suitable foot placement;
- **Dynamics:** compute posture and balance;
- **Legs:** carry loads of practical size and weight over uneven terrain.

(In our subsequent survey of robot developers, the expected (mean) year, by which the above behaviors will be achieved, was **2015**).

Within 10 years (of the start a suitable development program) a humanoid robot will be able to**:**

- **Manipulation:** pick up and carry a wounded soldier to safety; give injections and IVs to the wounded; apply telemedicine intervention; change a tire;
- **Perception and cognition:** detect, classify, and track moving objects, including humans and vehicles; interact safely with humans;
- **Dynamics:** run, jump, and crawl; fall safely and get up;
- **Legs:** operate in an outdoor urban environment with tactical posture and gait.

(In our subsequent survey of robot developers, the expected (mean) year, by which the above behaviors will be achieved, was **2019**).

Within 15 years (of the start a suitable development program) a humanoid robot will be able to**:**

- **Manipulation:** rescue victims from rubble and wreckage; suture wounds;
- **Perception and cognition:** analyze many tactical and other situations, solve problems, and devise solutions;
- **Dynamics:** climb, rappel, and parachute;
- **Legs:** operate in an indoor environment with stairs and halls filled with rubble, and outdoors in jungle and mountain terrain.

(In our subsequent survey of robot developers, the expected (mean) year, by which the above behaviors will be achieved, was **2023**).

3.2 Expert Panel White Paper

The panel submitted a White Paper on *humanoid* and *quadruped* robots (having previously excluded *hexapods* from further consideration).

3.2.1 White Paper Conclusions

- **Feasibility:** Advances in technology will occur in the near future that will enable significant improvements in the performance of robotic devices. If integrated into the proper architectural framework, these technological advances could enable humanoid and quadruped robots to walk, run, and jump with a level of strength, dexterity, and endurance that equals or exceeds human and animal capabilities. These technologies may also enable robots with near human levels of perception, situation assessment, decision making, planning, and manipulation of tools and weapons in tactical environments. These technological advances include:
    - Orders of magnitude growth in raw computational power
    - New technologies for sensing and perceiving the environment
    - Advances in the representation of geometric and symbolic knowledge
    - Advances in simulation, modeling, and graphics
    - Merging of virtual and real world environments
    - New approaches to real-time planning and intelligent control
    - Advances in efficiency, responsiveness, and strength-to-weight ratio of actuators

- ☐ **Military significance:** Robots that could maneuver as quickly and reliably over rough terrain as human soldiers or army mules while carrying comparable loads with equivalent strength and endurance would have enormous military significance:

  - Carrying weapons or supplies to support human soldiers in battle
  - Acting as forward scouts or decoys
  - Dropping by air behind enemy lines to provide eyes and ears on the ground for targeting missiles and smart bombs
  - Taking tactical risks and allowing themselves to be overrun without risk of casualties or the need to be rescued
  - Fighting fearlessly in the face of certain destruction
  - Entering and fighting in dangerous environments, such as caves, tunnels, and buildings.

- ☐ **Time table and funding constraints:** As usual, progress depends on the level of funding and the degree of focus in the development program (which is currently low in the U.S.). Assuming adequate funding and proper programmatic focus, it is the panel's belief that within the current decade, militarily useful biped and quadruped locomotion is technologically feasible.

  - **By 2015:** humanoid robots could achieve a degree of agility and intelligence that would enable a variety of tactical behavior on the battlefield
  - **By 2025:** cost and reliability could improve to the point that the cost and logistics burden of a humanoid robot will be less than or equal to that of a human soldier
  - **Before 2035:** humanoid robots could be as capable, efficient, and reliable as human foot soldiers in most battlefield situations

3.2.2 Technical Feasibility of Humanoid and Quadruped Robots

Technological advances that are relevant to the development of humanoid and quadruped robots include:

- ☐ Orders of magnitude growth in raw computational power
- ☐ New technologies for sensing and perceiving the environment
- ☐ Advances in the representation of geometric and symbolic knowledge
- ☐ Advances in efficiency, responsiveness, and strength-to-weight ratio of actuators
- ☐ Advances in simulation, modeling, and graphics
- ☐ Merging of virtual and real world environments
- ☐ New approaches to real-time planning and intelligent control
- ☐ An architectural framework that can integrate all of the above technologies into an intelligent control system

3.2.2.1 Computational Power

In terms of the growth in **raw computational power**, the current Pentium-4 chip generates about 2.4 x 10^9 operations per second (ops). A small network of Pentium computers can easily deliver 10^{10} ops. A larger network can deliver 10^{11} ops. Current supercomputers deliver 10^{13} ops or more. The current rate of growth in computational power provides an increase of a factor of 10 in computational power every five years, which is more rapid than predicted by Moore's "Law" (which, since Gordon Moore of the Intel Corporation stated it in 1965, predicts that the transistor density on integrated circuits doubles every two years, leading to rapidly increasing computational power at decreasing cost). There is good reason to believe that this rate of growth will continue over at least the next ten-year period. This means that by the year 2010, a single board PC will deliver more than 10^{11} ops and a small network will deliver more than 10^{12} ops. If the current growth continues another five years, by 2015 a single board will deliver 10^{12} ops and a small network 10^{13} ops. It has been estimated that 10^{13} ops may be **functionally equivalent** to the **computational power** of the **human brain**. (The human brain has about 10^{11} neurons. Assuming an average neuron has about 100 synaptic inputs, and each synapse computes a one-byte function about 100 times per second, this produces a maximum computational rate of 10^{15} operations per second. Because neurons are noisy and unreliable elements, the brain achieves precision and reliability with about two orders of magnitude redundancy. This suggests that the functional equivalent of the brain's computational power is around 10^{13} ops.)

Of course, more than raw computational power will be required to duplicate the functional capabilities of the human brain, but there is evidence that we may be on the verge of understanding how to use this computational power to provide the kind of functionality that is characteristic of human behavior. For example, recent experimental results have demonstrated that useful levels of autonomous mobility can be achieved in realistic natural environments with less than 10^{10} ops. The Demo III Experimental Unmanned Vehicles (XUV) demonstrated the ability for off-road driving over rough terrain, through wooded areas, and through fields filled with tall weeds and brush. Demo III has also demonstrated rudimentary on-road driving capabilities on various types of roads ranging from dirt trails, to gravel roads. Experimenters at CMU, NIST, and UBM have shown that autonomous mobility is feasible on paved roads, city streets, and highways using less than 10^{10} ops. While autonomous driving capabilities are still far below the level of human performance, there is good reason to believe that better sensors and faster computing (both of which are under development) will enable human levels of driving performance. For example, advances in LADAR technology will soon make it possible to deal with on-coming traffic, pedestrians, and complex intersections.

The 4D/RCS architecture developed for the Demo III program suggests that 10^{12} ops may be adequate to scale up the Demo III capabilities to human level driving performance. The Demo III vehicles already compare favorably with human performance in some situations, particularly at night. By 2010, autonomous driving systems could exceed average human performance in most situations. By 2015, autonomous driving system could exceed expert human driving performance in all situations.

Legged locomotion and driving a vehicle have much in common. Except for speed and scale (the speed of legged locomotion is slower and the scale is smaller), the requirements for terrain mapping, path planning, and navigation are essentially the same. Most of the image processing, world modeling, knowledge representation, and behavior generation issues are similar, if not identical. Thus, *much of the technology developed for autonomous driving will transfer directly to the humanoid robot domain*.

Of course, the control of legged locomotion is much more complex than for driving a vehicle. The dynamics of walking, running, jumping, and climbing are much more complicated. Walking requires dynamic computation of foot placement. It requires complex coordination of many actuators and degrees of freedom to provide balance, postural control, and gait. It requires the ability to recover from stumbling and get up after falling. Running requires that the runner have the ability to bound over the ground and spend a significant percentage of the time in the air. Climbing requires the ability to use elements of the environment such as ropes or tree branches to support body weight. It requires common sense knowledge of physics and the ability to estimate the effects of gravity and the strength of supporting structures.

While legged locomotion is by no means a solved problem, most of the fundamental problems are understood in principle, and algorithms have been developed. Work by Raibert has demonstrated the ability of legged machines to hop on one leg; walk, run, and jump with two legs; and walk, trot, bound, and gallop with four legs. Work by Khatib has demonstrated the ability to generate dynamically smooth, coordinated, graceful, and energetically efficient movements in multi-limbed robots. Work by Salisbury and others has demonstrated the ability to compute grasping behaviors for a variety of scenarios. Most of what remains to be done lies in four areas:

1. Better real-time performance
2. Coordination balance, gait, and foot placement with visual perception
3. Generation of adequate mechanical power with the right impedance
4. Design of an architecture that can provide control system integration

The humanoid project also involves manipulation. This is an entirely different domain from locomotion. Manipulation requires knowledge of objects and tools and how they interact physically with each other. Manipulation requires knowledge of how to approach, pick up, transport, and place parts; how to deal with contact forces; and how to perform a multitude of tasks such as picking, placing, cutting, joining, mating, squeezing, twisting, poking, pushing, pulling, lifting, polishing, painting, drawing, and writing. These features may be uniquely humanoid.

Of course, a militarily useful humanoid would not be required to perform the entire range of manipulation tasks that a human can perform. The near-term primary mission of a humanoid might be to serve as an armed companion to a human soldier. Associated with a human teammate, the humanoid robot will not be required to disassemble or assemble a weapon, handcuff a prisoner, or write a report. Thus, the manual dexterity of a useful humanoid need not be equivalent to that of the human hand. A minimal set of manipulation capabilities, such as the ability to open a door, cut a lock, aim and fire a weapon, and deal with concertino wire may be sufficient for most military missions. While manipulation in general is not a solved problem, most of the fundamental issues related to a militarily useful minimal set of manipulation tasks are understood in principle. More difficult tasks, such as scaling walls or cliffs, or rappelling down the outside of a building, may be possible further in the future.

In summary, it is our belief that the computational power required for real-time performance of militarily useful legged locomotion and manipulation can be achieved with 10^{12} ops computers. The mobility algorithms are essentially the same as are being developed for autonomous mobility in unmanned ground vehicles. Algorithms that select foot placement are simply scaled down versions of algorithms that select the desired path.

3.2.2.2 Energetics

A major problem of legged locomotion lies in the energetics. Walking, running, and recovering from stumbling requires a unique combination of strength, speed, and dynamical properties that are not possible to achieve with current **actuator technology**. **Electric motors** are too heavy and not powerful enough to provide the required low-end torque and high-speed dynamic response. **Gearing** is inefficient and produces a mechanical impedance mismatch that cannot be overcome. Current **hydraulic technology** is far too inefficient in terms of energy use.

The primary sources of energy for humanoid robots – mainly batteries – have also been deficient. The Honda battery-powered humanoid robots have about 12 minutes of endurance, which is insufficient for military missions (or most practical civilian applications). Small, heavy-fuel engines, being developed for small unmanned air vehicles, can be used (outdoors) in humanoid robots to provide sufficient power and endurance to perform useful tasks. A hybrid system consisting of an internal combustion engine for charging a battery, and the battery for powering the servos, may be sufficient in the near-term.

3.2.2.3 Sensing and Perception

There are new techniques and systems for robots to perform sensing and perception. LADAR (LAser Detection And Range) imaging is a major technology breakthrough of the past decade. The LADAR was largely responsible for the breakthrough performance of the Demo III vehicles. LADAR cameras produce images consisting of *range* pixels (picture elements) as opposed to (or in addition to) ordinary TV images consisting of *brightness* or *color* pixels. Each pixel in the LADAR image contains a measure of the distance from the camera to a region of space filled by a reflecting surface. When projected into a polar or Cartesian coordinate system, the result is a cloud of points in 3-D space that can be manipulated in many different ways and visualized from different perspectives. For example, a cloud of 3-D points can be viewed from the camera point of view; or can be transformed into a planar map view in world coordinates for path planning. Or it can be transformed into any number of other coordinate frames to simplify algorithms in computational geometry, segmentation, tracking, measurement, and object classification.

LADAR provides a major improvement in image understanding capabilities over what can be accomplished by processing images from intensity or color properties alone. For example, a range-threshold or range-window can be applied to the LADAR range image to segment an object (such as a tree) from the background (such as the forest), or to measure the slope of the ground, or detect objects that lie above the ground, or ditches that lie below the ground surface. In an intensity or color image, these types of segmentation problems are difficult or impossible to solve. In a range image, they are quite straight forward.

In an intensity or color image, range to objects is ambiguous. To infer range is difficult and computationally intensive. Computation of range from stereo image-pairs or from image flow requires a great deal of computing power, and is not robust in natural environments that contain dense foliage. Many cues for range (such as occlusion, shape from shading, range from texture, and range from a priori knowledge of size) require high-level cognitive reasoning and are imprecise at best. In a LADAR image, range is measured directly, robustly, and with great precision. Each pixel in a LADAR image can be unambiguously transformed into geometrical and dynamic model of the world that can support path-planning, problem-solving, and decision-making. Most important for walking machines, LADAR enables rapid and reliable algorithms for selecting foot placement locations, and for computing obstacle free foot-advancement trajectories.

LADAR can be used to build a precise, unambiguous geometrical model of the world directly from the image, and track the motion of entities through the world. By meshing the 3-D points, it is possible to define surfaces, and segment objects using only geometric methods that operate directly on the LADAR image. Color, intensity, and (in the case of FLIR cameras) temperature of surfaces can be registered and overlaid on this geometrical model. The model can be then be segmented into geometrical entities consisting of points, edges, surfaces, boundaries, objects, and groups. Once segmentation is accomplished, entity state (i.e., position, velocity, and orientation) can be computed and used to track entities through space over time. Entity attributes (e.g., size, shape, color, texture, and behavior) can be computed and compared with attributes of class prototypes. Entities whose attributes match those of class prototypes are assigned class membership. Class membership then allows entities to inherit class attributes that are not computable from the image. This process can be embedded in a recursive estimation loop at many different levels of resolution.

The basic technology is Lidar (light radar) that was first demonstrated feasible in the late 1980s. Current technology uses spinning mirrors to scan the Lidar beam over a portion of the egosphere (i.e., an imaginary sphere surrounding the robot) producing a LADAR image. The next generation of LADAR cameras will have focal plane arrays of Lidar detectors that will produce a simultaneous range image. Reflections from a single pulse of light will be detected in parallel by all the Lidar detectors in the focal plane. This will create a completely solid state device that will be compact, light weight, low power, and potentially inexpensive. Within a decade, the size, weight, power requirements, and cost of solid state LADAR cameras will enable a humanoid robot to have *perceptual capabilities that approach human levels of acuity and speed*.

3.2.2.4 Representing Geometric and Symbolic Knowledge

Increased computing power combined with LADAR technology have made possible advanced representations of real-time knowledge of dynamic, geometric, and symbolic information. Entities (such as occlusion edges, surfaces, and objects) can be readily detected in the image and can be simultaneously represented in images, maps, and symbolic data structures.

Entity attributes, state, class, and relationships can be computed in real time. Events can be detected and patterns of events represented in time. Relationships between images, maps, and symbolic entities and events in space and time can be represented and updated in real-time.

For example, the 4D/RCS architecture developed for the Demo III program specifies the simultaneous representation of information about entities and events in a hierarchical distributed knowledge database wherein information is presented in a form that is ideally suited for path planning and task decomposition. Maps are populated both with knowledge from a priori sources such as digital terrain databases, and with knowledge from sensors. The range and resolution of maps at different levels are specified to correspond to the range and resolution of planning algorithms. This limits the amount of computational power required to maintain maps and symbolic data structures with a latency that is acceptable for planning and reactive processes at each level.

3.2.2.5 Simulation, Modeling, and Graphics

Simulation and modeling are important elements of planning. The ability to simulate and model the results of hypothesized actions is a fundamental element in planning. The ability to analyze multiple hypotheses in a short time period is required for real-time planning. New hierarchical approaches to plan generation, together with dramatic increases in computational power, have reduced the time required for planning to the point where real-time reactive planning is achievable with computers of practical size and speed.

Real-time graphics are important for generating images from models to support model-based perception. Images generated from models can be compared with images from sensors for purposes of recursive estimation and tracking. Recursive estimation in the image domain is the essence of the 4-D approach (three dimensions in space and one in time) pioneered by Dickmanns. It is the 4D in the 4D/RCS architecture. Real-time updating of estimated state enables high performance tracking of moving objects from a moving sensor platform.

Real-time graphics are also important for generating operator displays that are intuitive and informative. Real-time graphics can enable operators to understand what the robot is doing, and thinking about doing.

3.2.2.6 Merging Virtual and Real World Knowledge

The merging of virtual and real world knowledge is the essence of recursive estimation and model-based perception. Virtual knowledge is used to generate predictions of sensory input. Sensory input from the real world can be compared with predictions generated by the virtual world. Differences between what is sensed and what is predicted can be used to update the virtual world. Correlation between what is sensed and what is predicted can be used to recognize that what is sensed in the real world corresponds to what is stored in the virtual world.

Merging virtual and real world knowledge is also important for software development, debugging, and testing. A real/virtual world can be constructed by building a virtual world that simulates the real environment, and by building virtual sensors that simulate real sensors. A real/virtual software engineering environment can be constructed by building two identical computing environments, one in the laboratory and the other embedded on a real vehicle in the real environment. In the real/virtual environment, algorithms can be tested first on simulated data from virtual sensors in the virtual world. Then they can be tested on real data from real sensors in the virtual world. Software installed on real vehicles can first be tested with simulated data from virtual sensors, and finally with real data from real sensors in the real world. All these various combinations and permutations enable algorithms to be tested and evaluated in a progression of increasingly difficult environments under increasingly difficult conditions. At each step, components and systems can be subjected to rigorous testing and evaluation. Real vehicles can operate with virtual vehicles, and virtual vehicles can interact with real vehicles. Algorithms can be tested on both real and virtual vehicles on various missions over a variety of terrains under a variety of weather and lighting conditions. Sensory processing algorithms can be tested on real data from real sensors on real vehicles and used to support a world model and behavior generation system for a virtual vehicle in a virtual environment. Data can be collected and ground truth established for both real and virtual experiments.

The 4D/RCS architecture has demonstrated how **real-time planning** and **reactive control** can be **merged** at many different hierarchical levels to generate *intelligent behavior*.

3.2.2.7 Actuator Efficiency, Responsiveness and Strength-to-Weight Ratio

One of the biggest impediments to building humanoid robots lies in the energetics of actuation. As we mentioned previously, most of the current humanoid robots are battery powered. The power density of batteries is such that battery powered machines typically have very limited range and payload capacity. Although advances in mechatronics by the Japanese have produced significant improvements in electric motors and gear mechanisms, the best battery powered humanoid robots can operate for only a few hours with a range of only a few hundred meters. Their lifting and carrying capacity is almost non-existent. Endurance is extremely limited.

One approach to this problem is to use an internal combustion engine or fuel-cell technology. The power density of fossil fuel is two orders of magnitude greater than that of batteries. However, there is a large speed and force mismatch between the power output of an internal combustion engine and the power requirements for leg motion. Legged locomotion requires short powerful bursts of high torque power, whereas the conventional internal combustion engine delivers power most efficiently at high speed, steady rate, and low torque. The power transmission and torque conversion required to couple an internal combustion engine to legs is highly inefficient. Large amounts of power and payload capacity are consumed in the transmission of power to the load. Power transmission by means of hydraulic or pneumatic fluid tends to suffer enormous inefficiencies. Electrical transmission is beginning to show promise for high speed wheeled vehicles, but the power-to-weight ratio of electric generators, motors, and gears for legged locomotion is far less than that of biological muscle. Even if electrical power is generated directly via fuel cell technology, the performance of electric motors and gears does not compare favorably with biological muscle. Furthermore, electric motors and gears tend to produce actuators that are stiff and resistant to back-drive. Thus, humanoid robots of this type do not perform well in situations requiring running, jumping, falling, and recovering.

Fuel cells and internal combustion engines are much more suited to wheeled vehicles than to legged mechanisms. Wheeled vehicles are very efficient for roadbeds with a hard smooth surface, but much less so for soft soil or for rough terrain where surface irregularities are larger than a few percent of wheel radius. This is the domain where legged locomotion excels. But, until the energetics problem is solved, legged locomotion will remain largely a laboratory curiosity.

3.2.2.8 An Architectural Framework for Intelligent Control

Development of a humanoid robot able to perform practical tasks will require more than a collection of individual technology breakthroughs. It will require that technological advances (such as those described above) be integrated into a coherent architectural framework. Nothing less will enable humanoid, quadruped, and hexapod robots to walk, run, and jump with a level of strength, dexterity, and endurance that equals or exceeds human and animal capabilities.

A desired architecture would enable the integration of the best algorithms with the best sensors and actuators. It would integrate the best behavior generation algorithms for path planning, navigation, and tactical behaviors with the best sensors and world modeling algorithms. It would fully integrate top down knowledge with bottom up sensory perception for focusing attention, grouping, segmentation, recursive estimation, classification, and computation of relationships. *It would integrate iconic and symbolic representations, deliberative/reactive behaviors, value judgment, and decision theory into a unified system.*

The desired architecture should consist of a multiplicity of computational nodes similar to functional modules in the brain that are dedicated to tasks of posture, gait, balance, motor coordination, gaze control, visual tracking and stabilization, manipulation, locomotion, path planning, navigation, task planning, decision making, cognitive analysis, and tactical behaviors. The computational nodes would incorporate elements of sensory processing, world modeling, value judgment, and behavior generation. The desired architecture would incorporate a communication system that allows messages to pass quickly and reliably between computational nodes.

There are a number of existing architectures which might be used to integrate the technologies required by a humanoid robot. Candidate architectures include SOAR, Subsumption, AuRA, TCA, DAMN, Sausages, Saphira, SFX, T3, 4D, and 4D/RCS among many others. Of all the possible candidates, the 4D/RCS architecture is the most comprehensive and inclusive, and in many ways, is a superset of the others. Other architectures such as JTA, JAUS, VRA, WSTAWG-OE are hardware architectures that are largely complementary to 4D/RCS.

The 4D/RCS architecture is a hierarchical, distributed, hybrid architecture wherein computational nodes are organized into a command and control structure. At each level and within each node, planned and reactive behaviors are tightly integrated and a world model represents knowledge over a range and at a resolution that is required for decision making in that node. At each level, sensory processing modules keep the world model current, and value judgment processes provide the cost/benefit analysis required for intelligent decision making. 4D/RCS is built around a rich internal world model that incorporates iconic images and maps, symbolic entities and events, geometric, logical, and semantic relationships, a representation of self, and a representation of external reality in terms of immediate experience, short-term memory, and long-term memory.

The 4D/RCS architecture also specifies interfaces to operator displays that enable human operators to view the robot's internal state and world model and visualize what the robot is thinking and planning. Operator interfaces will also permit humans to give commands or advice, to query internal states, to access internal images and maps, to perform diagnostic tests, debug programs, and input criticisms and advice for learning. 4D/RCS can support a speech understanding algorithms that would enable the robot to respond to spoken commands, and speech synthesis algorithms that allow the robot to express itself verbally.

The 4D/RCS provides a systematic, scientifically principled means for integrating the cognitive capabilities of reasoning, learning, explaining, with robust real-time behavior generation in the presence of noise, unexpected events, and even incorrect or misleading information. It is based on sound scientific and mathematical principles that are drawn from the neurosciences, artificial intelligence, image understanding, computational geometry, signal processing, game theory, and control theory. It is inspired by concepts derived from biological brains.

The current version of the 4D/RCS architecture includes multi-resolution maps as a world model representation that couples perception to planning and reasoning so that the most cost-effective behavior can be selected or generated for every situation. The current 4D/RCS architecture uses LADAR and color video to follow roads and avoid obstacles. It includes a perceptual system that can:

- ☐ Model the spatial geometry of the environment and generate maps
- ☐ Segment the environment into regions and entities that are represented by symbols
- ☐ Group temporal patterns into events that are represented by symbols
- ☐ Maintain relationships between images, maps, and symbolic representations
- ☐ Maintain relationships between entities, events, and places in the world
- ☐ Compute attributes of entities, events, places, and relationships
- ☐ Compute the temporal and dynamic states of entities
- ☐ Assign entities and events to classes
- ☐ Recognize entities and events that have been experienced before

Future versions of the 4D/RCS architecture will support recursive estimation, spatial and temporal reasoning, deductive, inductive, and causal reasoning; mathematics, logic, and linguistics; imagination, prediction, planning, and problem solving; focus of attention, gestalt grouping and segmentation; pattern recognition, classification of entities and events; value judgment, decision making, planning, reactive control, and learning.

The 4D/RCS architecture is extensible to multi-vehicle systems that can function together, with manned and unmanned systems, in military units at the squad, platoon, company, and battalion levels and beyond.

A first cut at a 4D/RCS architecture for a **humanoid robot** is shown in **Figure 3-1**. At the bottom level in Figure 3-1 are the actuators that power the joints in the humanoid skeleton – one actuator for each joint. Output from the servo level drives power amplifiers that move the actuators. Each actuator on the humanoid robot corresponds to a set of agonist and antagonist muscle bundles in a biological system.

Within the **servo level**, there is an executor for each actuator, i.e., there is a servo level executor for each degree of freedom in each finger, each joint in each arm, each degree of freedom in the torso, each degree of freedom in each toe, in each leg, in the jaw, tongue, lips, and face; each degree of freedom in the neck, in each eye, and (if the ears have the ability to point relative to the head) in the ears. Each servo executor may servo position, velocity, or force for its assigned actuator. Each executor takes input from a servo level planner and feedback from position, velocity, or force detectors in the joint actuator. Each servo level executor computes a new actuator command every 5 milliseconds (ms). In general, the servo level corresponds to the final motor neurons in a biological system.

Also within the servo level, there is a servo level planner (or scheduler) for each executor that generates a reference trajectory (or plan) for each actuator out to a planning horizon of 50 ms. This plan is designed to generate a smooth control signal that will achieve the goal of the servo level input task. The servo level input task is derived from an executor at the primitive (or dynamic) level that specifies desired joint positions, velocities, or forces at 50 ms intervals. The servo level planners correspond to spinal motor centers.

Within the **primitive level** there is a planner for each primitive executor that generates a reference trajectory (or plan) for coordinated motion of each finger, arm, toe, and leg, so as to accomplish desired motions of the fingers relative to the hands, arms relative to the body, toes relative to the feet, and legs relative to the body out to a planning horizon of 500 ms. Each primitive level input command is derived from an executor at the e-move (or subsystem) level that specifies desired state (position, velocity, force, orientation) of a finger tip, wrist, or torso relative to objects in the environment at about 500 ms intervals. The primitive level corresponds to human central nervous system (CNS) structures such as the cerebellum, the red nucleus, and the vestibular nuclei.

Within the **e-move level** there is a planner for each e-move executor that generates a plan for each hand and arm, each foot and leg, the mouth and throat, and the head and eyes out to a planning horizon of about 5 seconds (s). This plan is designed to generate coordinate motion of hands, arms, feet, legs, mouth, head, and eyes so as to accomplish tasks on objects in the environment. Each e-move level input task is derived from an executor at the task (or vehicle) level that specifies desired state of the entire body so as to accomplish task goals at approximately 5 s intervals. The e-move level corresponds to CNS structures such as the basal ganglia, the limbic system, and the sensory-motor cortex. (The sensory-motor cortex may also send commands directly to the primitive, or even to the servo level.)

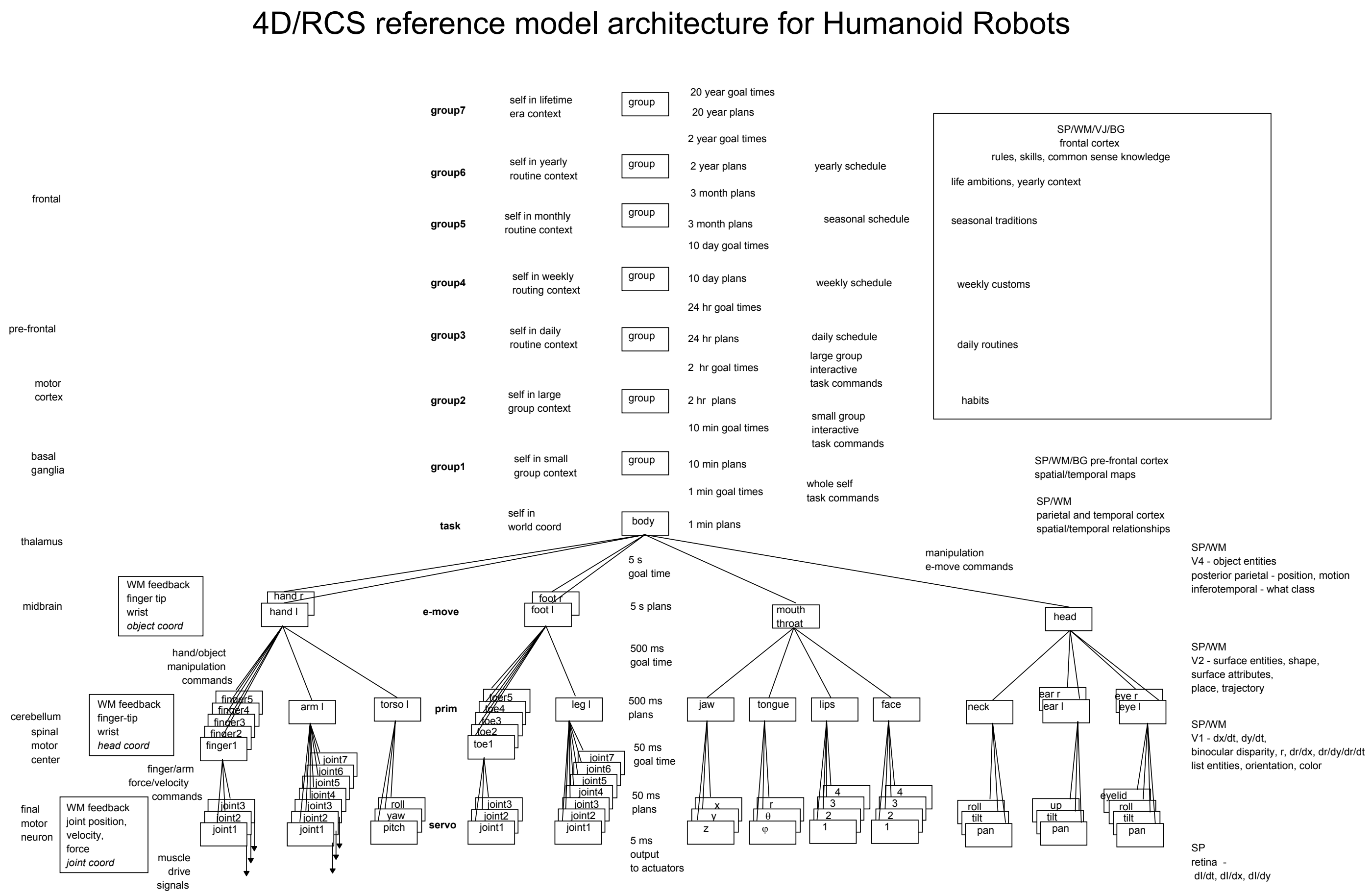


Figure 3-1: A Reference Model Architecture for a Humanoid Robot

Within the **task level**, there is a planner for each task level executor that generates a plan for the entire body out to a planning horizon of perhaps 50 seconds. This plan is designed to generate tactical behaviors relative to small groups of objects or other humanoids in the immediate vicinity. Each task level input command is derived from an executor at the first group level that specifies desired state of the individual robot relative to a small group so as to accomplish group goals at approximately 50 s intervals. The task level corresponds to CNS structures such as the pre-motor cortex.

Within the first **group level**, there is a planner for each group1 level executor that generates a plan for the individual out to a planning horizon of perhaps 10 minutes. This plan is designed to generate tactical behaviors relative to more extended groups of objects or other humanoids in the neighborhood. Each group1 level input task is derived from an executor at the group 2 level that specifies desired states of the individual relative to the larger group so as to accomplish group goals at approximately 10 minute intervals. The group1 level corresponds to CNS structures in the frontal cortex.

At **higher levels**, planners generate plans with planning horizons that extend out to 2 hours, 24 hours, weeks, months, and years. Executors cycle through their plans as feedback from the world model indicate goals have been accomplished. When failures occur, executors take immediate reflexive action, and planners generate new plans at the level where the failure is first detected. If remedial action or replanning at lower levels is unsuccessful, then executors and planners at higher levels come into play. This behavior hierarchy is supported by a distributed multi-resolution world model that provides a rich dynamic representation of the world in terms of image, maps, entities, events, and relationships at many different levels of range and resolution. The world model consists of immediate experience, short-term memory, and long-term memory. There is also a sensory processing system that keeps the world model current, and a value judgment system that provides the basis for making behavioral decisions. (These are described in more detail in Albus & Meystel, Engineering of Mind, and Albus, et al, 4D/RCS Version 2.0. Note: all references are in **Appendix J**).

It should be noted that **Figure 3-1** is only a first cut at a 4D/RCS architecture for a humanoid robot. A much more detailed analysis will be required if this project proceeds beyond this preliminary investigation. To the extent possible, the 4D/RCS architecture for the humanoid robot will duplicate the organizational structure of the human nervous system. That is, computational modules will roughly correspond to neurological modules in the central nervous system. To the extent that it is known, the functionality of the neurological modules will be embedded in the computational nodes of the 4D/RCS architecture. This is shown in **Figure 3-2**.

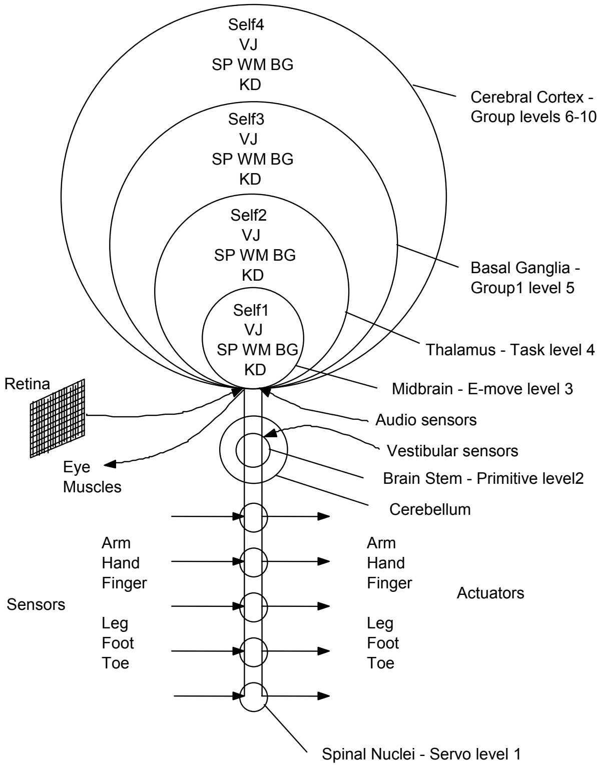


Figure 3-2: Model of the Brain Mapped onto the 4D/RCS Reference Model Architecture

3.2.3 Significance of Humanoid and Quadruped Robotics for the Military

The research effort required to build legged machines with perceptual and behavioral capabilities approaching that of biological creatures almost certainly will lead to a number of important military applications. Robots that can maneuver as quickly and reliably over rough terrain as well as human soldiers or army mules, while carrying loads equal to humans or mules with equivalent strength and endurance, would have tremendous military significance. They could:

- ☐ Support human soldiers in battle
- ☐ Carry weapons or supplies
- ☐ Act as forward scouts or decoys
- ☐ Be dropped by air behind enemy lines to designate targets for missiles and smart bombs
- ☐ Allow themselves to be perform risky tactical maneuvers, or be overrun, without risk of casualties or hostages and without need to be rescued
- ☐ Function fearlessly in the face of certain destruction

Studies should be done (perhaps by TRADOC) to define the **tactical requirements** for a humanoid robot. How will such devices be deployed? How will they be used? For example, should the humanoid serve as a forward scout, point-man, wing-man, or back-up for a foot soldier in military operations in urban terrain (MOUT), as shown in **Figure 3-3**.

PHOTOS BY KAREL PRINSLOO—ASSOCIATED PRESS

Figure 3-3: A Foot Soldier in an Urban Environment

3.2.4 Significance of Humanoid and Quadruped Robotics for Civilians

According to their own testimony, the Japanese are developing humanoid robots primarily to care for the ill, disabled, and elderly. Japanese society is aging more rapidly than most other nations, including the U.S., and the burden of providing long-term care for a growing population infirm people is increasing rapidly. However, as the “baby boomers” in the U.S. reach geezerhood, the U.S. will also experience the growing burden of providing care. Humanoid robots, especially those with a friendly, non-threatening demeanor, are ideal for providing patient care 24 hours a day, 7 days a week – assuming (and this is a big assumption) they can perform the care-provider functions appropriately, safely, and affordably.

In addition to solving the care-provider shortage, humanoid robots (eventually) will be able to:

- ☐ Provide childcare services
- ☐ Clean houses and commercial facilities
- ☐ Perform manual labor
- ☐ Provide security and law enforcement
- ☐ Operate machinery and vehicles
- ☐ Provide entertainment and companionship
- ☐ Do much of what humans do

3.2.5 Significance of Humanoid and Quadruped Robotics for Science

While there are clear military (and civil) advantages for developing humanoid and quadruped robots, there could also be important scientific implications as well. The humanoid robot project could provide the focus for a whole new debate on the **mind-body problem**. For example, how can consciousness arise out of matter? How does the brain give rise to the mind? What is the relationship between mind and brain? These are scientific questions that rank with those related to the structure of the atom, the origin of the universe, and the mechanisms of life. There are three **approaches to humanoid robotics**:

- ☐ Engineer systems with desired functionality
- ☐ Build a model of the mind
- ☐ Build a model of the brain.

The first approach, engineering systems with desired functionality, should certainly be the central focus of a DARPA program in humanoid robotics. A **systematic engineering effort** should focus on:

- ☐ Defining the functional requirements of the desired system
- ☐ Designing the functional modules and a system architecture that can satisfy these requirements
- ☐ Building software and hardware that meet the design specifications

The **desired functionality** includes the ability to:

☐ Plan and execute tasks of manipulation and locomotion
☐ Perceive and understand visual scenes and sequences
☐ Perform logical, spatial, temporal, and causal reasoning
☐ Predict the results of contemplated actions and make decisions
☐ Deal with uncertainty and probability
☐ Focus attention and set priorities
☐ Communicate and understand what is communicated
☐ Speak and understand spoken and written language
☐ Represent the world and use that representation to generate successful behavior

However, these capabilities will require the functional equivalent of many aspects of the human mind. Thus, a humanoid robotics project could stimulate scientific research in understanding the *computational equivalents* of all the functional properties of the phenomena we call *mind*. These would include capabilities such as image and speech understanding, spatial and logical reasoning, planning and decision making, emotions, feelings, imagination, and intelligent behavior.

An effort to **model the mind** should focus on attempting to:

☐ Model the phenomena of perception, cognition, emotion, and behavior
☐ Build computational modules that produce these phenomena
☐ Attempt to understand how these functional modules can be interconnected in a system architecture that exhibits intelligent behavior

The humanoid project might eventually be expanded further to include an effort to model the brain. This would involve an attempt to:

☐ Model the neuron and synaptic sites
☐ Model the interconnections between neurons within the various neurological structures of the brain
☐ Attempt to understand how these neurological structures compute the information required to generate the phenomena of perception, cognition, emotion, and behavior

This approach would stimulate scientific research in understanding the fundamentals of anatomy and neurophysiology. How are the neurons interconnected? What kinds of functions can be computed? How is information about the world represented? How does the brain store, retrieve, and use these representations? How do the fundamental computing elements of the brain perform the functions of image and speech understanding, logical, spatial, temporal, and causal reasoning, predicting, planning, and conniving? How does the neural substrate function to enable decision making, the recognition of duty, and the experience of fear, anger, guilt, and sexual desire? How is behavior generated and controlled that is both goal-directed and reflexive, both planned and reactive? How do neurons produce control signals that enable running, jumping, fighting, and fleeing behavior such as can be observed in insects, birds, mammals, and humans? What are the neural control mechanisms that produce normal everyday activities as well as world class professional achievements in sporting events?

This approach would stimulate research in neural nets and brain models that attempt to emulate the fundamental mechanisms that reside within various parts of the brain, such as the visual cortex, the superior and inferior colliculi, the cerebellum, the mid-brain, the temporal, parietal, and frontal cortex, and the various centers within the limbic system.

A great deal is known about the structure and function of the human motor system, including dynamic and energetic properties of human muscle, the generation of reflex actions, balance, posture control, integration of vestibular signals, generation of gait, and coordination of limb motion during reaching, grasping, manipulation, walking, running, and jumping. The anatomy of the human sensory-motor system is well known. All the major neural computing modules and the neural pathways that interconnect them have been mapped out in great detail. Detailed maps describe where axons from particular nuclei come from and where they go. For example, the pathways by which sensory neurons in the skin, muscle, and tendons transmit signals to computational modules in the spinal cord, cerebellum, thalamus, and sensory cortex are known in great detail. Neural pathways are well known by which signals from inertial sensors in the head are transmitted to vestibular nuclei in the midbrain, and from there to the motor nerves in the eyes (the vestibular-ocular reflex) to stabilize images on the retina. Neural pathways from vestibular nuclei to the motor nerves in the legs and torso (the postural stability reflex) that stabilize the body against gravity are also well known. The computational functions that stabilize gaze and posture could be modeled in a humanoid robot, thereby providing insight into the computational processes in the vestibular nuclei.

Currently, these types of neuronal processes are modeled only in the most general and imprecise manner. Most of the information about what computational modules in the brain actually do is gleaned from experiments that measure what behavioral deficits result when a particular nucleus is destroyed, or measure the kinds of spasmodic motions result when thousands of neurons in a particular nucleus are simultaneously given an electric shock. These kinds of experiments provide only the most general clues about what computations are being performed. They provide nothing specific about the exact form of the input/output transformations during the performance of normal activities. Positron Emission Tomography (PET) and functional Magnetic Resonance Imaging (MRI) technologies are beginning to give insights into functional relationships among neural modules, but the details of the computational algorithms are still shrouded in mystery. It would be a great scientific achievement to be able to model in detail the computational processes that take place within these modules. What kind of mathematical or logical functions are being computed, and with what precision? What is the transfer function between input and output? How are these computations influenced by goals, priorities, and intentions?

It would also be a great scientific achievement to be able to understand the syntactic and semantic structure of the messages that are carried on nerves that travel between neuronal nuclei. What is the information being conveyed? How is it encoded? Where does each piece of information go? What effect does it have on the computation being performed in the receiving nuclei?

The computational processes that take place within the neuronal nuclei of the brain are known only very generally. The neurological textbooks are replete with statements like “nucleus x receives input from nucleus y and nucleus z." But the message that the input conveys is largely unknown, as is the function that the nucleus performs. Only near the periphery is there any real understanding of the messages and functionality. For example, sensors that detect pain, vibration, temperature, or pressure, send axons with pulse trains in relatively well-defined nerve bundles. However, once these axons terminate on neurons in various nuclei within the spinal cord, midbrain, cerebellum, or cortex, this information is merged with inputs from many other sources. Functionality then becomes more blurred (e.g., coordination, gait control, posture). By the time a signal from the periphery reaches the frontal cortex, it has passed through at least five synaptic interfaces – and possibly many more through loops and feedback pathways. The sensory signal has been transformed many times, and its influence has reverberated through pathways that include loops of many different lengths. Thus, the functionality of nuclei in the frontal cortex are described in terms such as "long range planning" with very little known as to what computational processes are involved in long range planning, or how it is performed.

These are scientific questions of the highest order. They will be answered only when systems are built that can precisely model the functionality and communications that take place within the central nervous system. A humanoid robot project could provide the seedbed for such an effort.

3.2.6 Time Table and Funding

Much depends on the level of funding and the degree of focus in the development program. Assuming adequate funding and proper programmatic focus, it is the panel's belief that militarily useful biped and quadruped behavior is feasible within the decade. The panel estimates that to achieve this goal, two or three research teams of at least 10 researchers and 10 support personnel should be fully funded for the remainder of the decade for each of the following technical areas:

- ☐ Sensors
- ☐ Perception and world modeling
- ☐ Cognitive reasoning and learning
- ☐ Planning
- ☐ Actuators
- ☐ Control

This would total about 60 people full time for a period of eight years. Assuming fully loaded salaries of $200K per person, this would come to about $12M per year for eight years, or roughly $100 million over an eight-year period. (This is about the amount Honda spent developing its *Asimo* robot). If this level of effort were continued for another five years, the panel believes that humanoid robots could achieve a degree of intelligence and functionality that would enable autonomous tactical behavior on the battlefield by 2015.

If this level of effort were continued until the year 2025, the panel believes that the cost and reliability of humanoid robots could become such that the logistics burden of a humanoid robot will be less than or equal to that of a human soldier by that year. If this level of funding were continued until the year 2035, humanoid robots could become as capable, efficient, and reliable as human foot soldiers in most respects.

3.2.7 Expert Panel's Summary and Conclusions

The technology feasibility of humanoid and quadruped robots seems within reach. Advances in technology will occur in the near future that will enable significant improvements in the performance of robotic devices. These technological advances include:

- ☐ Orders of magnitude growth in raw computational power
- ☐ New technologies for sensing and perceiving the environment
- ☐ Advances in the representation of geometric and symbolic knowledge
- ☐ Advances in simulation, modeling, and graphics
- ☐ Merging of virtual and real world environments
- ☐ New approaches to real-time planning and intelligent control
- ☐ Advances in efficiency, responsiveness, and strength-to-weight ratio of actuators

If integrated into the proper architectural framework, these technological advances could enable humanoid, quadruped, and hexapod robots to walk, run, and jump with a level of strength, dexterity, and endurance that equals or exceeds human and animal capabilities. These technologies could also enable robots with human levels of perception, situation assessment, decision making, planning, and manipulation of tools and weapons in tactical environments.

Military Significance: Robots that could maneuver as quickly and reliably over rough terrain as human soldiers or army mules, while carrying loads equal to humans or mules with equivalent strength and endurance, would have tremendous military significance. They could support human soldiers in battle. They could carry weapons or supplies, and act as forward scouts or decoys. They could be dropped by air behind enemy lines to provide eyes and ears on the ground for targeting missiles and smart bombs. They could allow themselves to be overrun without risk of casualties or hostages and without need to be rescued. They could fight fearlessly in the face of certain destruction. In addition, humanoid robots are a natural way in which to incrementally insert automation on ships which were originally built without extensive automation and which will remain in the fleet for decades.

Time Table and Funding: If an adequate level of funding and a proper degree of focus in the development program can be achieved, it is the panel's belief that militarily useful biped and quadruped behavior is feasible within the decade. The panel believes that humanoid robots could achieve a degree of intelligence that would enable autonomous tactical behavior on the battlefield by 2015. The cost and reliability will become such that the logistics burden of a humanoid robot will be less than or equal to that of a human soldier by the year 2025. And the panel estimates that humanoid robots could be as capable, efficient, and reliable as human foot soldiers in most respects before the year 2035.

4.0 EXPERT SURVEY RESULTS

This section provides the results and analyses of our **survey of experts** (robot developers) concerning the potential usefulness of humanoid and other legged robots for military applications.

4.1 Expert Survey Results Summary

Appendix A lists the distinguished robotics experts selected as survey recipients, with survey respondents shown in italics. The expert survey form is given in **Appendix B**. The aggregated **survey results** are integrated in the survey form in **Appendix C**. There were 66 original recipients of the survey and 27 respondents, for a return rate of 41%. Another 10 recipients received the survey as pass-along recipients, for a total return rate (among 76 recipients) of 36%. The 41% - or even 36% - survey return rates is quite satisfactory, especially for a relatively long form with difficult questions. (One response was submitted too late for inclusion in the statistics, but its comments are included).

The survey provided interesting insights in the form of comments, opinions, and statistical analyses of the quantitative scoring. The relevant experience of our robotics experts is presented in **Question 1** of the survey form (please see **Appendix C**). The **frequency-distribution graph** (in the form of a bar chart) shows that most of the 27 respondents were employed by universities or non-profit organizations (15), followed by industry (7) and government (5). There are many years of aggregated experience among our respondents, several of whom have founded robotics-based enterprises or have toiled in academe robotics and robotics R&D laboratories. Their opinions are based on toil and sweat and cognitive contemplation. We retained all of the completed survey forms, which have the respondent's identity for each form. But to avoid any potential embarrassment – especially for the respondents' uninhibited comments and opinions – we offer their responses without attribution.

The respondents' views tended to range over the spectrum of possible question responses. And while it is apparent that some must be wrong if others are to be right, no one can say for certain now which is which. For example, if humanoid robots with human-like performance can never be achieved, then it cannot be achieved in 22 years, 22 years being much sooner than never (never is quite a long time). Two such opposing opinions may be proffered by two respectable robotics experts, each perhaps thinking the other mad. So we settled on semi-anonymity for the responses.

Question 2 in the survey asks about the current state of robotic technology relative to the development of militarily useful humanoid robots. The results for the question, as for the others with a quantitative scale, displays the calculated mean of all the responses on the scale itself, along with the numerical values for the number of respondents for that question (n), mean (M), standard deviation (Sta. Dev.), median (which is approximate and was not calculable for some questions), mode, and the range of responses. The **mean** (arithmetic average) of 3.4 is shown on the scale – a somewhat less than satisfactory rating. The **standard deviation** of 1.7 shows a clustering in the poor to satisfactory range. The **median** (half of the responses are lower and half higher) is about 3, indicating a greater frequency of responses on the "poor" side of the scale.

The **modal response** (highest frequency) of responses is 2, solidly in the "poor" section. The range of responses is from 1.5 to 6, so none of the respondents thought the current state of humanoid technology to be in the "excellent" section of the scale. The **response-frequency graph** (in the form of a bar chart) for Question 1 shows the distribution of responses. (Note: in the graph, responses were grouped into intervals of integer values for the convenience of the graphical display. Integer values falling exactly at the *end* of an interval [such as 1 in the range 0-1], are included in the *following* interval [such as 1-2]). In the graph, there are some relatively optimistic respondents who see solidly satisfactory (albeit not excellent) technology available for the development of military humanoid robots. But most of the respondents perceive the available technology to be less than satisfactory (although none scored it completely poor (less than 1).

The comments for **Question 2**, presented completely in **Appendix C**, include comments on lacking critical enabling technologies, such as perception (situational awareness), bipedal leg control for balance on uneven surfaces and for suitable gaits, object manipulation, power sources, and human interfaces. Software performance is seen as lagging that of hardware. Humanoid development can leverage current DARPA programs, but development must be motivated by real needs. The cost of available technology is also a concern. But cost can be reduced through large-scale commercialization.

Question 3 asks about the *year* by which technology would be at least satisfactory for the successful development of supervised autonomous military humanoid robots. The resulting **mean year** is 2012 (sta. dev. = 5.1 years), with the **median year** being 2011, the **mode year** between 2009 and 2011, and the **range** of responses between 2003 and 2022 (one response greater than 2021 was taken as 2022 to determine the mean). The **response-frequency bar chart** shows a strong central cluster between 2009 and 2013. There are a few optimistic forecasts between 2003 and 2007, but a few pessimistic respondents do not see foresee satisfactory technology until 2019 and beyond.

Comments for **Question 3** include experience in robot development (historically slow) as a basis for the prediction, and the importance of funding as the technology driver. The level of autonomy and the missions to be accomplished are also seen as important determinants of the feasibility date, with teleoperation enabled much sooner than full autonomy; and simpler missions are preferable to more complex ones. **Optimistic responses** (e.g., feasibility within 5 years from now) are generally predicated on the system having less autonomy and performing simpler missions, while **pessimistic responses** (e.g., feasibility in 15 or more years) are generally predicated on greater autonomy and more complex missions. One respondent opined that while initial missions for humanoid robots may be simple, their greater adaptability will ultimately enable them to become superior to robotic vehicles.

Question 4 asks about the expectation for military use of humanoid robots by 2020, whether their use will be non-existent or ubiquitous – or something in-between (used in several applications). The resulting **mean score** is 4.9 (used in several applications). The **standard deviation** of 2.1 reflects the broad range of predictions, as shown in the frequency bar graph (the range of responses is 0.5 – 8.0). The **median** (5.0) is almost identical to the mean, but the **mode**

is somewhat higher at 6.0. Thus the experts predict significant (although not ubiquitous) military use of humanoid robots by 2020.

Comments for **Question 4** include the view that humanoid robots will not replace humans or vehicles, but serve as tools for manned forces and supplements to ground vehicles (which are faster and more efficient at covering large distances). For fighting in dangerous urban environments, teleoperated humanoid robots (e.g., for telepresence) would be valuable even before more autonomous systems are available. The technology may be ready soon, but militarizing or hardening the systems will take time. Also, the historically slow pace of fielding unmanned (robotic) systems is extrapolated for a pessimistic view of the fielding of humanoid robots.

Question 5 seeks the most promising humanoid robot applications, missions, or combat functions for humanoid robots. For each (randomly listed) alternative mission, respondents were requested to score the alternative from 1 (most promising) to 15 (least promising). The table (in **Appendix C**) shows, for each alternative mission, the number of respondents (n), the mean response, the standard deviation, the median, and the range of responses. The accompanying response-frequency bar graphs show the distribution of responses for each mission type, with the **final chart** for **Question 5** showing the **mean score for each mission type**. The **most promising mission** is deemed to be reconnaissance, surveillance, and target acquisition (RSTA). The distribution of the means of the responses, shown in the **Question 5 bar chart** in **Appendix C**, is listed below in descending order (1 to 15) of promising mission:

- ☐ Reconnaissance, Surveillance, and Target Acquisition, RSTA (3.1)
- ☐ Military Operations by in Urban Terrain, MOUT (3.3)
- ☐ Target Designation (3.9)
- ☐ Satellite Operations and Space Exploration (4.5)
- ☐ Logistics and Materiel Handling (5.8)
- ☐ Special Forces and Counterterrorism 5.8)
- ☐ Infantry (6.1)
- ☐ Countermine Operations (6.8)
- ☐ Driving or Piloting Vehicles (7.7)
- ☐ Operating Indirect Fire Weapons (8.1)
- ☐ Operating Direct Fire Weapons (8.4)
- ☐ Operating Air Defense Artillery or Missiles (8.9)

The **frequency-response charts** for **Question 5** are given in the same (random) order of their listing in the question. The **first** response-frequency **chart** for **Question 5** (in **Appendix C**) shows the distribution of responses for the postulated **RSTA** mission. The mean score for RSTA is a high score of 3.1, but the median is an even higher at 1.5, and the mode hits the highest score possible of 1.0. There are, however, some respondents who scored RSTA toward the lower end of the scale (generally below 8), with one outlier with a very low score of 12. The **driving/piloting** mission scored a mean of 7.7 (moderately promising), a median of 7.5, and a mode of 1.0. As the corresponding response-frequency chart shows, the scoring was all over the scale, showing diverse views of whether this mission was or was not very promising. Likewise for the scattered chart for the **infantry** mission, with a mean of 6.1, a median of 5.0, and no clear mode. The mean does indicate that it is considered reasonably promising. The **direct fire** mission, as shown in the chart, is scattered across the scoring scale, but with a strong cluster between 7 and 11. Its mean of 8.4 and median of 8.5 indicate that it is considered not very promising as a potential humanoid mission. The **indirect fire** mission is also not very promising, with scattered scores in the chart and a mean of 8.1 and a median of 8.5. The **MOUT** mission, on the other hand, is deemed highly promising, with a mode of 1.0, a mean of 3.3 and a median of 1.5. The **countermine mission**, as the chart shows, is highly scattered, and the mean of 6.8 and median of 5.0 means that it is considered a somewhat promising mission. The **target designation** chart is clustered on the promising side, with a mode of 3.0, a mean of 3.9 and a median of 3.0. While views on the **logistics and material handling mission** are scattered in the chart, the mode is 1.0, the mean is 5.8 and the median is 5.5, indicating that it considered a moderately promising mission. The **air defense** mission is also scattered, but shifted toward the less promising side in the chart. The mean of 8.9, the median of 8.0, and the mode of 8.0 indicate that it is considered moderately unpromising. The **special forces and counterterrorism** mission, while scattered in the chart, has a mean of 5.8, a median of 4.5, and a mode of 2.0, showing that it is considered moderately promising. The primary clusters are at either end of the scale, but with most weighing in on the promising side. The **satellite operations and space exploration** mission is one that NASA is considering for humanoid robots (and funding relevant development projects), but there are potential military missions of this sort as well. With a mean of 4.5, a median of 2.5, and a mode of 1.0, the respondents consider this mission to be quite promising. The chart does show a small group of naysayers clustered at the non-promising side.

In **summary**, the expert survey clearly preferred humanoid robot missions for RSTA, MOUT, target designation, and, satellite/space missions. Logistics/materiel handling, counterterrorism/special forces, and infantry missions are also worthy of consideration.

Comments for **Question 5** observe that missions such as MOUT will very costly in the lives of U.S. soldiers and that these missions can justify the cost – and priority – of developing humanoid robots. Also, humanoid robots should not be used where robotic vehicles can do the job better. There are a number of suggestions for the "other" mission category (which received a mean of 3.0 and a median of 2.0 (meaning that each respondent liked his/her own suggestion as a promising mission) :

☐ *Other: as a physical interface to a range of personal assistant agents for various tasks of information gathering, planning and organization.*

☐ *Other applications for humanoid robots include NBC ops, medics, cooking (someone has to do it), and equipment repair.*

☐ *Other: The humanoid robot could also serve as a suit (exoskeleton) that a soldier could use for sustained life from chemical, biological, or radiation environments. It could also provide additive capabilities to make soldier stronger, faster, or have extended performance.*

☐ *Other: Medical*

- ☐ *Other: crew station work onboard military platforms, such as fire fighting aboard ship.*

Question 6 seeks to determine the *year* in which humanoid robots will have a *significant impact* on the U.S. military, commonly performing functions and missions. Three date conditions are sought: the optimistic, pessimistic, and most likely years. These three data points can be used in conjunction with the beta probability distribution to obtain a mean (expected value) and standard deviation for the forecast year. (This technique, which uses certain reasonable assumptions about the beta distribution, is a standard method in operations research). We calculated the mean responses for each condition and used them to calculate the beta expected value and standard deviation. The table (reproduced below) shows the means for the predicted date conditions:

TYPE YEAR	MEAN	STA. DEV.	N
Optimistic	2015	5.2	26
Pessimistic	2041	21.4	26
Most Likely	2022	7.2	26

Using the Beta distribution assumption, the **expected (mean) year** in which humanoid robots will have a significant impact on military operations is **2024,** with a **standard deviation** of **4.3 years** (i.e., roughly somewhere in the decade between 2020 and 2030).

The three **response-frequency charts** (in **Appendix C**), accompanying **Question 6,** shows the distributions for the optimistic, pessimistic, and most likely years. (Note: two pessimistic responses of "never" (or infinity) were taken as 2099 for the calculation – because we consider "never" to be an excessively long time). The **optimistic** distribution (with a mean of 2015), in the chart, is clustered sooner than 2030, with a mode in the 2010 interval. The **pessimistic** distribution is more scattered (as indicated by the large standard deviation of 21 years), with a mode in the 2020 interval, but a mean of 2041. The **most likely** distribution, with a mean of 2022 and a mode in the 2020 interval, is clustered sooner than 2040.

Comments for **Question 6** include the prediction that humanoid robots can have an important role in the U.S. military in the near-term, although a "significant impact" will take longer. The applauded use of small telerobotic vehicles for searching caves in Afghanistan is noted as an indication that a significant military impact may occur sooner rather than later.

Question 7 contemplates the potential of other types of **legged robots**, in addition to humanoid robots. (The original task was to examine the potential for hexapod, as well as humanoid, robots, but we have expanded the legged alternative designs in the pursuit of completeness). **Question 7** seeks to determine, from the robotics experts, which type of supervised autonomous legged robot might be the most useful, in general, to the U.S. military, ranked from 1 (most important) to 5 (least important). The choices are:

- ☐ **Bipedal Humanoid**: a robot that generally resembles a human, with a head on top, a torso, arms and hands (end effectors), and two legs and feet. It need not be an android, resembling a human too a remarkable degree; and it may be somewhat larger or smaller than the average person. Functionally, it should be able to physically replace a person in performing tasks with human-operated tools or equipment, or moving about in facilities designed for people.

☐ **Bipedal Non-Humanoid**: a two-legged robot that may have any upper-body shape and does not, in general, resemble a human (e.g., an octopus-like form walking on two legs).

☐ **Quadruped:** a four-legged robot that may have any upper-body shape (e.g., a truck on four legs; or a robotic horse)

☐ **Hexapod:** A six-legged robot that may have any upper-body shape (e.g., a robotic ant; or a truck on six legs)

☐ **Hybrids:** A robot combining elements of the other types (e.g., a centaur robot (a quadruped with a human-like upper body); a human-like robot with octopus-like tentacles; a large snake-like robot with a human-like head (for telepresence))

The statistical **results table** for **Question 7**, in **Appendix C**, is reproduced below.

Statistic	**Bipedal Humanoid**	**Bipedal Non-Humanoid**	**Quadruped**	**Hexapod**	**Hybrids**
N	26	25	26	26	25
Mean	2.4	3.7	2.6	3.5	1.7
Sta. Dev.	1.4	1.2	1.2	1.2	1.0
Median	2.0	4.0	2.5	3.5	1.5
Range	1-5	1-5	1-5	2-5	1-5

The table shows that **Hybrids** are deemed the **most important** in potential military usefulness, with a mean score of 1.7 (and a median of 1.5). The **Bipedal Humanoid** is rated second in importance (with a mean of 2.4), followed closely by the **Quadruped**. The **Hexapod** is considered unimportant, and the **Bipedal Non-Humanoid** the least important alternative design. In **Appendix C**, the results bar chart for **Question 7** illustrates the mean scores for the alternative legged designs. **Response-frequency bar charts** then show the results for each of the legged designs. The **Hybrid** chart shows almost a negative exponential distribution, with majority of the respondents assigning it a (modal) score of 1 (but one lone outlier deems it the least important configuration). The **Bipedal Humanoid** chart is more scattered, but with most respondents on the important side of the axis, and a mode of 1 (although several respondents deem it the least important alternative). The **Quadruped** chart, with diverse opinions as to its likely importance, shows almost a uniform distribution (although with fewer least important scores than the Humanoid). The **Hexapod** chart shows a shift to the lesser importance side of the axis, with many considering it the least important configuration. The **Bipedal Non-Humanoid** is considered even more of a non-starter design, with many experts considering it the least important of the alternatives.

Comments for **Question 7** include the judgment that a robot mule that can carry heavy loads over rough terrain would be most useful. A mule that can open doors and cut fences will also be useful. A biped will be more difficult and expensive, but eventually useful as a buddy on the battlefield. The extra pair of legs on a hexapod has little advantage from a control and dynamics standpoint, and simply is extra weight to carry around. And it is a fact of nature that there are no large land creatures with six legs, and there never have been. Another sees the hexapods as useful for simple robots, but they do not typically have the agility of other systems. Another sees the hexapods as an easier technological achievement, with evolution to other legged forms as technology permits. Manipulators (whether in conventional human arm/hand form or not) is seen as making robots more useful, whatever the body design. Applications will drive the robot's configuration, as constrained by existing technologies. Quadruped or hybrid robots may be nearer-term possibilities than humanoid robots, with available technology. There is little use for a non-humanoid biped because it is less likely than an anthropological form to be substituted for a person in a functional role.

Question 8 asks for a judgment (a score of 1 for the most difficult to a score of 5 for the least difficult) of the alternative legged robot forms most difficult to develop into useful military systems. The statistical results table is reproduced from the **Question 8** results in **Appendix C**:

Statistic	Bipedal Humanoid	Bipedal Non-Humanoid	Quadruped	Hexapod	Hybrids
N	26	26	26	26	25
Mean	1.5	2.3	3.4	4.1	3.4
Sta. Dev.	1.0	0.79	0.70	1.1	1.2
Median	N/A	N/A	3.0	N/A	N/A
Range	1-5	1-5	2-5	2-5	1-5

The table shows that the **Bipedal Humanoid** (with a mean of 1.5) is deemed the most difficult legged form to develop into a militarily useful system, followed by, in descending order of difficulty, Bipedal Non-Humanoid, Quadruped, Hybrid, and Hexapod. The bar chart for **Question 8** (in **Appendix C**) illustrates these results. **Response-frequency bar charts** (in **Appendix C**) show the scoring distribution of respondents for each legged robot type. The **Bipedal Humanoid** has a strong modal value of 1.0 (greatest difficulty), although a few respondents believe that development will easy. The **Bipedal Non-Humanoid** is also judged difficult to develop, although the strong modal value has shifted one notch easer than the Humanoid, to a value of 2. The Quadruped is considered even easier to develop, with a major cluster at 3 and 4 (and a modal value of 3). No one thinks that this will be the most difficult to develop. The **Hybrid** is more scattered in its difficulty scoring, possibly because different experts have different notions of the form it will take. The modal value is 3, but many experts consider it will be even easier to develop, with scores of 4 and 5. The **Hexapod** is deemed the easiest to develop, with a modal score of 5 (and most of the rest of the respondents scoring 3 and 4), although one respondent considers it the most difficult to develop.

Question 8 comments include the observation that a bipedal humanoid is the hardest to develop because of its posture, foot placement, and the dynamics of running, jumping, falling and recovering. A hybrid is more difficult than a quadruped when arms and hands are included for manipulation tasks. A quadruped is harder than hexapod because of need to compute dynamics for trotting, galloping, and bounding. And a hexapod is easiest because there is no need to worry about dynamics. The easier hexapod might be a useful stepping stone to developing quadrupeds, which would be a better alternative to hexapods because they are likely to be faster and more capable (if the robot is of any significant size) due to relatively decreased weight. While mechanics are a challenging problem, I feel that control and learning are the real challenges that will make legged robots capable – or not, as the case may be. A hybrid robot can be of any convenient and useful form (and not constrained, a priori, to some predetermined configuration), and so, from that perspective, it should be the easiest to develop into a useful military system. It would be most difficult to duplicate the manifold characteristics of the bipedal human form. For machines of small and medium size, a respondent finds it hard to imagine why six legs are not the best option in almost all cases. As the number of legs decreases, locomotion challenge increases, and this has to be duly justified. By the time we are down to two legs, its mission should be worth the complexity of balance and locomotion. Humans are bipedal due to the process of evolution, but why do our robots need to be?

Question 9 seeks to determine the estimated cost (in today's dollars) of a militarily useful, supervised autonomous humanoid robot, as it might exist in 2020. Once again, to employ the Beta distribution procedure for calculating an expected value, optimistic, pessimistic, and most likely costs are requested from the experts. The statistical results table is reproduced below from **Question 9** results in **Appendix C**.

TYPE COST	**MEAN ($)**	**STA. DEV. ($)**	**N**	**MEDIAN ($)**	**Range ($)**
Optimistic	285,700	336,516	20	150,000	9,000-1,000,000
Pessimistic	482,500	3,141,080	20	1,500,000	100,000-10,000,000
Most Likely	813,750	973,783	20	650,000	50,000-4,000,000

The table shows a very large **range** of predicted costs, for all three cost types, as estimated by the experts. We discarded two outliers for each case – the highest and lowest predicted value. For the optimistic case, we dropped $5,000 and $1,250,000; for the pessimistic case, $50,000 and $200,000,000; and for the most likely case, $35,000 and $10,000,000. We also excluded responses where the costs were given as development costs, not unit procurement costs. The **result (**using the assumption of a Beta distribution) provides an **expected (mean) unit cost** of **$1,003,866** (with a **Standard Deviation** of **$366,133**). Given that an autonomous robotic HMMWV (with relatively limited performance) now costs about $500,000, the humanoid robot cost (in today's dollars) seems within the ballpark, despite the highly diverse estimates of the respondents. And, with the standard deviation, it might less (or more) by a third of a million dollars.

Question 9 comments include assumptions about production quantities (whether for hundreds or thousands of units), where production volume will have major impact on cost (perhaps, in one view, costing no more than an expensive automobile). Cost can also be leveraged (the lease on the Asimo humanoid robot is said to be about $20,000 (but cost in excess of $100 million to develop). One respondent thought that humanoid robots should cost no more than a smart weapon. A few would not deign to venture a cost estimate.

Question 10 is similar to that of Question 9, except it focuses on the estimated 2020 cost of quadruped or hexapod robots. Once again, to employ the Beta distribution procedure for calculating an expected value, optimistic, pessimistic, and most likely costs are requested from the experts. The statistical results table is reproduced below from **Question 10** results in **Appendix C**.

TYPE COST	MEAN ($)	STA. DEV. ($)	N	MEDIAN ($)	Range ($)
Optimistic	173,750	184,632	20	150,000	5,000-500,000
Pessimistic	1,870,000	3,171,020	20	550,000	100,000-10,000,000
Most Likely	633,750	1,131,146	20	200,000	50,000-5,000,000

The table again shows a very large **range** of predicted costs, for all three cost types, as estimated by the experts. We discarded two outliers for each case – the highest and lowest predicted value. For the optimistic case, we dropped $1,000 and $1,000,000; for the pessimistic case, $50,000 and $200,000,000; and for the most likely case, $20,000 and $10,000,000. We also excluded responses where the costs were given as development costs, not unit procurement costs. The **result (**using the assumption of a Beta distribution) provides an **expected (mean) unit cost** of **$763,125** (with a **Standard Deviation** of **$282,708**). This is less than the expected value of the humanoid unit cost. Again, given that an autonomous robotic HMMWV (with relatively limited performance) now costs about $500,000, the hexapod or quadruped robot cost (in today's dollars) seems within the ballpark, despite the highly diverse estimates of the respondents. And, with the standard deviation, it might less (or more) by about a quarter of a million dollars.

Question 10 comments include some views that the hexapod should cost about the same as the humanoid because, while control and sensing are simpler, there are more and heavier actuators and mechanical structures, as well as more legs than a humanoid. Today's Packbots, it is noted, cost $45,000 per unit, and may cost less than $5,000 by 2020. While most respondents assumed larger-sized robots, small, insect-sized legged robots could be quite inexpensive. Production quantities, as with humanoids, will have a major impact on unit cost.

Question 11 concerns the **key technologies** which need the most R&D in order to achieve significant improvement in the development of supervised autonomous humanoid robots (where a score of 1 indicates the need for the *most* R&D, and a score of 11 indicates a need for the *least* R&D). The results table from **Question 11** in **Appendix C**, with the mean scores for each technology, is reproduced below. It shows that **computer hardware** is judged to need the least R&D (with a mean of 8.6 and a median of 8.5. The aggregated results are illustrated in the bar chart for **Question 11** in **Appendix C**. **Propulsion and energy sources** for humanoid robots were judged as needing the most R&D.

Technology/Statistic	**Mean**	**Sta. Dev.**	**N**	**Median**	**Range**
Sensors	5.9	2.4	26	5.5	3-10
Sensor Processing	4.2	2.5	26	4.0	1-9
Computer Software	5.0	3.3	26	4.5	1-11
Software Tools	7.0	3.0	26	6.5	1-11
Control Sys Arch	4.4	2.6	26	4.0	1-9
Databases, Modeling	6.2	2.8	26	6.0	1-10
Bipedal Leg Control	3.5	2.9	26	2.5	1-11
Arms, End Effectors	5.6	2.8	26	6.0	1-10
Computer Hardware	8.6	2.6	25	8.5	1-11
Propulsion, Energy	2.6	1.9	26	2.0	1-8
Interfaces	6.4	3.1	26	6.5	1-12
Other	2.0	1.7	3	2.0	1-4

There are response-frequency bar charts for each humanoid robot key technology in **Appendix C**, showing how the respondents judged the need for R&D. The chart for **propulsion/energy** shows a strong cluster at scores 1 and 2 (needing much R&D), with a mode of 1. No one opined that this technology needed the least R&D. The chart for **bipedal leg control** also indicates a need for much R&D, with a mean of 3.5 and a strong modal value of 1, but there are scattered opinions across the spectrum, including a few asserting that it needs little R&D. **Sensor processing** needs moderate R&D, with a mean score of 4.2, a median of 4, and a mode of 4. The sensor processing bar chart shows scattered opinions, but with significant clustering at the greater R&D end of the scale. **Control system architecture** technology, with a mean score of 4.4 and a median of 4, also requires moderate R&D, according to the experts, but there is a heavy concentration (almost half the respondents) at the greater R&D end of the scale (at scores 1, 2, and 3). **Computer software** (with a mean score of 5 and a median of 4.5) is deemed to require moderate R&D, although there are judgments across the scale, and modal number of respondents judge it to need the most R&D (with a score of 1). However, almost as many experts judge it to need very little R&D (with a score of 9). This disparity may arise from different notions of the nature of the computer software (i.e., software for cognitive perception versus software for path planning). The distribution of views regarding the R&D needed for **robotic arms and end effectors** is almost uniformly distributed across the scoring scale, but with a modal value of 7. The mean for this technology is 5.6, and the median is 6, meaning it is considered to require moderate R&D. The **sensor technology** distribution of scores is bimodal, with clusters at 6 and below and 8 and above. The mean of 5.9 and median of 5.5 represents a moderate need for R&D. The scoring distribution for **databases and world modeling** is scattered across the scoring scale, but with a mode at 5. The mean of 6.2 and median of 6 indicates that it is deemed to need modest R&D. Technology for **human/robot interfaces** is scored across the scale, with a mode at 6, a mean of 6.4 and a median of 6.5, indicating the need for only modest R&D. The scores for **software tool** technology is also scattered across the scale, but with a strong mode at 10, indicating the need for very little R&D. Its mean of 7 and median of 6.5 indicates that it is judged to need very little R&D. The least R&D is needed by **computer hardware** technology, according to the respondents, with a modal value of 11, a mean of 8.6, and a median of 8.5.

Comments for **Question 11** include the statement that the artificial equivalent of leg muscles is biggest challenge, followed closely by a power source that can produce enough power from heavy fuel with good efficiency; and that sensors and perception are next in requiring R&D, followed at considerable distance by the other technologies. Another respondent claims that software is the key technology for the success of humanoid robots. Yet another respondent asserts that the key to humanoids will be control, learning and adaptation, that we need the ability to quickly reconfigure humanoids and teach them new tasks. Also, world modeling and debugging techniques will be required pervasively to make humanoid robots really work. Another sees all of the key technologies as important, and that we require multiple areas of R&D to progress simultaneously to reach our goal. Some of the technologies, it is noted, will be covered by the private sector regardless of government funding (e.g., computer processors and architectures will continue to advance at great speeds without government funding), while other technologies, such as original humanoid robotic hardware, need specifically targeted R&D, such as from DARPA, because the private sector has no motivation for funding this research. It was also suggested that the technology of systems integration is needed to develop humanoid robots successfully.

Question 12 asks for an estimate of the *year* by which supervised autonomous robots will be able to demonstrate a defined collection of useful military behaviors:

(1) **Manipulation:** load, aim, and shoot a rifle; unlock a door with a key; collect environmental samples; disable explosives; cut the pant leg of a wounded soldier and apply appropriate pressure to a wound;
(2) **Perception and cognition:** locate and map suitable foot placement;
(3) **Dynamics:** compute posture and balance;
(4) **Legs:** carry loads of practical size and weight over uneven terrain.

The results are a **mean** year of **2015**, a standard deviation of 6 years; and a **median** year of **2014**. Responses ranged from 2005 to 2030 (responses greater than 2022 on the scale were taken as 2030 to compute the mean year value). The response-frequency bar graph in **Appendix C** shows the distribution of responses in the selected year scale intervals (2004-2008; 2009-2013; 2014-2018; 2019-2022; >2022).

Question 12 comments include the usual observation that the timing of these accomplishments depends heavily on the level and timing of funding (e.g., starting a program now). Several said that the manipulation task (especially treating a wound) was the most difficult of the set, and that the other behavior could be demonstrated sooner. A respondent thought that these behaviors could be demonstrated soon, but that fielding operational systems is a longer prospect. Another thought that the robot's knowing *how* to perform these behaviors was easier to achieve than enabling it to know *when* to perform the behaviors.

Question 13 is similar to Question 12, but asks by which *year* a more difficult set of supervised autonomous humanoid robot behaviors will be demonstrated:

(1) **Manipulation:** pick up and carry a wounded soldier to safety; give injections and IVs to the wounded; apply telemedicine intervention; change a tire;

(2) **Perception and cognition:** detect, classify, and track moving objects, including humans and vehicles; interact safely with humans;
(3) **Dynamics:** run, jump, and crawl; fall safely and get up;
(4) **Legs:** operate in an outdoor urban environment with *tactical* posture and gait.

The results are a **mean** year of **2019**, a standard deviation of 7.7 years; and a **median** year of **2017**. Responses ranged from 2005 to 2030 (responses greater than 2022 on the scale were taken as 2030 to compute the mean year value). The response-frequency bar graph in **Appendix C** shows the distribution of responses in the selected year scale intervals (2004-2008; 2009-2013; 2014-2018; 2019-2022; >2022).

Question 13 comments include the concern about funding level and the need to start *now*. The manipulation task is again judged the hardest task by several respondents, and there is concern about the robot performing IV procedures (although as I once again look at my black and blue arm, caused by subcutaneous bleeding from a human nurse's inept poking with a needle for a blood sample, I look forward to robots performing this task).

Question 14 is similar to Questions 12 and 13, but asks by which *year* an even more difficult set of supervised autonomous humanoid robot behaviors will be demonstrated:

(1) **Manipulation:** rescue victims from rubble and wreckage; suture wounds;
(2) **Perception and cognition:** analyze many tactical and other situations, solve problems, and devise solutions;
(3) **Dynamics:** climb, rappel, and parachute;
(4) **Legs:** operate in an outdoor urban environment with tactical posture and gait.

The results are a **mean** year of **2023**, a standard deviation of 7.2 years; and a **median** year of **2021**. Responses ranged from 2006 to 2030 (responses greater than 2022 on the scale were taken as 2030 to compute the mean year value). The response-frequency bar graph in **Appendix C** shows the distribution of responses in the selected year scale intervals (2004-2008; 2009-2013; 2014-2018; 2019-2022; >2022).

Question 14 comments include the greater need for perception and cognition for these tasks, and the need for human supervision.

Question 15 seeks the minimum level of autonomy (characterized in the scale from full teleoperation (a score of 0) to full autonomy (a score of 10)) needed for most practical military applications of humanoid or other legged robots. The results are a **mean** of 4.4, a **median** of 5, and a **mode** of 5, indicating a level of semi-autonomy in missions that is about half teleoperation and half autonomy. The response-frequency bar chart in **Appendix C** shows the distribution of responses, clustered toward the middle of the scale. No respondent thought that full autonomy (i.e., scores of 9 and 10) was needed for most practical military missions.

Question 15 comments include the opinion that full teleoperation is not feasible as a useful mode of operation for military applications, while full autonomy is unnecessary for most military applications. Another opinion is that teleoperation can be valuable, especially with telepresence allowing the human operator full perception of the remote battlefield.

Question 16 seeks expert opinions as to what is needed to develop tactically, useful, military humanoid robots.

Responses (verbatim or edited) include:

- ☐ *The most important requirement is for moderate, but sustained and slowly growing, funding over a 20 year period. Funding should be at a rate that will enable slow and steady technological progress, and slow and steady growth in the community of people working on the problem.*

- ☐ *We need work on system integration and design – and good mechatronics like the Japanese have demonstrated.*

- ☐ *We need an aggressive humanoid robotics research program, which simply does not exist in the U.S. at this time.*

- ☐ *We need to identify plausible tactical needs, and match them with acceptable projected costs.*

- ☐ *Current humanoid robots have very little mobility; there could be legged or wheeled solutions. Object recognition and arbitrary object manipulation are major challenges.*

- ☐ *Industry must start producing humanoid systems that research institutions can use to address the key research issues of control, learning, human/robot interaction. If we don't achieve this, then there is a great danger that other countries will investigate humanoids successfully before the U.S. (e.g., Japan is already far ahead).*

- ☐ *We should develop humanoid robots in a spiral development process, developing telepresence applications first to get past social issues.*

- ☐ *A humanoid robot will be useful as soon as teleoperation works well. This means that the lowest level functions of walking and obstacle avoidance must be handled by the robot. If it works robustly and is relatively simple to operate it will be highly effective. Additional autonomy will allow for a higher ratio of robots to operators and thus cost savings. Additionally, if the robot must enter areas where communication with a teleoperator is difficult, additional autonomy will be necessary.*

- ☐ *If it accomplishes a job better than the man, and takes man out of harm's way, it will be successful. The robot is a tool, but it must become economically viable. It must also be proven in the field as something useful, with very minimal limitations.*

- ☐ *The technical risk areas for a humanoid type robot are in the areas of: (1) mobility (balance), (2) dexterity and manipulation, and (3) "cognitive" processing, i.e.*

interpretation of and interaction with its environment. Research in these areas must progress if this type of project were to succeed. These are not simple tasks.

- ☐ *Most importantly, investment in humanoid robot technologies is needed. While arms and hands have been significantly advanced in this country, lower body work, particularly bipedal, needs further development. The integration between functional lower body systems and complex, versatile upper bodies with human size and human strength is likely to be quite complex. Finally, making autonomous robots with these characteristics is likely to be more difficult than we would like. It seems quite likely to me that initial implementations will focus on the robotics hardware and rely upon teleoperation and semi-autonomous behavior until the hardware issues have all been resolved.*

- ☐ *A suitably funded, coherent, 20-year project is needed. The project should be coordinated with other robotic development projects, including FCS, and funded at an average of about $25 million per year for 20 years.*

- ☐ *We need a pointed program to integrate sub-disciplines (hardware, programming, and interface) that succeeds in coordinating geographically distributed scientists and engineers, and will make a sufficiently long-term commitment to encourage technology developers to address this problem.*

- ☐ *We need a comprehensive program that addresses the technology gaps and deals with the integration of these technologies into a robust working system.*

- ☐ *There are some key lacking abilities and technologies: (1) the ability to move arms in real time to reach for and manipulate objects and people, as well as respond to urgent situations; standard trajectory planning methods from classical robotics do not scale to complex humanoids, and alternatives are only being explored; (2) bipedal balance and locomotion; (3) construction and control of human-like bodies, involving springy, compliant properties instead of rigid (and thus less robust) constructions; (4) the ability to provide on-board energy that is not so heavy as to require major changes in the humanoid design and can enable it to function for some useful time-period; (5) the ability to interact with humans in a natural fashion; (6) the ability to learn from humans from task demonstration and imitation and to adapt to complex environments and tasks.*

- ☐ *We need coordinated funding efforts, with a focus on achieving realistic short-term milestones in a series that work toward the ultimate goals.*

- ☐ *One of the major functions to be developed is that of mobility over natural terrain. This heavily depends on control and sensing. Propulsion and energy systems also continue to be a major problem in remote operations.*

- ☐ *Funding is needed for direct research and, I believe, some continuity with research aimed at more private sector enterprises and health enterprises. There is an overlap between humanoid robots, exoskeletons, rehabilitative robots, and prosthetic and orthotic devices. By tapping into the research and corporate funds for other non-military* *applications, the military state of the art can be achieved faster and for less money. For example, funding to develop orthoses for paralyzed patients (high-profile because of Christopher Reeve) will lead to technologies that will enable bipedal robots.*

☐ *We need more research and development on: (1) Gait algorithms. There is a lot of progress to be made here and a lot of low hanging fruit. A lot can be done with little sensing and no cognition. A lot of human walking is spinal or lower-brained. These capabilities still need to be successfully demonstrated on a robot. (2) Dexterous anthropomorphic arms and hands. The NASA Robonaut is a good example along these lines. To make a case for having a humanoid, it's important to have the manipulation capabilities of a human. (3) Human-machine interfaces. I believe teleoperation is crucial and therefore, better morphing of man and machine is necessary. (4) High power density actuators and power supplies. I believe there should be a separate program for these technologies, rather than masking funding for them through a robotics program. Some of the best universities and companies for developing these technologies might not be part of a program that they think is for robotics and not purely for power and actuator sources.*

☐ *Major advances in cognitive systems and power are needed, as well as significant advances in most other humanoid systems.*

☐ *A multidisciplinary research program is needed to build appropriate hardware, develop appropriate actuators and appropriate sensing and control tools. Collaboration with biologists and behavioral psychologists would be useful. A team of experts (about 20-30 total) at universities and professional lab/companies should be assembled to direct a well-coordinated research program with clear milestones. A common hardware platform should be developed that can be given to other labs such that they can conduct additional research. Realistic performance metrics need to be suggested and integrated into a research plan. Initial research can focus on control and sensing issues in tethered hardware and off-board computing. At a later stage, on-board power and computing will have to be developed, possibly by dedicated VLSI design. Adaptive control and autonomous learning might be among the most important issues to accomplish flexible and robust sensory-motor control in complex and dynamically changing environments. Incorporation of principles from primate neuroscience could help to speed up development cycles, and also have a positive spin-off towards clinical applications.*

☐ *I would start out by selecting a very small repetitive task which requires a robot to be in a human form to perform effectively. That means it would either involve the operation of a vehicle or work in a facility in which mobility or operation of equipment requires human type mobility and manipulation, as well as space considerations. For example having a humanoid robot enter and drive an obstacle breaching vehicle, in which there is a high degree of risk. Perhaps the driving is relatively simple, involving moving forward in a fairly straight path. I would then expand it so the robot could operate or drive more complex vehicles, perhaps a truck or a tank. I would look at replicating jobs which robots have already shown an ability to perform, such as security or washing toxic agents off vehicles. But I would look at doing these jobs in environments in which a* *humanoid is better capable than a wheeled or tracked robot, such as performing security in a building with lots of stairs, or in external environment requiring lots of climbing.*

- ☐ *On board naval, airborne, and space platforms (where mobility is constrained and power available), we should begin development of humanoid robots within the next few years. For walking systems (ala Honda P3), portable, compact power will be the pacing item for the foreseeable future.*

- ☐ *More study of embodied intelligence is needed. Mechanisms of this complexity cannot be programmed by hand. They must learn to interact with the environment.*

- ☐ *I believe the need for humanoid robotics comes mainly in the ability for robots to use tools designed for humans. Otherwise it is not clear that the human shape is best for most situations. If we instead focus on building robots to use human tools/machinery, then a human shaped robot is perhaps useful, but even then not necessarily optimal. In many cases robots may be made specifically for specific machinery which would drastically increase their usefulness and timeliness. In this case, the natural progression will be to develop military tools and machinery (not the robot part) that is suited for use by both humans and robots (easy to use by both) as there may be both cases when one is be better than the other. This approach would lead to significantly different estimates of the previous 14 questions in terms of time estimates, costs, and usefulness.*

- ☐ *We need a concrete vision and must identify military needs such that the humanoid approach is the best alternative.*

Question 17 asks for additional comments. These include (verbatim or edited):

- ☐ *The U.S. is far behind in this area compared to the Japanese; a lot of catching up needs to be done. But no one can predict scientific progress accurately, as it often depends on breakthroughs.*

- ☐ *There are numerous parallel benefits to the development of military humanoid robots, especially with respect to medical and patient care applications.*

- ☐ *This is very interesting and exciting work. Please keep me posted.*

- ☐ *I tend to be pessimistic on my technology extrapolation projections. Most engineers seem to be optimistic for some reason. Or perhaps those are the ones that make it into books, magazines, and TV. I have faith in our capabilities to build things that do not require cognitive abilities. That's why I am gung-ho about teleoperated robots. Put as much as possible in the robot, but use the tremendous cognitive and dexterous capabilities of a real human. Humanoid robots are a hard sell since they are so difficult. I believe that there should be lots of funding in this area. It's just hard to justify it through a short timeline (20-year) military payoff. The potential long term payoff (100+ years) is tremendous. And like exploring outer space, making humanoid robots is one of man's* *grand challenges and should be heavily funded. One of the best application selling points for humanoid robots is that there is as little need for interpretation between the human operator and the robot. In fact there is the possibility that the human operator, through telepresence, could feel as though he/she IS the robot. Therefore I believe humanoid robots and telepresence go hand in hand. If there is no operator, then other types of robots are better suited for just about any situation. One of the best science selling points for humanoid robots is to better understand ourselves. I'd be happy and willing to do a follow-on interview or provide any other help or information.*

- ☐ *The Japanese are investing in this area, even with the dismal state of their economy. It would be a shame if DARPA failed in its assigned mission to "prevent technological surprise."*

5.0 USER SURVEY RESULTS

This section provides the results and analyses of our **survey of prospective robot users**, in the U.S. military, concerning the potential usefulness of humanoid and other legged robots for military applications.

5.1 User Survey Results Summary

Appendix D lists the prospective users of military humanoid and legged robots who participated in our survey. The user survey form is given in **Appendix E**. The aggregated survey results are integrated in the survey form in **Appendix F**. There were 70 survey recipients and 16 respondents, for a return rate of 23%, which was lower than the number of respondents (27) and return rate (41%) for the survey of experts. We hypothesize that the experts are more motivated to participate in a relatively time-consuming survey because they are familiar with the subject matter and are aware that they are stakeholders in subsequent robot programs. Also, it has become more difficult to identify, locate, and contact relevant U.S. military personnel, in general, because of counter-terrorism measures, such as removing organizational charts and personnel contact information from websites. We did, however, contact key headquarters, such as the Army's various Training and Doctrine Command (TRADOC) centers, and request that the survey be distributed to suitable recipients. And our robotics panel provided lists of suggested users, which generated some completed surveys. There was however, a marginal response from the prospective users and limited representation of the services among the respondents (while survey recipients were allocated about equally among the services, most of the responses was from the Army). Nevertheless, the results are instructive.

There were 12 surveys completed by Army personnel, 1 from the Navy, 2 from the Air Force, and 1 from the Special Operations Command (SOCOM). As was the case for the experts, the user survey provided interesting insights in the form of comments, opinions, and statistical analyses of the quantitative scoring. The prospective users are asked about their knowledge of robotics in **Question 1** of the survey form (please see **Appendix F**). Most of the respondents have prior knowledge of robotics and unmanned vehicles (which may have motivated them to complete the survey, as compared prospective users who currently know nothing about the subject of the survey). As was the case for the experts, we retained all of the completed survey forms, which have the respondent's identity for each form. But for confidentiality, we offer their responses without attribution.

Question 2 in the survey asks the user how he or she might be a potential user of humanoid military robots. In the comments presented fully in **Appendix F**, some said they would likely be limited users (e.g., in maintenance functions), but others said they would use them for such missions as:

- ☐ Countermine
- ☐ Explosive ordnance disposal (EOD)
- ☐ Obstacle breaching
- ☐ Military operations in urban terrain (MOUT)
- ☐ Bridging and construction

☐ Search and rescue
☐ Chemical, biological, radiological, and nuclear (CBRN) reconnaissance missions, especially in confined spaces
☐ Re-fueling and re-arming tasks at an aircraft forward area refueling and reaming site
☐ Aircraft nuclear, biological, and chemical (NBC) decontamination
☐ Reconnaissance, surveillance, and target acquisition (RSTA), especially in a MOUT environment
☐ Support of dismounted infantry

Question 3 asks about the potential military worth of humanoid robots. The resulting **mean score** is 6.9 (out of a maximum of 10), indicating that the users predict that humanoid robots will be quite useful. The standard deviation of 2.3 reflects a range of views, as shown in the **frequency bar graph** (accompanying **Question 3** in **Appendix F**). The scoring responses **range** from 1.9 to 10, with a **median** of about 7. The frequency graph shows two outliers at the low end of the scale of usefulness, but most of the responses foresee humanoid robots as being moderately useful to very useful.

Comments for **Question 3** include the ability of such robots to save lives, perform the dull, dirty, and dangerous tasks of the soldier, and provide the highest level of usefulness for dismounted operations. A family of various types of robotic platforms would be most useful, and each type of robot should be suited for its mission and environment (e.g., negotiating difficult terrain versus speed). Special-purpose robots may be more useful than general-purpose robots. Applications should be selected using common sense, with easier missions attempted first to achieve success and gain acceptance by the users.

Question 4 asks the users to predict the extent to which humanoid robots will be fielded by the U.S. military in the 21st century, assuming they become technically and economically feasible. The **mean score** of 5.8 out of 10 shows that the users expect humanoid robots to be used in several applications, but will not be ubiquitous in the military. The **median** was about identical to the mean, 5.8, and the **standard deviation** of 2.1 reflects the **range** of scores (1.9 to 9.9). The **frequency bar graph** (in **Appendix F**, as are all of the graphs for this section) shows a few respondents foreseeing limited use (but none predicting no use), but most foreseeing significant to nearly ubiquitous use. By comparison, the survey of experts had a somewhat lower mean score of 4.9 (albeit, for the specified year of 2020 instead of for any time during the 21sts century). But both **experts and users** predict humanoid robots will be used for a number of military applications.

Comments for **Question 4** include the need for sensitivity in replacing human functions with a machine, the need for properly training users, instilling in them an understanding of the systems and how to use them, and eliciting the trust of users in the systems. The best initial applications are those involving high risk to soldiers, but weapons-firing robots will require more time to develop trust and gain acceptance. Fundamentally, the humanoid robots (as any new military system) must prove its worth to troops and commanders.

Question 5 seeks the most promising humanoid robot applications, missions, or combat functions for humanoid robots. For each (randomly listed) alternative mission, respondents were asked to score the alternative from 1 (most promising) to 15 (least promising). The table (in **Appendix F**) shows, for each alternative mission, the number of respondents (N), the mean response score, the standard deviation, and the range of response scores. The accompanying response-frequency bar graphs show the distribution of responses for each mission type, with the **final chart** for **Question 5** showing the **mean score for each mission type**. The most promising mission is deemed to be countermine operations. The distribution of the means of the responses, shown in the **Question 5 bar chart** in **Appendix F**, is listed in **Table 5-1** below in the user's descending order of promising mission. For comparison, the results of the expert survey are also shown in the table (although Medical and Food service applications were added for the user survey).

Table 5-1: Promising Humanoid Missions: Comparison of User and Expert Scores

APPLICATION	USER MEAN SCORE	EXPERT MEAN SCORE
Countermine Operations	4.0	6.8
RSTA	4.6	3.1
Target Designation	4.9	3.9
MOUT	5.0	3.3
Satellite/Space Operations	6.5	4.5
Logistics/Material Handling	6.9	5.8
Infantry	7.6	6.1
Operating Direct Fire Weapons	8.2	8.4
Operating Indirect Fire Weapons	8.5	8.1
Medical	8.7	N/A
Operating Air Defense Systems	8.7	8.9
Driving or Piloting Vehicles	8.8	7.7
Food Service	8.9	N/A
Counter-Terrorism/Special Forces	9.1	5.8

Table 5-1 shows that, in general, the users are more pessimistic about the promising missions for humanoid robots – their scores tend toward the higher (least promising) end of the scale. Perhaps reflecting their EOD orientation, the users see countermine operations as the most promising application, while the robot experts placed it in the middle of the pack. But many other applications were scored similarly by both groups. For example, both the users and the experts placed RSTA as a highly promising application, scoring it in second and first place, respectively. Both groups favored target designation (scored third by both groups) and MOUT (scored fourth by users and second by experts). Users scored logistics/material handling applications sixth, while experts scored it fifth. The infantry application was in the middle of the pack, seventh place, for both groups. One significantly differing view was of the counter-terrorism and Special Forces mission. The users scored it at the bottom, while the experts had it in the middle of the applications. Air defense scored the same for both groups, toward the less promising end of the scale.

The **frequency-response charts** for **Question 5** are given in the same (random) order of their listing in the question. The **first** response-frequency **chart** for **Question 5** (in **Appendix F**) shows the distribution of responses for the postulated **RSTA** mission. The mean score for RSTA is a high-end score of 4.6, but the mode hits the highest score possible of 1.0. There are, however, some respondents who scored RSTA toward the lower end of the scale, including one outlier at the extreme end. The **driving/piloting** mission scored a mean of 8.6 (moderately promising) and a mode of 10. As the corresponding response-frequency chart shows, the scoring was all over the scale, showing diverse views of whether this mission was or was not very promising. Likewise for the scattered chart for the **infantry** mission which has a mean of 7.6 and a mode of 6.0. The mean does indicate that it is considered reasonably promising. The **direct fire** mission, as shown in the chart, is scattered across the scoring scale, but with a strong cluster between 6 and 11. Its mean is 8.2 and there is no clear mode, indicating that it is considered modestly promising as a potential humanoid mission. The **indirect fire** mission is also modestly promising, with scattered scores across the chart and a mean of 8.5 and a weak mode of 8.0. The **MOUT** mission, on the other hand, is deemed highly promising, with a mean of 5.0. The **countermine mission**, as the chart shows, is highly favored, and the mean of 4.0 and mode of 1.0 shows that it is considered a highly promising mission (although there is an outlier at the least promising end of the scale). The **target designation** chart is clustered on the promising side, with a mode of 1.0 and a mean of 4.9. While views on the **logistics and material handling mission** are scattered in the chart, with a cluster in the 9-12 range, the mode is 10.0 and the mean is 6.9, indicating that it considered a moderately promising mission. The **air defense** mission is also scattered, but shifted toward the less promising side in the chart. The mean of 8.7 indicates that it is considered moderately promising. The **Special Forces and counterterrorism** mission, while scattered in the chart, has a mean of 9.1, showing that it is considered moderately unpromising. There are clusters are at either end of the scale, but with most weighing in on the unpromising side. The **satellite operations and space exploration** mission is one that NASA is considering for humanoid robots (and funding relevant development projects), but there are potential military missions of this sort as well. With a mean of 6.5 and a mode of 1.0, the respondents consider this mission to be reasonably promising. The chart does show a small group of naysayers at the least-promising side. The **medical applications**, deemed modestly promising, are clustered in the middle of the chart, with a mean of 8.7 and a mode of 10.0. The food service applications are scattered almost uniformly across the scoring spectrum, from most to least promising. The mean of 8.9 judges it to be moderately promising (or the flip side of the coin, moderately unpromising). The “other” applications cited by the users have a mode of 1.0 and a mean of 6.6, indicating that they favor their own suggestions (although it would seem that they might have scored their own suggestion higher – two even scored their own suggested applications as least promising).

In **summary**, the user survey clearly preferred humanoid robot missions for countermine and EOD, RSTA, target designation, MOUT, and satellite/space missions. Logistics/materiel handling, infantry, and medical missions are also deemed worthy of consideration by the potential users.

Comments for **Question 5** observe that robots should be designed to best fulfill the mission for which they are intended. While soldiers currently perform the RSTA mission, the human body is not optimized for that mission. Something which could move faster, closer to the ground, and perhaps telescope higher, would be better suited to the RSTA mission. Robots should not be constrained by our limitations. Other suggested applications include: military police, search and rescue, force protection (e.g., securing an area that is reasonably well-defined but requires some level of persistence that may cause humans to lose effectiveness), infantry ambush, EOD/UXO.

Question 6 contemplates the potential of other types of **legged robots**, in addition to humanoid robots, to determine, from the potential users, which type of supervised autonomous legged robot might be the most useful, in general, to the U.S. military, ranked from 1 (most important) to 5 (least important). The choices are:

- ☐ **Bipedal Humanoid**: a robot that generally resembles a human, with a head on top, a torso, arms and hands (end effectors), and two legs and feet. It need not be an android, resembling a human too a remarkable degree; and it may be somewhat larger or smaller than the average person. Functionally, it should be able to physically replace a person in performing tasks with human-operated tools or equipment, or moving about in facilities designed for people.

- ☐ **Bipedal Non-Humanoid**: a two-legged robot that may have any upper-body shape and does not, in general, resemble a human (e.g., an octopus-like form walking on two legs).

- ☐ **Quadruped:** a four-legged robot that may have any upper-body shape (e.g., a truck on four legs; or a robotic horse)

- ☐ **Hexapod:** A six-legged robot that may have any upper-body shape (e.g., a robotic ant; or a truck on six legs)

- ☐ **Hybrids:** A robot combining elements of the other types (e.g., a centaur robot (a quadruped with a human-like upper body); a human-like robot with octopus-like tentacles; a large snake-like robot with a human-like head (for telepresence))

The statistical **results table** for **Question 6**, in **Appendix F**, is reproduced below.

Statistic	**Bipedal Humanoid**	**Bipedal Non-Humanoid**	**Quadruped**	**Hexapod**	**Hybrids**
N	15	15	15	15	15
Mean	3.2	3.3	2.3	3.5	2.9
Sta. Dev.	1.7	1.1	1.2	1.2	1.8
Median	3.5	3.5	2.0	3.5	3.0
Range	1-5	2-5	1-5	2-5	1-5

The table shows that **Quadrupeds** are deemed the **most important** by the users for potential military usefulness, with a mean score of 2.3 (and a median of 2.0). The **Hybrid** is rated second in importance (with a mean of 2.9), followed closely by the others, with mean scores of 3.2, 3.3, and 3.5. In **Appendix F**, the results bar chart for **Question 6** illustrates the mean scores for the alternative legged designs. **Response-frequency bar charts** then show the results for each of the legged designs. The **Quadruped** chart shows almost a negative exponential distribution, with majority of the respondents assigning it a (modal) score of 1.0. The **Hybrid** chart is more scattered, with a mode of 1.0 although several respondents deem it the least important alternative. The **Bipedal Humanoid** chart, with diverse opinions as to its likely importance, is scattered across the scale (although with a mode of 5.0). The **Bipedal Non-humanoid** chart shows a shift to the lesser importance side of the axis. The **Hexapod** is also shifted toward the less promising side of the scale, although the mode is 2.0.

Table 5-2 compares the mean results for the user survey with the expert survey.

Table 5-2: User and Expert Mean Scores for Legged Robots

TYPE OF LEGGED ROBOT	EXPERT MEAN SCORE	USER MEAN SCORE
Bipedal Humanoid	2.4	3.2
Bipedal Non-Humanoid	3.7	3.3
Quadruped	2.6	2.3
Hexapod	3.5	3.5
Hybrids	1.7	2.9

As shown in **Table 5-2**, the experts clearly favored hybrids, while the users favored quadrupeds (although both scored quadrupeds similarly). The close scores by the users for the humanoid, non-humanoid, and hexapod configurations may be a result of less familiarity than the experts with legged robot technology.

Comments for **Question 6** include the judgment that robots should be designed to best fulfill the mission for which they are intended, and that a quadruped seems to be the easiest version to field. A variant that could operate in either mode (quadruped or biped) would seem optimal for MOUT and complex terrain situations. One thought that the definition of “hybrid” is too wide open to adequately compare it with the other four configurations. Another opined that without seeing examples and understanding exact capabilities of each design it is nearly impossible to evaluate one design over another. But the respondents could see applications for all the platforms, although “ranking them is very difficult.”

Question 7 seeks to determine the estimated cost (in today’s dollars) of a militarily useful, supervised autonomous humanoid robot. Once again, to employ the Beta distribution procedure for calculating an expected value, optimistic, pessimistic, and most likely costs are requested from the users. The statistical results table is reproduced below from **Question 7** results in **Appendix F**.

Table 5-3: User Estimates of Humanoid Robot Cost

TYPE COST	N	MEAN ($)	STA.DEV.	RANGE ($)
Optimistic	13	115,000	78,500	5,000-250,000
Pessimistic	12	895,800	569,100	200,000-2,000,000
Most Likely	12	351,870	226,860	45,000-750,000

The table shows a very large **range** of predicted costs, for all three cost types, as estimated by the experts. We discarded two outliers for each case – the highest and lowest predicted value. The **result (**using the assumption of a Beta distribution) provides an **expected (mean) unit cost** of **$403,100** (with a **Standard Deviation** of **$130,100**). This compares with the higher expected unit cost, as previously calculated from the *experts*, of $1,003,866 (with a standard deviation of $366,133). In this case, the users are more optimistic (realistic?) than the experts.

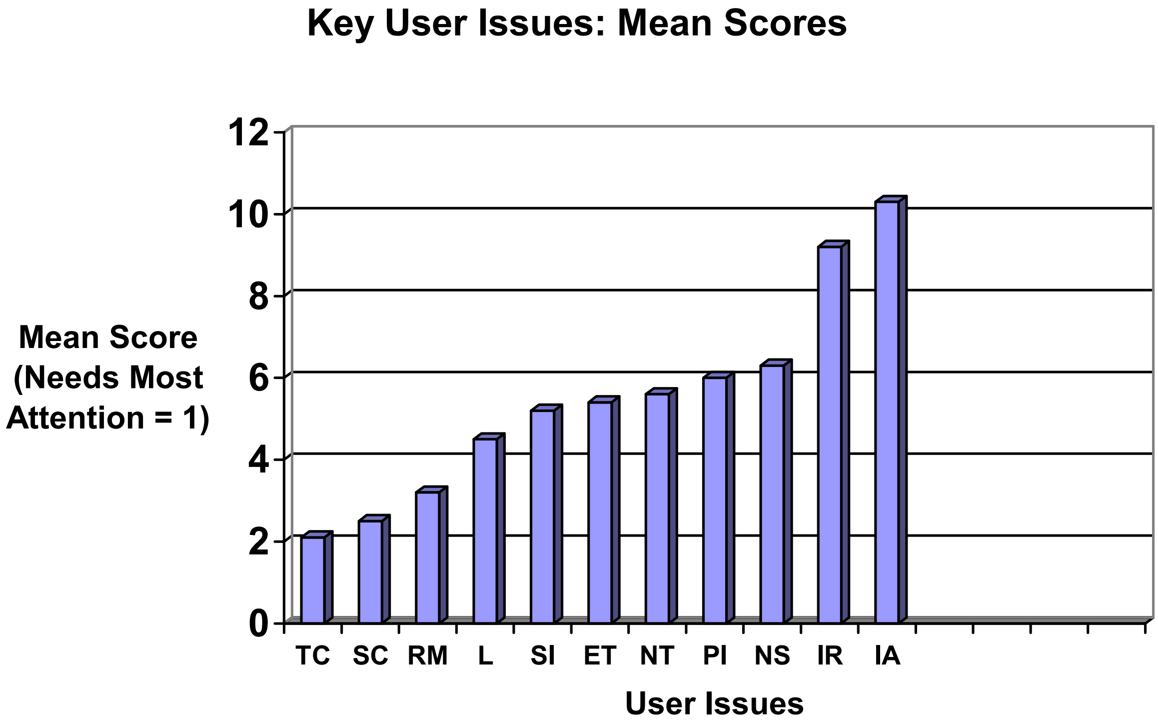
Question 7 comments include the view that unit cost is not a good metric – the total ownership cost/capability is more important (although a more difficult question to answer in a survey). The cost depends very much on capabilities and quantities, and at least one respondent's estimates assume high-production run quantities on the order of 50,000 to 75,000 robots. And as technology advances, costs will drop. While low cost is desirable, if the robot is used in an Immediate Danger to Life and Health (IDLH) environment, then perhaps a high unit cost will be acceptable. Also, one should not forget the cost of payloads.

Question 8 asks about the key user issues which require the most attention in order for humanoid robots to be introduced into the military to perform useful missions. **Table 5-4**, reproduced from **Question 8** in **Appendix F**, shows scoring of the user's key issues (in the random order presented in the survey question).

Table 5-4: Key User Issues Scores

KEY USER ISSUE	N	MEAN	STA.DEV.	RANGE
Technology Concerns	16	2.1	1.5	1-6
Safety Concerns	16	2.5	2.5	1-10
Political/PR Issues	16	6.0	3.2	1-11
Educating/Training	16	5.4	3.4	1-11
Reliability/Maintenance	16	3.2	2.2	1-7
Logistics	16	4.5	2.9	1-9
Systems Integration	16	5.2	2.9	1-11
New Tactics	16	5.6	2.4	1-10
New Strategy & Doctrine	16	6.3	2.7	1-12
Intra/Inter Service Rivalry	16	9.2	2.5	2-15
Issues with U.S. Allies	16	10.3	1.3	9-15
Other	3	6.7	5.5	1-12

The user's mean scores, in descending order of perceived importance, as reproduced from **Question 8** in **Appendix F**, follows:



Key to User Issues on Chart

TC = Technology Concerns
SC = Safety Concerns
RM = Reliability/Maintenance
L = Logistics
SI = Systems Integration
ET = Education/Training
NT = New Tactics
PI = Political/PR Issues
NS = New Strategy/Doctrine
IR = Intra/Inter Service Rivalry
IA = Issues with U.S. Allies

Technology is the key issue, followed closely by **Safety**, according to the users. The **frequency response chart** for technology concerns, in **Appendix F**, shows a strong skewing to the "most attention" side of the scale (where the mode is 1.0 and mean is 2.1). This is a reasonable, and expected, user requirement for any new weapons system, i.e., that it performs as promised, required, and expected. A close second issue is a concern for **safety.** The corresponding frequency response chart for safety shows a strong mode of 1.0 (and mean of 2.5), with the lowest score a 10 (safety would have been in the primary issue if not for that one least-attention outlier). **Reliability and maintenance** concerns are third in importance to the users, with a mean of 3.2 and a mode of 1.0. But the judgments are more scattered toward the "less attention" part of the scale. **Logistics**, with a mean of 4.5 and a mode of 4.0, is the fourth issue in needing attention. But the judgments are more scattered in the frequency-response chart. The issue of **systems integration**, with a mean of 5.2, is even more scattered across the frequency response diagram. **Education and training** concerns follow logistics in importance, with the users' judgments scattered across the frequency response chart and a mean of 5.4. Next in importance is the users' concern about **new tactics** needed to deploy humanoid robots properly, with a mean of 5.6 and a mode of 6.0. The remaining distribution of views is almost uniformly distributed along the attention scale. Similarly distributed is the issue of **political and public relations**, but skewed a bit more toward the lesser importance end of the scale and with a mean of 6.0 and a mode of 5.0. The users consider **strategic and doctrine issues** in the deployment of humanoid robots, with a mean score of 6.3, to be of lesser concern than tactical issues (with a mean score of 5.6). The frequency response chart is almost bifurcated, with a cluster between 1 and 5 and a cluster between 8 and 11. The sensitive issue of **inter and intra service rivalry** which may be manifested with the introduction of humanoid robots (as happened in the past with the introduction of robotic air vehicles) is not much of a concern for the users, having a mean score of 9.2 and all but one outlier response clustered at the "lesser attention" end of the scale. The issue of least concern to the users is that of potential difficulties with U.S. **allies** when humanoid robots are integrated with the force. The mean score is 10.3, with a strong modal value of 11.0.

Question 8 comments include the need to improved remote power cell/battery life and communications range for practical robots. Doctrine has not caught up to some systems that were fielded years ago, and it should be developed in conjunction with robotic applications. And public opinion must be taken into account.

Question 9 requests the users' view of the minimum level of autonomy (characterized with a scale from full teleoperation, with a score of 0, to full autonomy, with a score of 10) needed for most practical military applications of humanoid (or other legged) robots. The results are a **mean** of 5.2, a **standard deviation** of 1.9, a **median and mode** of 5, and a **range** of 1 to 9. **Table 5-5** compares the responses of the users and the experts to this question.

Table 5-5: Level of Autonomy Needed by Humanoid Robots

GROUP	N	MEAN	STA.DEV.	MEDIAN	MODE	RANGE
Experts	26	4.4	2.5	5	5	0-8.5
Users	16	5.3	1.8	5	5	1-9

As the table shows, the users favor somewhat more autonomy than the experts for military humanoid robots, but both groups have identical medians and modes representing semi-autonomy exactly halfway between no autonomy and full autonomy. The user mean is nearly the same as the median and mode, which is a characteristic of a normal distribution (which the response frequency chart for **Question 9** in **Appendix F** resembles – and which is quite unlike the corresponding chart, which is an irregular distribution, in the survey of experts).

Question 9 comments include the need to avoid having a dedicated operator for each robot, which must be at least semi-autonomous, but that ultimately the robot relies on the human because it is a tool. The system needs to be flexible to allow a supervisor to manage many robots, but be able to interact when necessary: it should be "as autonomous as needed and as interactive as desired." The humanoid robot may be used with full teleoperation for recon missions, but with full autonomy for ambush tactics or mine clearance. But there may be a definite fear of completely autonomous robots.

Question 10 solicited suggestions from the potential users as to what humanoid robot developers might do to earn the acceptance of humanoid and other legged robots by military users. Responses included the comment that the robots should be able to surpass the mobility of a human soldier, be affordable, be able to perform for extended periods of time greater than four hours of continuous operation, and be easily maintainable by young soldiers who have numerous other tasks and distractions in the field and on the battlefield. Safety should be the number one priority, and failsafe systems should be implemented, along with fire control. Education and training are key elements, and reliability must be near 100%. Also, the human for should be justified by the task. Make sure the robot works, and make the robot fit the mission, not the mission fit the robot. First show the utility of these systems through experimentation and limited in the field-testing. The user/robot interface (OCU) should be part of the soldier's uniform and not a separate box. Start with simple high-risk missions (such as CBRN recon and countermine). Get the price down so that the loss of a few systems will not slow down programs (if it is not disposable, it should be repairable modularly). Get them in the field and out of the laboratory and let the soldiers show you how to use them. Men in cubicles who have never been in the military have a very different view of what the military does than the grunt in the foxhole. Engage the end users early and often. Trust is going to be the critical issue for effective use of autonomy in the future. If the operators do not understand or trust the system, they will never relinquish any authority to the autonomy and will therefore never step back into the supervisory role. There must be more than one type of robot for situations and tasks, and the robots must be easy to deploy and use. The robot must be able to perform as stated. It must become a mission essential piece of equipment and not be a weight burden. It must have sufficient power and mobility, with a minimal logistics footprint and ample communications capability so as not to put the operation at risk. It should preferably be dropped into place rather than emplaced. Ensure total human control of the robots (even if they are autonomous).

Question 11 seeks additional comments from the users. These include the exhortation that humanoid robots should be introduced "the sooner the better." They are a must in order to keep soldiers out of harm's way. The Joint Service EOD community is interested in assessing humanoid/legged robots for EOD applications. The EOD users recently submitted a **needs document** that extols the benefit of humanoid robots to EOD, and they would like to explore a possible collaboration to see where the technology currently stands. Also consider disposable attack robots – the equivalent of smart toys with explosive charges, items that can be deployed by the hundreds for area denial.

6.0 METRICS FOR HUMANOID AND LEGGED ROBOTS

This section describes the **metrics and submetrics** that we selected to evaluate prospective alternative **humanoid or legged robots** suitable for military applications. The Analytic Hierarchy Process (AHP) is used as a tool to define and weight the relevant metrics and submetrics against which to evaluate and rank the prospective **alternative systems** (as they are designed and proposed). When the alternative robots are selected and their variables characterized (e.g., their physical and operational characteristics), they can be evaluated against the weighted metrics, using the AHP, leading to a scored, rank-ordering of the alternatives.

6.1 The Analytic Hierarchy Process (AHP)

This section provides a brief **overview of the AHP process**.

The AHP process has been favorably reviewed by the operations research community (as a technique for multivariate decision-making) and has gained popularity in the defense industry for aiding in the evaluation of weapons systems. There are more than 600 papers and books describing the theory and diverse applications of the AHP.

As limited human beings with limited brain capacity, we find it difficult to make decisions about complex problems involving conflicting criteria and several alternatives. Our short-term memory can hold only a limited amount of data "chunks" - like a grocery list or a phone number. If we try to compare a number of attributes (such as size, speed, development risk, cost, reliability, etc.) among a number of choices for prospective robotic vehicles all at once in our head, we typically get entangled. Our decisions are less than the best.

Complex systems or problems can be simplified by decomposing them into smaller, comprehensible elements or tasks. Human society has done this for thousands of years with organizations (the *bureaucracy*) and complex projects (such as building the pyramids or nuclear submarines). The AHP technique enables the decision-maker to transcend mental limitations by restructuring a complex problem in the form of a hierarchy. Each *attribute*, *criterion*, or *metric* (measure of merit) is identified or defined along with sub-metrics in a systemized way and then used, step by step, to evaluate the alternative choices. This ability to structure a complex problem, and then focus attention on individual components, improves decision-making.

The AHP makes it possible to look at the elements of a problem in isolation: one element compared against another with respect to a single criterion. The decision process reduced to its simplest terms - pairwise comparisons. There is never a need to look at more than **two** things at a time - well within our limited mental capacity. The user just focuses on the basic elements of the problem and the process leads to all of his or her judgments being synthesized into a unified whole in which the alternative solutions are clearly ranked and placed in **priority order** - from best to worst.

The decision-maker's judgments form the basis of the AHP process. Judgments are made about **pairs of elements** relevant to a criterion or property that they have in common. For example, one might examine the data on two robotic vehicles and note **objectively** that the first is heavier than the second, uses more fuel per mile than the second, has more payload capacity than the second, or costs more than the second. We can also judge **subjectively** that the first is less of a development risk than the second. Judgments are derived from a multiplicity of such pairwise comparisons of alternatives against various criteria (using objective data whenever it is available). The resulting decisions are more **objective** and **rational** than they would be otherwise.

The **number of criteria** considered in a particular decision can be large. For example, robotic vehicles may be compared according to measures of size and weight, payload capacity, sensor requirements, acquisition cost, maintenance cost, range, fuel efficiency, safety, reliability, road speed, cross country speed, and so on. The measures of merit - MOM - may often be categorized as **measures of effectiveness** (*doing the right thing*) or **measures of efficiency** (*doing things right*). It is futile to pursue the wrong objective even in a highly efficient manner. But pursuing the right objective inefficiently wastes resources, and the objective ultimately may not be achieved. In any case, the AHP makes it easy to **organize and simplify** complex problems with a large number of criteria.

While it is preferable to use **objective data** (such as size and cost) in the decision-making process, **qualitative factors** such as perceptions of risk, aesthetic judgments, psychosocial behavior, and political issues, are difficult to assess solely in terms of objective or physical measurement. However, such seemingly non-measurable factors can be **included** in the evaluation process. Just as we can distinguish and measure physical quantities, such as meters for length or dollars for cost, we can do the same with our perceptions of qualities. Even objective characteristics may be treated as subjective in the **absence of data** that would otherwise quantify them. Because we can discriminate subjectively, we can develop relationships among the elements of a problem and to determine which elements have the greatest impact. The AHP can accommodate both **quantitative and subjective inputs**, and merge them into a single overall measure to determine which alternative solution is the most desirable.

Various researchers have tested the AHP. They determined that its technique of **scale measurement** works in fields where the units of measurement are already known, such as physics, economics, and other fields where standard measures already exist. In the scaling process, the user expresses the relative importance or preference of one entity over another, with respect to a given criterion, either **verbally or numerically**. Verbal comparisons can be used for comparing social, psychological, political or other subjective factors, while numerical comparisons can be used for comparing physical, economic or other objective factors.

The underlying **mathematical process** in the AHP is matrix algebra and solving for Eigenvalues.

One difficulty with the AHP is for the evaluator to be **consistent** in making pairwise comparisons. **Consistency** is mathematically a **transitive property** of preference. It requires that if entity A is preferred to entity B, and entity B is preferred to entity C, then entity A should be preferred to entity C. (If you prefer a Ford to a Chevy, and a Chevy to a Buick, you should prefer a Ford to a Buick). The AHP process calculates a measure of **inconsistency**. This measure is useful in identifying possible errors in expressing judgments as well as actual inconsistencies in the judgments themselves. However, the usual method does not preclude all inconsistencies in judgments because many decisions must be made in the context of inconsistencies that exist in the real world.

6.2 Evaluation of Metrics

We used *Expert Choice* software to evaluate suggested metrics and submetrics (against which prospective robots can be assessed). For convenience, the figures illustrating the results of applying the AHP method to the robot evaluation are grouped in **Appendix G**.

Figure G-1, in **Appendix G**, shows a tree diagram of the metrics and submetrics (we have not decomposed the submetrics further into sub-submetrics) that we suggest for the goal state ("Select a Legged Robot"). The goal state and the defined metrics are suitable for either evaluating a set of alternative *humanoid* robots (whether proposed designs or prototype systems), or a set of alternative *legged* robots of various types (e.g., humanoid, non-humanoid, bipedal, quadruped, hexapod, hybrid, or other forms).

The metric taxonomy that we have defined may be modified, with metrics and submetrics added or removed, based on needs or preferences of the customer, lead system integrator, or vendors. The **four metrics** are: **effectiveness**, **efficiency**, **life cycle cost**, and **development risk**, the first three of which are further decomposed into submetrics. The abbreviations for these metrics and submetrics are defined in each figure.

The effectiveness of the robot is decomposed into submetrics for the robot/human interface, movement ability, safety, manipulation ability, task completion ability, and level of autonomy. The efficiency of the robot includes the submetrics of size (weight and volume), energy consumption rate, failure rate, and mission endurance. Life cycle costs include the development cost, acquisition cost (unit cost), training cost, operating cost (e.g., cost per mission, cost per mile, etc.), and maintenance and repair cost. Development risk does not have submetrics here.

Figure G-2 also shows the tree diagram of metrics and submetrics, but in addition shows the calculated results of the AHP metric scoring process (the synthesis of the metrics and submetrics ("leaf nodes") with the respect to the goal state), for each metric and submetric, as is detailed in the subsequent figures. (The three significant figures of the metric weights are an artifact of the software – two significant figures would be sufficient). All of the inconsistency ratios were within the acceptable maximum of 0.10.

The results of our evaluation (weighting) of the metrics are shown in **Figure G-3**. In order for a new technology to gain acceptance among users (and the public at large) it must work. That is, it must perform its intended function reasonably well (i.e., faster, better, or cheaper than the technology it replaces) and accomplish its defined tasks. Inefficiencies can be tolerated until the technology matures a bit (as was the case with early automobiles and aircraft). Thus **effectiveness** was deemed more important and scored higher (0.424) than **efficiency** (0.227).

The **life cycle cost**, if excessive, can sink a new technology before it can be established. But the life cycle cost of a new technology is uncertain. And for many technologies, it tends to decrease as the technology evolves (e.g., the life cycle cost of televisions in 1949 was far higher, in constant dollars, than televisions in 2003). Thus the life cycle cost was judged to be less important than effectiveness and (by coincidence) scored the same as efficiency (0.227).

An excessive **development risk** can also sink a new technology development program. If the expected payoff is judged sufficiently high, then an expected low probability of success can be tolerated in allowing the program to proceed (e.g., development of fusion generators and the Strategic Defense Initiative). In the case of autonomous military robots, including legged robots, the expected payoff is judged high and the probability of success (within a reasonable time) is judged to be at least moderate; thus development risk, as a metric for the technology, is deemed to have the least importance of the metrics (with a score of 0.122). (Specific alternative robot designs, of course, can be judged to have a high development risk, and so they will do poorly when evaluated against the development risk metric).

The **submetrics** for the **effectiveness metric** are evaluated in **Figure G-4**. The submetric **movement** is deemed to be the most important of the submetrics (with a score of 0.259). If the humanoid (or other legged) robot can do little else but move well over a variety of surfaces, it will be able to accomplish much (e.g., as a reconnaissance platform). Without the ability to move well, the legged robot is useless for military applications.

While the safety of military technology is important, especially new technology where users need to establish confidence in its performance, safety is not necessarily the premier submetric for system effectiveness; functional performance can be more important. Some safety risk is inherent in most military systems and activities, and performance cannot be sacrificed for safety. So the **safety submetric** is judged somewhat less in importance to the robot's ability to move appropriately on suitable surfaces (with a score of 0.232).

The ability of the robot to complete defined tasks successfully is a submetric that may be reasonably judged to be the most important – if the set of all tasks were known and specified completely. Some tasks (or missions) can be specified and tests can be designed for them in simulations and field exercises. However, given that tests are likely to include only a subset of the tasks that might be performed by the robots, the submetric of **task completion** is judged third in importance (0.192), after safety.

For humanoid (and certain hybrid) robots the ability to manipulate objects in the environment, whether with the equivalent of arms, hands, and fingers – or tentacles – is intrinsic to their functionality and a key capability. The **manipulation submetric** (the ability to manipulate objects for designated tasks) is scored fourth in importance (0.144).

The level of autonomy needed by a tactically useful humanoid or legged robot varies according to the state of the technology and the mission. For some missions telepresence, where the operator is sensory-immersed in the robot and perceives himself to be in the remote environment, may be the desired operational mode. For other missions, teleoperation may be tolerable, if not ideal. Supervised autonomy, with various levels of operator involvement, can accommodate many missions – perhaps most missions. Complete autonomy (assuming the robot can perform its tasks successfully without human intervention) is desirable in that it reduces the demand for operators and bandwidth – and the associated cost. The **autonomy submetric** (with a score of 0.105) favors robots which are capable of greater autonomy (although teleoperated supervision may be invoked when necessary).

The robot/human interface can be critical for some configurations (e.g., telepresence or highly teleoperated), but it is much less critical for autonomous robots. All in all, the **human/robot interface submetric** is judged to be the least important (with a score of 0.069) of the effectiveness submetrics. (If the set of legged robots being evaluated were all designed primarily for telepresence, then the metrics would have to be re-weighted to reflect the increased importance of the interface).

The submetrics for the efficiency metric are weighted in **Figure G-5**. The **expected failure rate** is defined here to be a submetric of efficiency because failure reduces the efficiency of a system in its attempt to function or successfully complete a task or mission. Especially for a new technology, such as humanoid or legged military robots, it is judged to be the most important submetric (0.356).

The **endurance** of the system, which constrains the length of time that can be allotted to the task or mission, is deemed the second most important efficiency submetric (0.326). Some current humanoid robots, employing battery power, can function for only 12 minutes before recharging. This is excessively limiting for useful military, as well as civil, applications. Having to recharge – or refuel – excessively during a task can significantly reduce the system's efficiency.

The **energy (or fuel) consumption rate** affects endurance in conjunction with the energy storage capacity of the system. A large storage capacity can compensate for a high consumption rate; but it is not expected that the systems will have a large storage capacity. As with automobiles, greater fuel efficiency is desired as long as other requirements are met. The energy efficiency of the system is scored third in importance at 0.194.

The optimum **size** (weight and volume) of the humanoid or legged robot depends on its specified functions and missions. Sometimes smaller is better; other times larger is better. The evaluation of alternative humanoid or legged robots against this submetric (with a weight of 0.124) will depend on the size-dependent system requirements.

The **life cycle cost metric** is decomposed into the submetrics shown in **Figure G-6**. The **development cost** (with a weight of 0.356) is judged the most important submetric. Unless there is an a priori demand for a new technology from the highest levels of government, the expected development cost is a sensitive determinant of whether a program will be undertaken in the first place. There is no such current clamor for humanoid or legged robots from either the President or the Secretary of Defense (albeit, until recently the military hierarchy was not hollering for UAVs either). Nevertheless, the development cost must be kept under control if a humanoid program is to get off the ground.

The **acquisition (unit) cost** submetric is judged next in importance (0.235). A system's military worth will determine, in part, whether its cost is acceptable. A new technology will be compared with tried and true, known systems (e.g., tanks, HMMWVs, artillery, etc.) – and the number of existing systems that might have to be traded for the new technology. The acquisition cost must represent genuine value added for the military in order for it to be acceptable.

The **maintenance and repair cost** submetric (with a score of 0.192) is deemed third in importance. This cost also impacts the efficiency and effectiveness of the system – the less maintenance and repair that is needed, the greater the availability of the system for missions, the fewer backup systems are needed, and the greater the probability of successfully completing a mission.

The **operational cost submetric** (with a weight of 0.136) is likely to be more important for selecting alternative systems in an established technology than a new one. The new technology (presumably) offers significant advantages (e.g., faster, better, cheaper) over an existing technology, and operating costs can be tolerated if they are higher (within limits) than the technology being supplanted. However, as the new technology matures, competitive pressures (and evolving technology) should drive down the operating cost – but increase its importance in evaluating competitive systems.

Training costs (scored last at 0.082) can be considerable for some systems, but properly designed robotic systems, with training simulations, should minimize operator training and associated costs. Training personnel for the maintenance of complex systems may, however, be expensive. As a basis of comparison, note that training costs for pilots of high performance aircraft can exceed $10 million per pilot, and that: flying an F-16 fighter costs an estimated $5,000 an hour, compared to $500 per hour in a simulator; driving a tank costs $75 per mile, while a tank driver simulator costs $2.50 per mile; and operating an Apache helicopter cost $3,101 per hour, while a simulator costs $70 per hour. But training costs can be reduced if trained personnel (or robots) can be retained once they are trained.

7.0 FUNCTIONAL ANALYSIS

Just as there are various reasonable definitions of "intelligent," there are multiple views of the nature of "autonomy." One definition, shown in **Table 7-1**, consisting of a hierarchy of system attributes for robotic ground vehicles as defined for the FCS Program (modified here), can serve for humanoid and legged robots as well:

Table 7-1: Levels of Autonomy (as Defined by the FCS Program)

Level	Level Description	Observation, Perception, Situation Awareness	Decision Making	Capability	Characterization, Example
1	Remote control	Mobility sensors	None	Remote operator, steering command	Basic teleoperation
2	Remote control with robot state knowledge	Local pose	Basic health and robot state reporting	Remote operator steering commands using robot state knowledge	Teleoperation with operator knowledge of robot pose & situation awareness
3	Pre-planned mission	World model database; collision avoidance	Autonomous navigation system (ANS) commands steering based on planned path	Basic path following with operator help	Basic robotic following and intelligent operation
4	Knowledge of local environment	Perception sensor suite	Negotiation of simple environment	Robust leader-follower with operator help	Precision robotic following and convoying
5	Hazard avoidance or negotiation	Local perception and world model database	Path planning based on hazard estimation	Basic cross-country semi-autonomous navigation	Cross-country with significant operator intervention
6	Object detection, recognition, avoidance, or negotiation	Local perception and world model database	Planning and negotiation of complex terrain and objects	Cross-country with obstacle negotiation with some operator help	Cross-country in complex terrain with limited mobility speed
7	Fusion of local sensors and data	Local sensor fusion	Robust planning and negotiation of complex terrain, environmental conditions, hazards, and objects	Cross-country with obstacle negotiation and little operator help	Cross-country in complex terrain with full mobility speed
8	Cooperative operations	Data fusion of similar data among cooperative robots	Advanced decisions based on shared data from other similar robots	Rapid effective execution of ANS objectives with minimal operator help	Autonomous coordinated group accomplishment of ANS
9	Collaborative operations	Fusion of ANS and RSTA among operational force robots	Collaborative reasoning	Accomplish mission objectives through collaborative planning and execution with operator oversight	Autonomous mission accomplishment with differing individual goals and little supervision
10	Full autonomy	Data fusion from all participating battlefield assets	Total independence to plan and implement to meet defined objectives	Accomplish mission objectives through collaborative planning and execution with no operator oversight	Fully autonomous mission accomplishment with no supervision

In **Table 7-1**, as autonomy increases, capabilities subsume or replace capabilities from lower levels. The same behavior operating in different terrain or environmental conditions may result in different levels of autonomy. A key technological issue, discussed below, is how to achieve autonomy.

Appendix H shows a diagram illustrating the **major functions of any legged robot** (sensing, processing, effecting, and interfacing) in terms of the corresponding subsystems. A robot, as such, must be able to **interact with its environment**, sensing it and acting upon it. A robot must be able to **connect sensing** (sensors) **with acting** (effectors) – with **processing** (computer hardware and software). While a **human interface** is not *essential* to the concept of "robot," especially for autonomous robots, it is *important*, especially for military robots. The major **functional systems** are **decomposed one level down** into major subfunctions and subsystems (e.g., control system architecture; mobility; etc.). The placement of the subfunctions in the diagram is **solely for clarity** and **does not imply relative importance.** The major **functional subsystems**, as shown in Appendix H, are:

- ☐ **Computer Control Systems**
    - Control system architecture
    - Software tools
    - Sensory perception
    - Databases and world modeling
    - Internal and external communications
    - Mobility
    - Hardware architecture
- ☐ **Sensor Systems**
    - Internal and external sensors
    - Sensor processing
    - Sensor architecture
- ☐ **Effector Systems**
    - Platform and mobility design
    - Structural dynamics and kinematics
    - Manipulators and end effectors
    - Propulsion systems
- ☐ **Human Interface Systems**
    - Controls and displays
    - Testing
    - Maintenance and support
    - Training

7.1 Control System Architecture

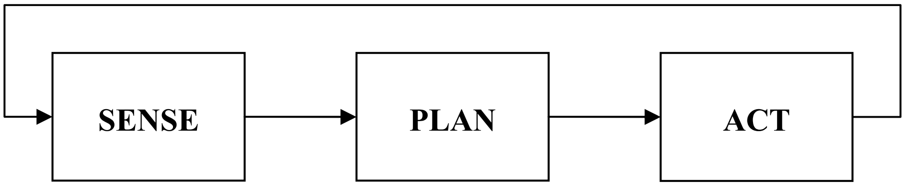
The **control system architecture** provides the **framework** for the robot's **"intelligent" control system.** There are countless definitions of intelligence. **A pragmatic definition of intelligence** is**:** the ability to make an appropriate choice or decision**.** The organism or machine's "appropriate" intelligence depends on **context,** including its **purpose** (e.g., survival and reproduction; accomplishing mission) and **SWOT** (strengths, weakness, opportunities and threats in the context of the environment). The necessary intelligence of an application for a robot may be that of an ant, a dog, or a person, depending on **mission requirements** and **feasibility** (technical, operational, and economical).

A taxonomy was devised to illustrate **six degrees of intelligence**, distinguishing the system from its intelligent control system [Mystel and Messina]. Consider, for example, an air conditioning unit and its climate control system:

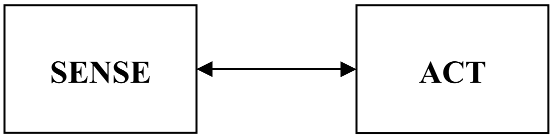
- 1st Degree of Intelligence
    - The air conditioning unit only knows a threshold for when to turn the compressor on or off.
- 2nd Degree of Intelligence
    - The system can stay within a temperature interval with a given accuracy, as well as a humidity interval with a given accuracy. The system's goal is not a single goal-state, but a zone determined by an external function (e.g., based on a human's preference).
- 3rd Degree of Intelligence
    - The system can learn the human's preferences (based perhaps on the number and type of adjustments he makes to the desired temperature and humidity) and reduce the need for human intervention.
- 4th Degree of Intelligence
    - If there are more than one human user, and they have different preferences, the system can minimize the number human interventions (as by determining a consensus preference).
- 5th Degree of Intelligence
    - If the system's owner (such as a landlord) wants, for example, to reduce the cost of energy while keeping the users happy, the system can minimize the average number of complaints while minimizing energy consumption. The control system autonomously assigns the schedule for the functioning of the air conditioner.
- 6th Degree of Intelligence
    - Instead of being merely subserviently intelligent (i.e., controlling its own behavior but having its goals determined by the user), the control system has a concept of self and, while keeping the users and landlord satisfied, it also is concerned about its own lifespan, reducing aging, increasing reliability, etc.

There are many prospective control systems architectures for autonomous and semi-autonomous robots. There are three fundamental types of robot control systems architecture: **hierarchical (deliberative); reactive; hybrid (deliberative/reactive).** (The figures below [except for NIST figures] are from *Introduction to AI Robotics*, Robin Murphy, MIT Press, 2000).

HIERARCHICAL



REACTIVE



HYBRID

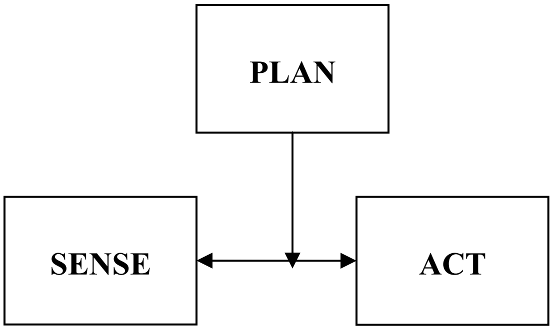


Figure 7-1: Hierarchical, Reactive, and Hybrid Control Systems

There a number of hierarchical control system architectures, including the **Nested Hierarchical Controller** (NHC) and the NIST **Hierarchical Real-time Control System** (RCS); the RCS, however, has evolved into a **hybrid** control system, now known as the 4D/RCS (for the four dimensions of space and time). The advantages of hierarchical architectures are such that with a planner and world model, the system can (potentially) emulate human intelligence. It has the ability to plan and learn. A disadvantage of hierarchical architecture is that the planner and world model can slow performance excessively, and it requires burdensome a priori programming – and the ability to foresee contingencies - for the world model. Also, none are yet fully operational (although the NIST RCS has been partially implemented in a number of robotic vehicles).

The **Nested Hierarchical Controller** (NHC) architecture is similar to the NIST RCS, but it emphasizes **planning for motion** (as opposed to planning for other functions, such as communications, group tactics, group coordination, etc.). The NHC was never implemented and tested on a real mobile robot (but it was tested in computer models). The Nested Hierarchical Controller (NHC) decomposes planning to support navigation: mission planner, navigator, and pilot. The **mission planner** receives mission from human or generates one itself; the **navigator** generates path to goal; and the **pilot** gives low level actuator commands.

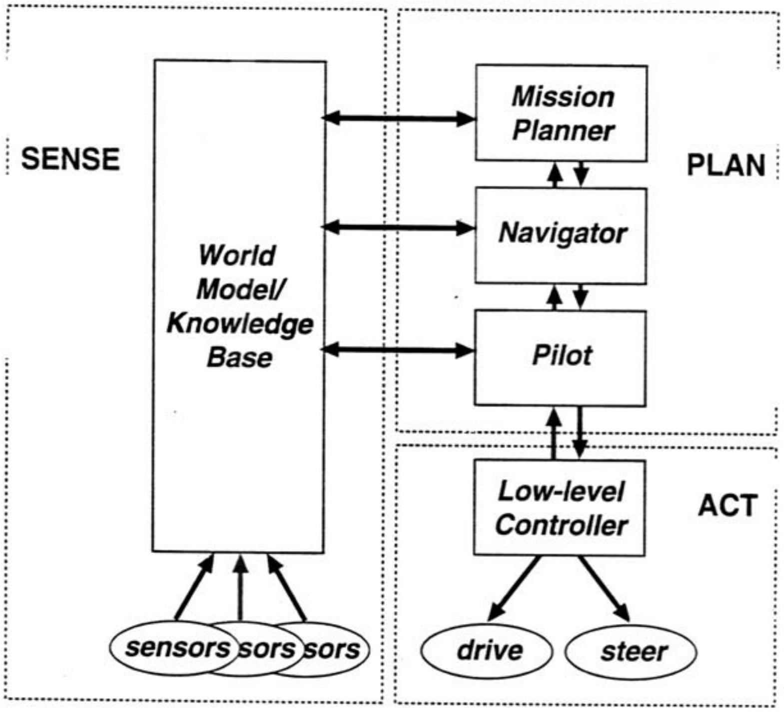


Figure 7-2: Nested Hierarchical Controller

The **NIST Hierarchical Real-time Control System (RCS)** architecture can have **many layers**, perhaps as many as 7 or 8. There are 8 layers to control **groups of robots** and **strategic planning**, as shown in the figure below. An **operator interface** can also be incorporated. The raw **sensory data** is converted into **perception.** The **world model** is updated if necessary and the **value judgment module** determines behavioral (or mission) priorities. The priorities determine the **plan and its decomposition** into subtasks and actions (down to **instructing individual servos).** Commands flow down the hierarchy, and status feedback and sensory information flows up. Large amounts of communication may occur between nodes at the same level, particularly within the same subtree of the command tree. (The abbreviations in the figure are: UAV = Unmanned Air Vehicle, UARV = Unmanned Armed Reconnissance Vehicle, UGS = Unattended Ground Sensors).

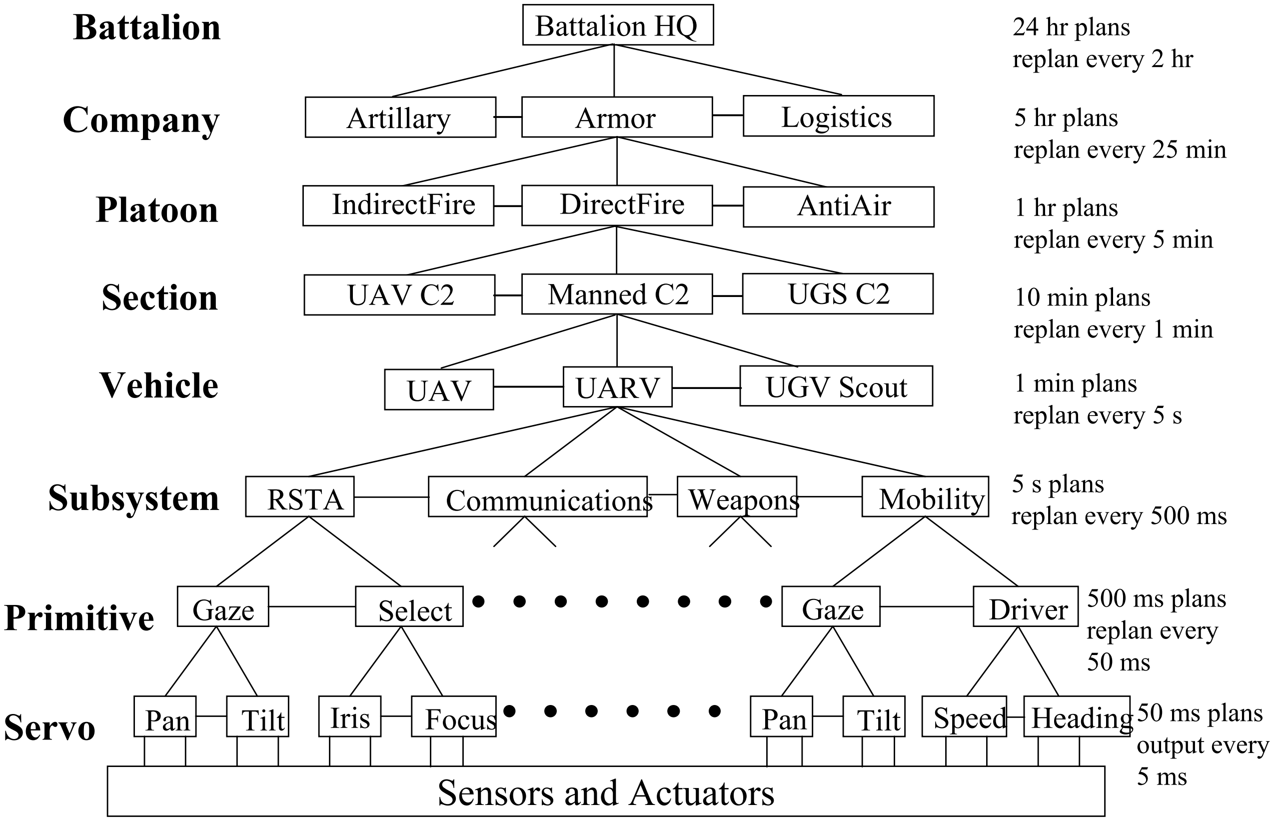


Figure 7-3: High Level Diagram of a Typical 4D/RCS Reference Model Architecture

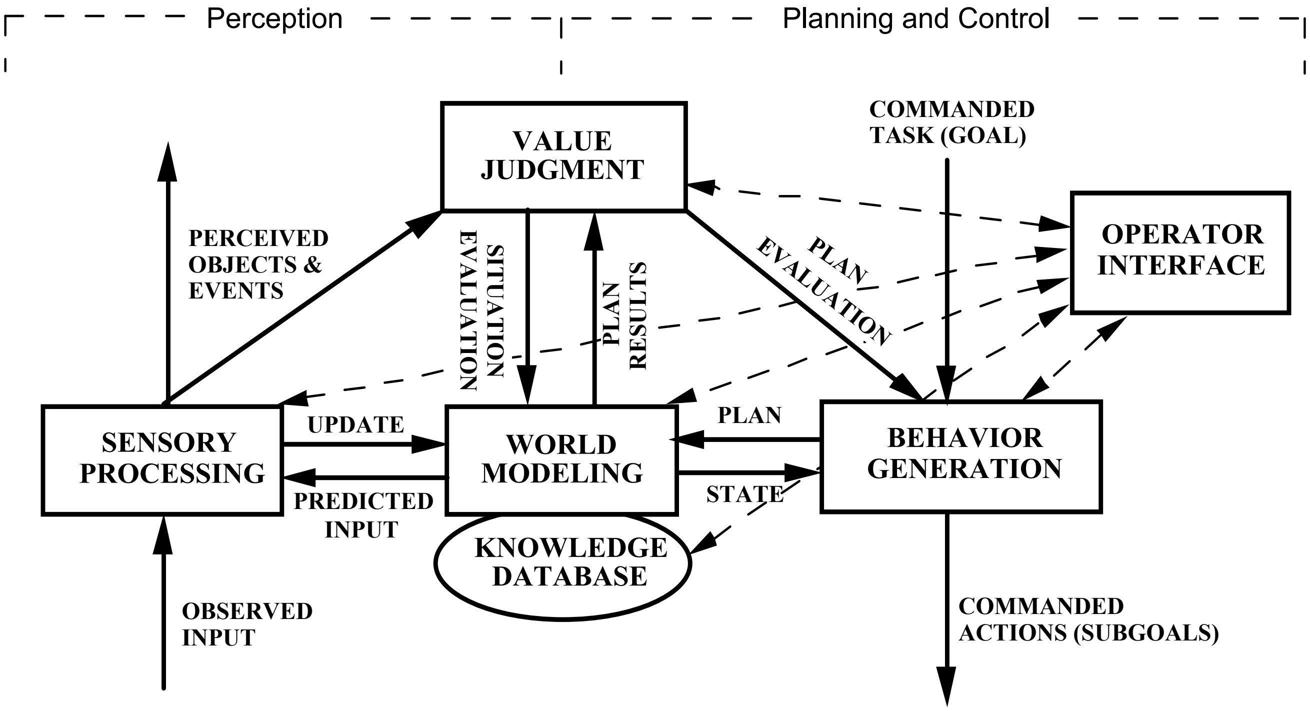


Figure 7-4: A generic node in the NIST 4D/RCS architecture

As shown in **Figure 7-4**, the 4D/RCS architecture is a generic framework in which to place, connect, and activate the intelligence of complex systems. It was developed over nearly two decades as part of a research program in industrial robotics at NIST in which tens of millions of dollars have been invested. The 4D/RCS, designed originally for industrial robots, is a mechanism by which sensors, expert systems, databases, computer models, and machine controls may be linked and operated such that the system behaves as if it were intelligent.
The 4D/RCS can perform **complex real-time tasks** in the presence of sensory or other information input. It can decompose high-level goals into low-level actions, making real-time decisions in the presence of noise and conflicting demand for resources. It provides a framework for linking artificial intelligence techniques with real-time control in a rapidly changing environment. There are actually several hierarchies in the 4D/RCS. An *organizational* hierarchy with a single chain of command has a complex task controlled within a *computational* hierarchy, itself consisting of three parallel hierarchies: sensory processing, world model, and task decomposition.

The **sensory processing** hierarchy consists of a series of computational units, each of which extracts the particular features and information patterns needed by the task decomposition unit at that level. Feedback from the sensory processing hierarchy enters each level of the task decomposition hierarchy. The **world model** hierarchy consists of modules which model (remember, estimate, and predict) and evaluate the state of the system's world. It contains knowledge bases with information on state variables, maps, lists of objects and events, and attributes of objects and events. The **world model** is the system's best estimate and evaluation of the history, current state, and possible future states of the world. **Value judgment** determines the significance of perceived objects and situations, the priorities of tasks and plans, and the need to reconcile perceived and expected objects and situations. **Behavioral task decomposition** means that *each level* in the computational hierarchy generates a plan leading to an executor ordering the corresponding behavior in the system being controlled (e.g., sensor, end effector). The **mission planner** develops the strategy for a mission, such as the detection of an asymmetric threat; it may also determine the goals of the mission, or the goals may come from outside the system. The planning horizon may be minutes or hours at the top level, but grows progressively shorter as the plan is decomposed at successively lower levels.

Reactive control system architectures (e.g., the MIT subsumption architecture) have been successfully implemented in small mobile robots. The *potential fields*-types of reactive architectures have certain design advantages over other reactive architectures. The **advantages** of reactive architectures include: **emergent complex behavior** from simple programming; the lack of a planner and world model allows for **fast responses**; **minimal programming** is required; and the systems are **inexpensive** to build. Disadvantages of reactive architectures include an inability of the system to learn or to replicate human intelligence even in narrow domains (e.g., military tactics); and conflicts can arise among concurrent behaviors.

Reactive architecture sensing, as illustrated below, is behavior-specific sensing, where each behavior has its own dedicated sensing. Sensing is local but can be shared, and sensors can be fused locally by behavior. But **one behavior does not know what another behavior is doing or perceiving.**

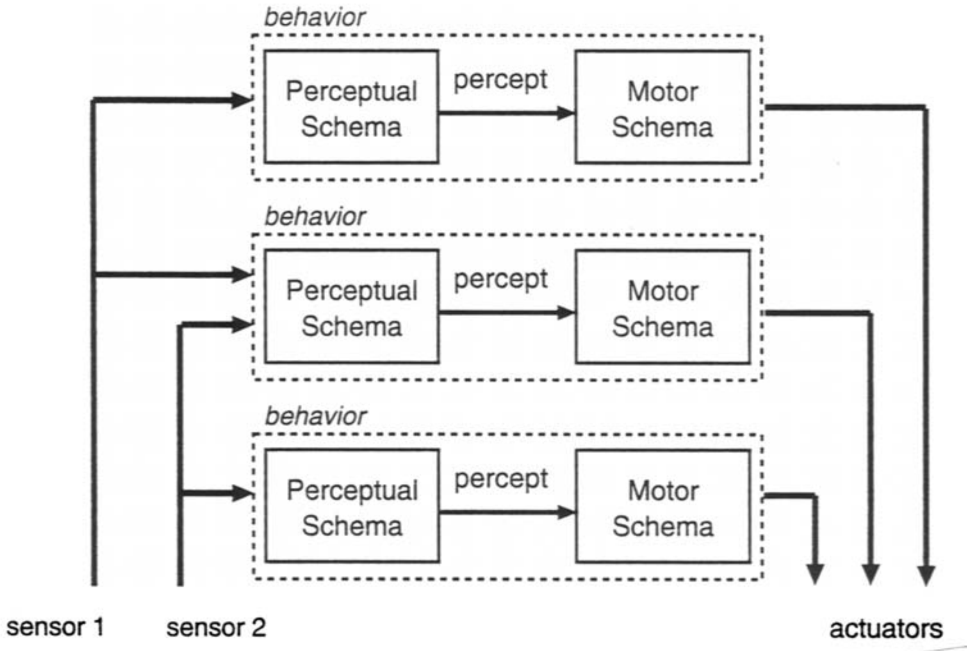


Figure 7-5: Example of Reactive Architecture Sensing

Hybrid architectures combine the best of hierarchical and reactive architectures**:** they have planners and world models, but they use a **reactive mode** whenever it is appropriate (e.g., to avoid hitting a tree at full speed). A number of hybrid systems have been designed, such as: the **NIST 4D/RCS**, the **3T architecture** used by NASA, and the **Saphira architecture** used by SRI on a variety of mobile robots. (The bulk of this architecture is concerned with planning and uses a type of reactive planner called "Procedural Reasoning System-Lite" (PRS-Lite))**.** The **Task Control Architecture** (TCA) is used by NASA in mobile robots.

The Saphira **hybrid architecture**, shown below, is used on a number of mobile robots. It emphasizes need for: coordination, coherence, and communication, and it has distinct deliberative and reactive layers.

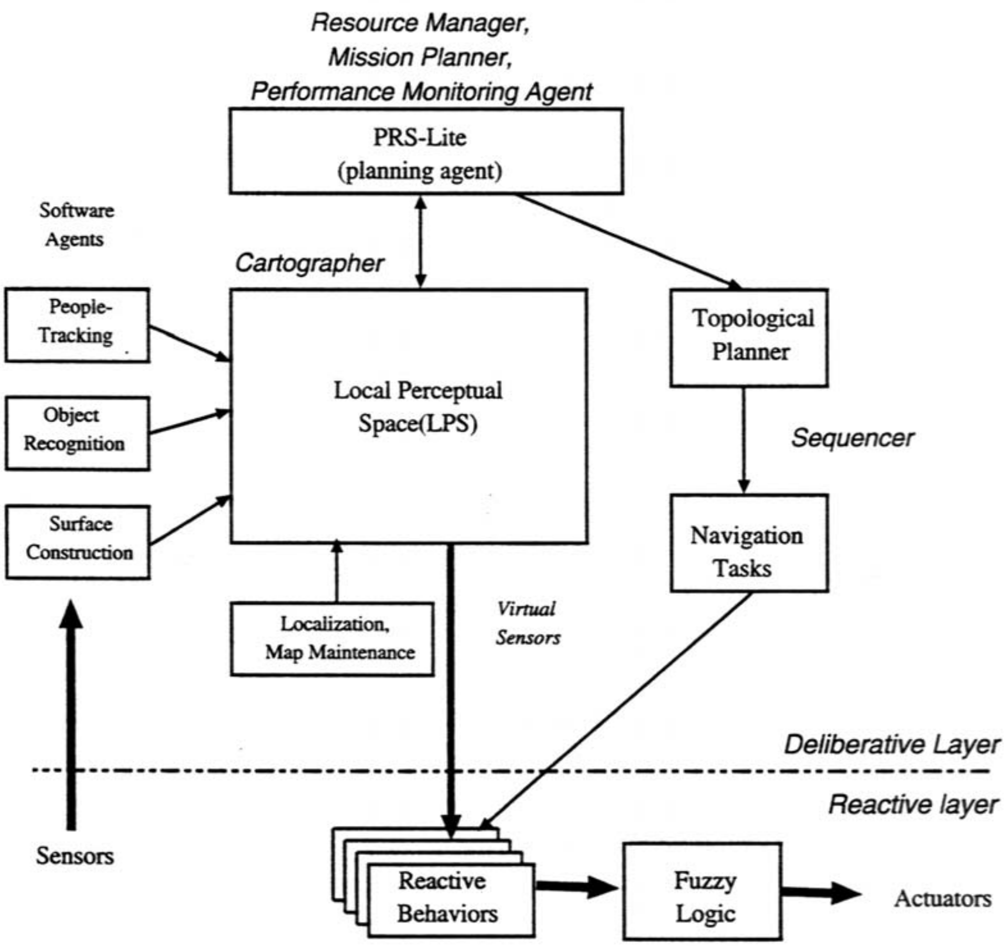


Figure 7-6: Saphira Hybrid Architecture

7.2 Computer Control Systems: Sensory Perception

A hierarchical or hybrid control system incorporates **higher-level** sensor processing while the separate ***sensor system* module** performs the **lower-level** sensor functions. This is analogous to an organism's sensor system in which the sensor and the neuronal pathways to the brain perform **initial filtering and processing** on the incoming information, while the **brain performs the final processing** needed for perception, i.e., what is being sensed and its **significance** in the context of the organism's (robot's) world model and purpose. **First order image processing** employs algorithms for edge detection, surface texture, shape, dynamic shadowing, spatial relationships, etc. It might discern a moving object having certain dimensions and other properties. **Second order image processing**, perhaps using look-up tables or neural networks, might conclude that the object is a human. **Third order image processing**, perhaps using expert systems, might conclude that the human is an intruder and provide the robot with an understanding of the significance of an intruder and the appropriate response - i.e., **perception.**

Sensory perception is the ability to fully understand the object that is sensed in the **context of the situation and environment**. A number of levels may be defined. **Level 1:** sense (as with vision) a **shape** correctly (e.g., an object that is a rectilinear parallelepiped). **Level 2: recognize** the object represented by the shape (e.g., it is a tank – or better, it is an enemy tank). This is sufficient for automated target recognition. **Level 3: understand the significance** of the recognized object (e.g., enemy tanks are dangerous and must be avoided or killed; I must seek cover and concealment and I must report the sighting of the enemy tank). **Perception** in robots depends on the **sensors, sensor processors, and intelligent control system architecture** (e.g., the world model). **No robot** has yet achieved **Level 2 perception** in a broad domain. Achieving **level 3 perception** represents perhaps 60% of the way toward achieving human-level intelligent robots.

7.3 Computer Control Systems: Software Tools

The programming of robotic vehicles has largely been ad hoc. Requirements for **robot programming languages** include:

- ☐ Clarity of program structure
- ☐ Naturalness of the application
- ☐ Ease of extension
- ☐ Debugging and support facilities
- ☐ Ability to incorporate data from sensors
- ☐ Decision-making capabilities
- ☐ Interaction with external devices and sensors
- ☐ Concurrent operation of devices
- ☐ Interaction with world modeling systems
- ☐ A complete set of motion commands
- ☐ User interface suitable for experienced and inexperienced users

There is **no universal standard** yet for a **robot programming language** (although attempts have been made). **Task level programming languages** allow the user to command the robot in terms of **tasks**, rather than specifying the details of each movement and action. A **reusable software framework** would permit robots to synthesize the desirable features and capabilities of **deliberative** (symbol mediated) and **reactive** (sensor mediated) control. To allow robots to adapt and function in **uncertain environments**, software should be created by **conventional programming** (hand coding) and **learning-derivation** (automated coding)**.** This would mitigate the intractability of exclusively hand encoding all software-derived robot behavior.

Soft computing, emphasizing programming, is a collection of software technologies designed to be **tolerant of imprecision**, including such technologies as **fuzzy logic, neural networks, and probabilistic reasoning** (including evolutionary algorithms, chaos theory, and belief networks). Various types and levels of behaviors (or schemas) are programmed, with learning employed to refine the execution and coordination of those behaviors. Soft computing takes a ***behavior-centric*** approach to the incorporation of human knowledge and direction in the robot.

Robot shaping (training), emphasizing a balance between programming and learning, employs a more **automated approach** to creating the software. Humans provide the **domain and task knowledge**, generally in the form of training protocol, while the computer provides most of the low-level learning needed to compile the taskings into procedural instructions. This facilitates combining learned sub-behaviors into higher level behaviors without explicit human direction. Robot shaping takes a ***training-centric*** approach to incorporating human knowledge and direction in the robot. **Imitation** creates software through robot learning. It emphasizes the robot's ability to observe, understand, and reproduce a desired behavior – it may take the form of supervised, unsupervised, or **self learning**. Imitation employs an ***interactive-centric*** approach to incorporating human knowledge and direction in the robot. Advanced robot software designs are still in early stages of development, but there have been sufficient accomplishments to incorporate robot-oriented software into near-term intelligent robots.

7.4 Computer Control Systems: Communications

Internal communications include communications within platforms (e.g., among internal and external sensors, processors, and effectors). It is generally not a major problem for mobile robots. However, complexity and length and quantity of wires and other connections can lead to failure – but bandwidth is not an internal communications problem. The robot, however, may be vulnerable to electromagnetic pulse (EMP) effects. Shrinking robot subsystems onto chips reduces internal communications problems. New chips and types of links (e.g., optical) can replace wires and improve performance.

There are a number of types of **external communications**, including **radio frequency (RF)** where **benefits** include no physical tether; and RF systems are compact, very common, and well-understood. **Problems** with RF include**:** generally low bandwidth; vulnerability to noise, jamming and intercept (unless coded); without satellite, UAV, or meteor burst relays – there are usually line of sight (LOS); antenna problems. Another type is **fiber optic**, where **benefits** include**:** high bandwidth; low noise; no jamming; secure; beyond LOS (BLOS) capability. Fiber optic **problems** include: physical tether; usually not recoverable; relatively expensive; can be broken or cut; mechanical deployment; relatively little experience.

The benefits of **laser** communications links include: high bandwidth; secure; low noise; hard to jam; can be compact on platform (e.g., modulated retro-reflector). Laser link **problems** include**:** LOS limitations; subject to unintentional or intentional obscurants; developmental and little experience with laser links. The benefits of **acoustic** communications links include: BLOS capability; simplicity and low cast. **Problems** include**:** low bandwidth; ambient or intentional noise; intercept; short range. The benefits of **pheromone** communications links include: BLOS (trail); covertness; and it would be unexpected by enemy. **Problems** include**:** low bandwidth; short range; ambient noise and adverse weather; and it is experimental. Most **external communications** with – and among – robotic platforms will be over RF links.

7.5 Computer Control Systems: Databases and World Modeling

A **world model** contains **global memory, knowledge bases, maps, object lists, state variables**, etc. It may ask "what if?" questions of a task planner and "what is?" questions of a task executer. It may **update** itself based on sensory input and predict expected sensory input - predicted sensory events may be compared with **actual** sensory events and differences can lead to changes in the world model. It may be a recipient of **plans, tasks, and priorities** as they are generated by various programs. A model is a **formal representation of a system**, and a world model is a representation of the world that is not a direct perception of the world. Humans and other organisms map their own brains onto the world, creating a world model. A model is an **abstraction of reality, a set of rules and relationships** which has the necessary and sufficient means for intelligent action. It is a **simplified representation of reality** that can be substituted for it under certain conditions; it is easier to understand and manipulate than the real system.

The **distinction between a system and its model** is that the **system is a perception, by an observer, of an underlying reality**, while the **model is a representation of the perceived system.** The model is further removed from reality in that it does not explicitly depict causality; the system is *one order removed* from reality, while the model is *two orders removed*. **Iconic models** possess some of the physical properties of the things they represent, usually on a different scale (such as a model car). **Analog models** have properties which are used to describe another set of properties in the real system (such as graphs in which line lengths can represent weight - or electric current can represent velocity); they are often used to represent dynamic situations. **Symbolic models** use symbols (numbers, letters, etc.) to represent the real system, i.e., mathematical and computer models.

Hierarchical and hybrid intelligent control system architectures employ world models. It is very difficult to know, a priori, everything that must be in a world model. It is very **difficult to program** a world model for general-purpose behavior. However, effective world models, once created, can be amortized, updated, and evolved. Also, the robots can learn from experience (and share their experiences in the field in near-real time) and **improve their own world models** through **learning**. **Reactive architectures** do not use world models – but applications for the robots are then limited.

A **database** is a critical part of a hierarchical or hybrid intelligent control system. The contents of the database consist of **spatial and temporal entities** consisting of **states, events, objects, attributes, and processes**. **Examples** are:

- ☐ Mission objectives
- ☐ Tasks
- ☐ Times
- ☐ Object taxonomies
- ☐ Plans
- ☐ Algorithms and heuristic computational tools
- ☐ Constraints and optimization criteria
- ☐ Maps, paths, waypoints, and recovery points
- ☐ Vehicle data
- ☐ Threats and threat locations
- ☐ Search areas
- ☐ Targets and target descriptions
- ☐ Weather data
- ☐ Friendly force locations and descriptions
- ☐ Models of sensors
- ☐ Scenes
- ☐ Terrain markers
- ☐ Artifacts
- ☐ Tactics and strategies
- ☐ Imagery overlays
- ☐ Video and graphics
- ☐ Internal and external sensor data

There has been recent progress in the development of **intelligent databases** in the field known as *data mining*. Data mining is the process of **automating information discovery** and the application of algorithms for **extracting patterns from data.** It is a subset of the larger process of **knowledge discovery in databases** (KDD), which is the overall process of discovering useful knowledge from data. A related technology is that of **data warehousing**, which involves the **collecting and cleaning of transactional data for on-line retrieval**. The technology is available for designing advanced intelligent databases for robots.

7.6 Computer Control Systems: Hardware Architecture

Computer hardware still obeys *Moore's Law* and doubles in processing speed and memory every 18 months or so. Today's hardware is sufficient for robots at a useful level of intelligence. Tomorrow's hardware will provide the basis for superior cognition, but the achievement of this cognitive potential will still depend primarily on **advances in software**. The architecture of the hardware is another contributing factor to achieving robot intelligence. As with neuronal architecture in the organic brain, which uses parallel processing to speed cognition otherwise based on slow individual neurons, the *arrangement* of processors can be important. For example, a project to develop a Cellular Automata Machine – an "artificial brain" – was based on Field Programmable Gate Arrays and evolutionary programming. The initial goal was to develop inexpensive processing modules having the computational speed of ten thousand Pentium-based computers. Many other projects are developing parallel processing arrays using inexpensive personal computer type processors.

7.7 Computer Control Systems: Mobility

Robotic mobility is determined by the design of the platform and its mobility components (discussed separately) and the ability of the control system **to plan, navigate, and pilot the robot.** **Reactive architectures** have demonstrated mobility through the sense-act paradigm. But this is too limited for most complex applications. Reactive behavior can be used effectively by the autonomous pilot to avoid obstacles and threats. **Autonomous mobility** has been demonstrated to a degree in a number of programs, especially the Army/DARPA Demo II and Demo III robotic vehicle programs.

Autonomous mobility has been demonstrated for: Road following; Waypoint operation; Multi-vehicle cooperative mobility and formation driving; Semi-autonomous turnaround; Reverse path following; Obstacle map sharing; Stereo obstacle detection; Negative obstacle detection; Field-of-regard control; Stereo FLIR at night; Navigation LADAR; Multi-spectral terrain classification; Obstacle avoidance; Route history maintenance; Sensor-based hill cresting; and Advanced inertial navigation. The **4-D/RCS program** has already demonstrated the ability of its control system to drive autonomously at 35 kph off-road and 100 kph on-road.

7.8 Sensor Systems: Internal and External Sensors

The major elements of a **robot's sensor system** are its **internal and external sensors**, the **processing** needed to extract information from the sensors which can be used by the robot, and the **architecture of the sensor system**. The number and type of sensors needed by the robot will depend on its size and mission. **Internal sensors** might include those for: guidance, navigation, and attitude (such as global positioning system, mechanical or laser gyroscope, and other inertial and dead reckoning systems, accelerometer, pitch and roll sensors, wheel encoders, steering position sensors, compass, odometer, gravitometer, etc.). **Status sensors** might include those for fuel, temperature, engine speed, ground speed, equipment functionality, etc.

External sensors might include: passive and active optical imaging (video, low light level, forward looking infrared, laser scanner [LADAR], structured light, stereo vision); acoustic detection; proximity sensors (such as ultrasonic acoustic ranging [sonar], laser ranging, microwave radar ranging, Doppler radar, limit switches, bumpers, and whiskers); touch sensors; force sensors; electric field sensors; meteorological sensors (sensing temperature, precipitation, humidity, wind, atmospheric pressure); smell and taste sensors (such as chemical, biological, and radiological sensors). All of these sensors are suitable for near-term use in robots (sensors that are smaller, cheaper, and more capable are being developed in numerous programs). Many satisfactory sensors are available commercially.

7.9 Sensor Systems: Sensor Processing

While there have been many advances in sensor processing, key objectives such as automated target recognition, have not yet been fully achieved. Machine vision, whether for mobile robots or manufacturing robots, still cannot perform many tasks easily performed by human vision. For manufacturing robots, object recognition and 3-D perception are required to automate many assembly tasks; but **current technology cannot approach the capabilities of a**

human. There has been progress in developing **machine vision** with a **number of approaches**, such as: coded or structured light; hypothesis generation and verification; anthropomorphic vision with binocularity, foveal vision, and gaze control; 3-D image ranging algorithms; shape and texture recognition algorithms.

For **mobile robot** applications, current sensor processing allows the robot to avoid obstacles and otherwise move about autonomously in known or relatively simple environments. There has been recent progress in **cross-country mobility** with the 4-D/RCS architecture employing a LADAR as the primary vision sensor. The state of **signal processing** is satisfactory for the robot's **active sensors**, including microwave, laser, and acoustic (sonar), used primarily for obtaining range data. **Passive** acoustic (sound recognition) is suitable for language understanding and other sounds on which the robot can be trained. **Image processing** for passive vision in mobile robots is still quite limited compared with human vision.

7.10 Sensor Systems: Sensor Architecture

The ability of the robot to sense its environment depends, in part, on the kinds of sensors on the robot, how they are interfaced with the robot, how they are arrayed spatially, and how they are integrated with each other and the robot' cognitive processes. **Sensor fusion** involves combining data from multiple sensors into one data structure, usually within the world model, so that the sensor data can be processed into coherent and accurate knowledge about the world. The equivalent of sight, hearing, touch, and smell are combined in the robot to obtain a unified sensorium better than the sum of its sensory parts. In the **reactive architecture**, where there is no world model, **sensor fusion** is replaced by **sensor fission** and **behavior fusion** (i.e., the individual behaviors triggered by various sensors are fused into a coherent set of behaviors, but the sensory data is not directly fused). The proper arraying of sensors on robots is reasonably well understood. But the ability to fuse sensor output is still limited. **Behavior fusion** is less computationally intensive, but the reactive architecture is not appropriate for many complex missions. In relatively **well-structured or understood environments**, current sensor architecture technology is generally **sufficient**. More development is needed for sensor architectures in unstructured, hostile, and adversarial environments.

Behavioral sensor fusion in the form of **sensor fission** is illustrated (from Murphy) in **Figure 7-7**. In sensor fission there is one sensor per behavior. Behaviors can share a sensor stream – but without knowing it. To an observer, there is **emergent complex behavior.** But sensor fusion at the behavioral level is **illusory.** This method is used in the reactive **subsumption architecture**. Behavioral sensor fusion in the form of **action sensor fusion** is illustrated in **Figure 7-8**. In action sensor fusion, sensor fusion occurs in behaviors (as it does in at least some organisms). Sensor data is transformed into a **behavior-specific representation** in order to **support a particular action** – not to construct a world model. Behavioral sensor fusion in the form of **sensor fashion** is illustrated in **Figure 7-9**. In sensor fashion there are coordinated sensors. It implies the **robot changes sensors** with changing circumstances (as people change clothes with changing circumstances). For **example:** Motion detected by an **infrared sensor** may cue an **acoustic sensor** to listen in that direction.

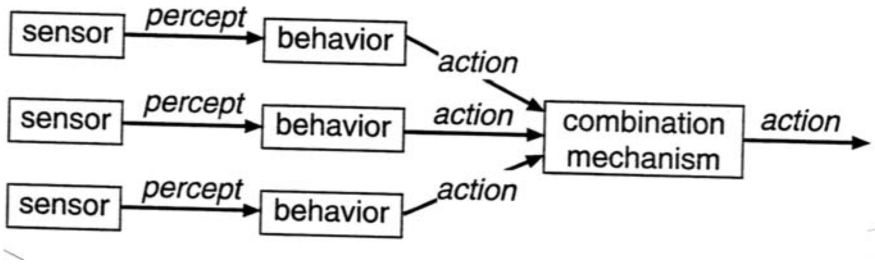


Figure 7-7: Sensor Fission

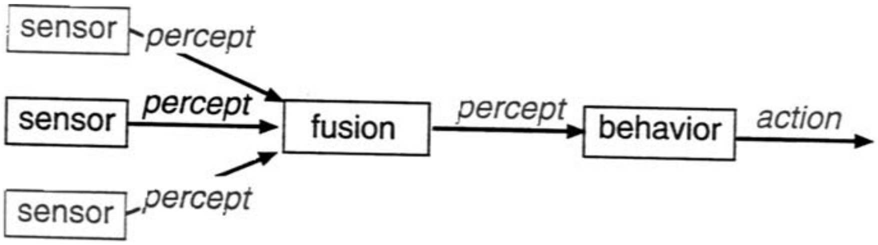


Figure 7-8: Sensor Fusion

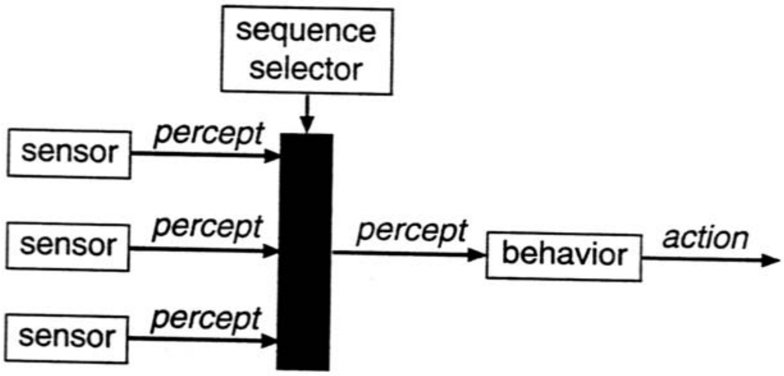


Figure 7-9: Sensor Fashion

The cognitive sensor fusion model is a neurophysiological model of sensing - based on studies of sensing in cats. Processing is initially local to each sensor. It is consistent with robot behaviors and supports sensor fission approach and is the basis for the sensor fusion effects (SFX) architecture. The SFX architecture is based on the **cognitive neurophysiological model** of sensing. Functions which are equivalent to those in the **superior colliculus** are implemented in the **reactive layer.** Functions which are equivalent to those in the **cerebral cortex** are implemented in the **deliberative layer**. Branching in **perception** is done through the use of **whiteboards.**

Reactive architecture sensor processing is a form of behavior-specific sensing. Each behavior has its own dedicated sensing, as was shown in **Figure 7-5**. Sensing is local but can be shared, and sensors can be fused locally by behavior. But **one behavior** (generated by the robot) **does not know what another behavior is doing or perceiving**.

7.11 Effector Systems: Platform & Mobility Design

The U.S. Army Tank Automotive Command has been developing **"intelligent mobility"** concepts where the inherent design (intrinsic, physical mobility assets) of the robotic platform allows it to move better in an unstructured environment without the need for excessive active participation of the intelligent control system. Example: vehicles with better wheel or track design, or articulated vehicles, are better able to cross terrain gaps (e.g., ditches) or climb hills and slippery slopes. Hybrid track/wheel designs, for example, look especially promising; they are flexible, lightweight, and suitable for much cross-country terrain.

Perhaps a similar "intelligent mobility" approach might be used for **humanoid and legged** robots. The current state of the technology, as discussed below, is such that robust and agile humanoid mobility has yet to be achieved.

7.12 Effector Systems: Structural Dynamics and Kinematics

Structural dynamics is a function of structural geometry and intelligent control. It is concerned with the forces associated with the robot. The robot's kinematics is its motion in the abstract without reference to force or mass. Dynamic stability is a measure of the ability of the robot to maintain its balance while in motion. This is not a problem for conventional wheeled or tracked vehicles (except on rough terrain); a two-legged (or two-wheeled) robot may be stable while moving and unstable at rest. Adverse structural dynamics is generally not a problem for conventional mobile robots. However, it is an issue for bipedal and other legged robots, as well as robotic manipulators and end effectors, where improvements in structural dynamics will lead to the ability of legged robots to move at higher speeds with greater payloads and increased accuracy and precision.

7.13 Effector Systems: Manipulators and End Effectors

It would be useful for some robotic vehicles and legged robots to have **manipulator arms and end effectors** to move objects; it is mandatory for a humanoid robot qua humanoid.

A **manipulator** consists of a robot **arm** and **gripper** at the end of the arm. An **end effector** is a device or tool connected to the end of a robot arm - the design depends on what the arm is supposed to do. An end effector might consist of a gripper, welding torch, circular saw, screw driver, probe, anthropomorphic hand with fingers, water jet nozzle, etc. Most current mobile robots (vehicles) **do not have manipulators and end effectors.** Many robotic vehicles do have **tools which can be considered as end effectors:** dozer blades, backhoes, buckets, etc. There are many applications in which manipulators would be useful on mobile platforms (i.e., people find arms and hands to be useful). **Humanoid robots**, as such, should have arms and end effectors, and other legged robots (especially hybrids) may have them as well.

One development goal is the advanced, **high-precision robot wrist**. Typical robot wrist is a three degree of freedom device which is mounted at the end of a robot manipulator. An alternative strategy to a high-precision wrist is the idea of coarse-fine manipulation in which the robot manipulation task is divided into **coarse and fine domains**. Manipulator provides the **coarse motion** while the wrist provides the **fine motion**. Since the wrist need only provide limited motion and has relatively low inertia, it can provide high bandwidth as well as compliant motion.

There have been many attempts to **duplicate the human hand** – without great success. While designing a good mechanical hand is itself a difficult problem, the real problem appears to be integrating the control, sensory, and perceptual components of manipulation. A growing area of research concerned with the theory of grasping and the development of universal gripping strategies. **Dexterous manipulation**, in one taxonomy, is divided into:

☐ Grasp stability analysis
☐ Grasping force analysis
☐ Contact conditions
☐ Finger tip sensors
☐ Manipulation of objects

Areas of research for grasping include: grasp taxonomy, grasp quality measure, grasp type of contact, grasp compliance, and grasp stability. Recent developments include a layered control architecture for coordinating hand and arm control. For most manipulation tasks, the hand requires complementary motion of the arm. It is important to coordinate the motion of the hand and arm to perform cooperative motions. One approach is to use a three-layered system architecture has been used, with planning, sensory, and control layers. An alternative to a general purpose hand is to develop specialized hand mechanisms for specific tasks. There are many useful manipulators and end effectors, but more development is needed to achieve the dexterity, accuracy, precision, speed, and relative strength of the human arm and hand.

7.14 Effector Systems: Propulsion Systems

Propulsion systems, consisting of a **power source** and **mobility** system, are used in all robotic vehicles. Power sources for robotic vehicles are typically **internal combustion engines** of various types or **electric motors of various types**, or **hybrid** combustion/electric engines. Humanoid and legged robots are typically powered by battery-driven electric motors.

Robotic vehicle engine types include: four and two cycle reciprocating internal combustion engines, rotary engines, turbines, electric, etc. **Energy sources** include: gasoline, gasoline/oil mixture, diesel oil, kerosene, batteries, fuel cells, solar cells, etc. **Mobility systems**

are the proximate cause of the robot's motion employing wheels, tracks, legs, propellers, jets, etc. Under development are: exotic **new types of engines** (such as new types of external combustion engines), **energy sources** (such as beamed microwaves), and **mobility systems** (new wheel-track designs). Near-term humanoid and legged robots for practical (outdoor) applications will likely need a hybrid internal or external combustion engine and battery combination, with fuel cells a future possibility.

7.15 Human Interfaces: Controls and Displays

The interface between the robot and the human controller or supervisor consists of controls and displays. It also consists of the attentions to the robot which must be paid by people over its lifetime: testing, maintenance, and support. People associated with the robot must be trained in its operation, maintenance, and repair. The communications system (command, control, and data links, antennas, transmitters, receivers, power supplies, computers, signal processing, etc.) is also an interface system - even autonomous robots will generally be supervised or transmit sensor information to a control center. Robotic systems should have a control station architecture that is open, interoperable, and common. **Open architecture** allows different modules to be inserted easily into the system (as in home stereo systems). **Interoperable architecture** allows each control center to work with different robotic platforms, payloads, and communications networks. **Common architecture** means that each control center uses the same hardware and software as other control centers.

Each control center will typically have computers and software for: controlling or supervising the remote robot and its payload; planning missions; processing data and sensor information; communicating with the robot; testing the performance of the robot; and training operators. It also displays of the status of the vehicle and payloads and associated controls. There might be digital map displays for mission planning and monitoring and tracking the robot's path and progress. There are usually data recording and playback devices (e.g., disks and tape) and input/output devices (e.g., keyboards, monitors, plotters, printers, etc.). Graphic displays and reconfigurable, touch screen controls are improving rapidly, along with voice control. Mission and path planners are also becoming proficient.

For telerobotic or supervised autonomous humanoid robots, interactive haptic devices, for simulations and physical control, are being developed (Khatib, et. al.). The haptic device can provide input information to the user, by means of a force on a hand or finger, for example, or provide control information to the robot (simulated or physical) through force applied by the user to the interface mechanism. Virtual reality and synthetic environments, as a means of robot control, are also being developed and would be especially useful for teleoperation or supervised autonomous control of humanoid robots.

The human/robot interface might serve as a means of conveying *anthropopathetic* behavior, designed to foster and maintain emotional relationships with human users (Swinson). The robots would be able to perceive and respond to human emotion, as well as possess an intrinsic emotional system modeled on those of humans. The robot's emotional state would be more than superficially expressed behavior, but permeate the control architecture and influence the robot's fundamental underlay the robot's values and consequent behavior. Such behavior might include the equivalent of human semiotic body language (e.g., smiles and frowns, hand gestures, etc.), as well as task re-prioritization and performance. Perhaps 75% of human communication occurs through body language. Control efficiency can be increased significantly if the human/robot interface is able to engender this type of mutual communication.

7.16 Human Interfaces: Testing

A continuing testing program will be needed for humanoid and legged robots to ensure safety, reliability, and efficacy. A test plan will be needed to describe the types of tests, the level of the tests, and the test processes for each application. For example: the types of tests might include pre-employment tests (ground/bench tests and operational tests) and user tests (pre-operation, during operation, post-operation). The level of tests might range from chips through boards, subsystems, modules, and systems. Test processes might include, among others, status checks or diagnostics. The means for designing appropriate test plans are available, but the plans for testing various robotic systems do have to be developed.

7.17 Human Interfaces: Maintenance and Support

Maintenance and support for humanoid and legged robots will include issues and plans relating to: **reliability** (e.g., mean time between maintenance and mean time between failures); **availability** (e.g., systems readiness requirements and mission performance requirements); and maintainability, which includes considerations of: design (robustness and redundancy); production (suitable parts and quality control); environment (system insensitivity and ease of repair); resources (personnel, equipment, and funding); and tasks (type, location, sequence, and duration). The requirements for maintenance and support (and testing) should be part of the metrics used in designing humanoid robotic systems.

7.18 Human Interfaces: Training

Simulators may used to train humanoid robot supervisors or operators – and they can be used to train the robots themselves. Suitable simulator technology is needed for training operators of humanoid robots. Physical training facilities are also needed to validate the simulators. They can provide experiences, often unexpected, which are not included in the simulations. Training will be made more difficult if humanoid and legged robotics encompasses a wide variety of robotic types and applications.

8.0 STATE of HUMANOID and LEGGED ROBOT TECHNOLOGY

As discerned from the literature and our survey of experts, humanoid robots will exist and be able to completely replace human soldiers on the battlefield during this century – but not necessarily immediately. The humanoid (and other legged) robots, however, can **supplement human soldiers** in the near future, just as robotic air and ground vehicles are beginning to do so. The humanoid and legged robots will provide valuable force-multiplier and life-saving services to military units in combat environments and engagements that favor legs over wheels or tracks for mobility and maneuver.

8.1 Telepresence

Teleoperation (remote control) and telepresence (teleoperation with sensory and other interfaces such that the human operator perceives herself to be in the robot's location) are at the lowest levels of the FCS autonomy scale. One might look at the scale as an **evolutionary hierarchy** toward achieving full robotic autonomy. For example, one approach, suggested by Dr. Jeff Cerny (of Unmanned Systems, Army AMRDEC), is to begin a humanoid robot development program by developing a "Combotoid," a humanoid telerobotic system that emphasizes telepresence for military human operators instead of autonomy, especially for training applications. According to Cerny, the operators will maintain their fighting skills through directly telepresence, with the forward-deployed Combotoid in one-to-one operations. Individual soldier skills will be executed in conducting such operations as fire and maneuver, clearing buildings, and remote reconnaissance. An early version of the kind of virtual space needed exists today at the Dismounted Battle Lab at Fort Benning, as part of the simulation environment there. According to Cerny, telepresence is better than no presence, and it provides true force projection without endangering soldiers.

A contrary view is that, in principle, autonomy cannot be developed from pure teleoperation because the technologies are too different for such an evolutionary approach to work (e.g., the same as trying to evolve digital calculators from their electro-mechanical predecessors). An **evolutionary approach** to autonomy would be more feasible if an initial **autonomous architectural framework**, which includes a telerobotic interface, is first established such that evolutionary improvements can be made as technology progresses. Telepresence could then be emphasized for early humanoid systems as autonomy improves for later systems (although, in the future, telepresence may remain useful for various missions even as autonomy becomes efficacious).

The NASA Robonaut [Ambrose et. al.] is an astronaut-sized robot with two arms, two five-fingered hands, a head, and torso – but no legs, per se. During extra-vehicular activity (EVA) astronauts usually keep their feet inserted in a foot restraint for stability. Robonaut duplicates this stabilized position with a single leg that can be attached to the space vehicle in various ways. A combination of **teleoperation and autonomy** allow the robot to perform a number of astronaut-type tasks with a number of end-effector tools which may be used. And instead of controlling a single effector, haptic control might be used for humanoid robot whole-robot control [Khatib, et. al.].

In 1998, the Japanese launched a multi-year project to integrate virtual reality and robotics (the **Real-Time Remote Robotics** (R-Cubed) project), and to focus on **Humanoid and Human Friendly Robotics Project** (HRP). The goal is to provide efficient and human-friendly machines able to attend to the growing population of elderly and handicapped people. The humanoid robot is being developed by Honda; the "telexistence" control center is being developed Matsushita Electric Works, Kawasaki Heavy Industry, FANUC, and the University of Tokyo; and the humanoid simulator is being developed by Hitachi, Fujitsu, and the University of Tokyo [Tachi]. The teleoperation interface is being provided with **kinesthetic sensing and feedback** [Itoko and Kobayashi].

Telepresence is, to a reasonable extent, technologically – and perhaps economically – **feasible now**. It removes the operator from harm's way, but it can be a burden without some degree of autonomy. It can be operationally useful and serve as a foundation for evolving the humanoid toward greater supervised autonomy.

8.2 Hexapod Robots

As we mentioned previously, there are good reasons why nature has not made any hexapod large animals. For insects, spiders, and millipedes, the mass of the legs is small, and the **mechanical stability advantage** (of six or more legs) for small brains (with limited intelligence) is large. However, if the brain has sufficient computing capacity to control perception, gait, and balance, there is a big advantage in not carrying around an extra pair of legs (and nature does not like to waste structure and energy). All pack animals have four legs, and the fastest running animals also have four legs – although bipeds have greater endurance at cruising speed than quadrupeds (perhaps benefiting from not having an extra pair of legs). All of this presupposes sufficient control for legged motion; with insufficient control the greater stability of hexapods becomes an advantage. Six (or more) legs are best for creatures that weigh less than a few grams, like insects – or in the case of lobsters, crabs, and octopi, spend most of their time underwater. Six-legged machines became popular in robotics laboratories with people that were working with computers having limited abilities. But even with more capable computers, adaptive locomotion has been harder to generate and coordinate than previously expected. The walking performance of robotic hexapods is not yet comparable to insect performance, indicating as yet undiscovered system complexities. Nevertheless, they may offer advantages to larger legged robots for certain applications. And there has been a significant amount of research on hexapod robots which may be applied for practical applications.

For example, there is a prototype shoe-box sized hexapod robot [Altendorfer et. al.] that travels at speeds greater than one body length per second over terrain that would be difficult to traverse by others forms of robot locomotion. The robot, *RHex*, employs **hierarchical control** of a spring loaded inverted pendulum (SLIP), which is a template for all animal running. RHex and other hexapod prototypes have used biological principles (biomimetics) to achieve animal-like performance. Computer models have examined biological principles both for the geometry of the robot and the architecture of the controller [Pfeiffer et. al.]. Pfeiffer first analyzed the biological principles from measurements of the **walking stick** insect and then calculated the best drive combination in the leg joints as a non-linear optimization problem. Contemplating the severe load-to-weight problem of walking machines, the researchers investigated the ideal motor-gear combination for the joints and weight-optimized single-leg construction. They used **decentralized, three-layer hierarchical control**, which was a biological-like controller. The resulting hexapod robot was able to move on unknown, uneven ground, automatically detecting and climbing obstacles. A neural network, *Walknet*, was used to control hexapod robot's stick insect-like walking [Cruse, et. al.], and it developed interesting emergent behaviors (such as accommodating successfully to a massive perturbation to the legs).

In addition to the **walking stick** model described above, other insects have served as biomimetic hexapod robot models, including the ever popular and agile American **cockroach** [Delcomyn and Nelson]. The prototype was somewhat more than an order of magnitude larger than a cockroach, but it had insect-like leg structure and placement, and actuators that mimicked muscles. The robot employed six legs with three segments each, to emulate the cockroach, and, like the roach, had pairs of legs that were of different lengths and had somewhat different functions. Each leg had multiple touch, strain, and angle sensors, and muscle-like actuators.

Experimental intelligent control systems for hexapod robots have employed **genetic algorithms** to evolve dynamical neural networks for controlling the locomotion of the hexapod [Gallagher et. al.]. The evolved controllers were robust to the loss of sensory feedback and environmental variations. The genetically-evolved controller was demonstrated in simulated and physical hexapod robots. While the instantiation of the controller into a physical robot, from its origination in a computer simulated robot, was not trivial, it was accomplished successfully. It was also found that a hexapod robot, employing **distributed control and local leg reflexes** like insects, can easily cope with terrain that would defeat other types of legged robots [Espenschied, et. al.]. A genetic algorithm fuzzy logic approach (GA-fuzzy) was used to generate an optimal path and gait simultaneously for a hexapod robot [Pratihar, et. al.]. The combined path and gait generation employed three steps: (1) determining the robot's trajectory; (2) selecting a foothold; and (3) designing a sequence of leg movements. Traditional approaches have not been entirely successful in accomplishing this ability, while the GA-fuzzy system was able to solve the problem of combined path and gait generations simultaneously for a hexapod, although additional research is needed to further optimize hexapod motion.

The **cyclic genetic algorithm** (CGA) was developed as kind of evolutionary computation for robot learning. Experiments were conducted to apply this technique, which involves the co-evolution of model parameters, to **learning gaits** for hexapod robots [Parker]. (Without going into too much technical detail, the cyclic GA differs from the conventional GA in that the chromosome is in the form of a circle with two tails and the genes that can represent tasks that are to be completed in a predetermined segment of time.) The results of the CGA simulations were implemented on a physical hexapod robot. Tests showed that the method allowed the robot to adapt to changes in the robot's capabilities and provided an effective means of anytime learning.

One study compared three **insect-inspired locomotion controllers** [Ferrell], all of which were tested on the same hexapod robot. The controllers are: reflexive controllers, hybrid controllers, and patterned controllers. The **reflexive controller** employs stimulus-response reactions to generate motion. The motion of each leg, and the coordination among legs, is a function of proprioceptive information which is used to adjust excitatory and inhibitory impulses that regulate the behavior of the leg effectors. Locomotion is the result of continuously computing sensory inputs and the resulting motor responses. The **hybrid controller** is not adapted from a single insect model of locomotion, but it employs aspects of several models. In this case, the hybrid used pre-programmed leg motions for locomotion. It uses proprioceptive information to generate biologically-inspired timing signals to coordinate the pre-programmed leg motions, where the signals consist of excitatory and inhibitory signals. The **patterned controller** produces locomotion by coordinating pre-programmed leg motions. Oscillators provide timing information which is used to generate the cyclic motion of each leg and coordinate between legs. Also, proprioceptive information is used to compensate for leg perturbations rather than for basic walking behavior. The patterned controller was the most successful, with the particular hexapod robot and environment used in the experiments, in terms of allowing the robot to remain stable over a variety of gaits and disruptions (e.g., leg loading, leg disabling, and leg disturbances).

Models of **gaits in hexapods**, centipedes, and millipedes were used to explore modular networks for legged locomotion [Golubitsky et. al.]. Networks of coupled cells are used as models of central pattern generators and they obey identical systems of differential equations. They can provide the standard gaits of hexapods (as well as quadrupeds and other legged variations).

In addition to walking sticks and roaches, investigators have examined **behavioral models** of the **praying mantis** as a basis for robotic behavior [Arkin et. al.]. A schema-theoretic model of the praying mantis, derived from behavioral and neurological data, was implemented on a hexapod robot and provided a range of visually-guided behaviors, including obstacle avoidance, prey acquisition, predator avoidance, and chantlitaxia (i.e., search for a suitable habitat) behaviors.

8.3 Quadruped Robots

Quadruped robots (or hybrid quadrupeds, such as a Centaur-type robot) are more promising for near-term military applications of human-scale platforms than hexapods (which are more useful for micro-scale robots). Quadruped robots are already commercially successful in entertainment robotics [Veloso], with **robotic dogs**, such as the Sony Aibo, serving as popular pets and even playing a form of soccer.

Programmable versions of the Aibo, available since 1998, are serving as modified hardware platforms for researchers to explore advanced quadruped robot behavior, especially in the adversarial environment of soccer. Algorithms have been programmed into the Aibo's processor for **autonomous image processing, localization, and control**. The vision algorithm, which processes data from a color camera, computes the distance and angle of the robot to objects and assigns confidence levels to its state identifications. The localization algorithm processes visual information from fixed colored landmarks in the field of view and provides the coordinate location of the robot. New research is being conducted in probabilistic localization in an adversarial environment (which might be a soccer game or combat), where the robot's position is not necessarily due to its own motion (e.g., it may be pushed or slip). Behavior-based planning allows the Aibo to control itself differently as a function of the accuracy of its knowledge of the world (e.g., it will approach an object differently, depending on whether it knows its location with high or low probability). In another development, Marc Raibert (founder of the MIT leg laboratory and president of Boston Dynamics), together with the Sony Corp., modified the Aibo leg design to create a version able to run at about 2 mph [Shaw].

As with hexapod robots, the robot-specific technology issues for quadruped robots concern the optimization of **gaits and gait control**. For example, **discontinuous gaits** have been found in analysis and experiments to offer advantages over the periodic **wave gaits** on irregular terrain [de Santos and Jimenez]: they are more stable, more energy efficient, and are faster. Other research investigated an attitude/position control strategy based on sensors (such as contact sensors, inclinometers, and joint position sensors) and sensor-dependent algorithms to control wave gaits [Jimenez and de Santos]. This control method can maintain the quadruped robot's desired attitude, altitude, and trajectory. In other research, a quadruped robot was dynamically modeled using force sensors for force control of the quadruped robot's attitude and position as an alternative method.

In conjunction with classical control theory, **rule-based reasoning** (i.e., an *expert system*) was applied to manage, in real-time, the locomotion control of simulated quadruped robots [Martins-Filho and Prajoux]. The rule-based reasoning determined the **force distribution** for the legs using input-output linearization for attitude control and optimized linear control for overall locomotion. The knowledge-rules concerned walk events and feet-force calculations, and the control of force distribution provides the robot with greater adaptability and flexibility under a variety of conditions than other techniques. An example of a **rule** for a controlled stop of the robot follows:

```
If      (number of feet collisions > 0
        or number of feet waiting contact > 0
        or number of slipping feet > 1
        or number of sinking feet > 1
        or (number of slipping feet = 1
                and number of sinking feet = 1))
        and not control failure
Then    memorize stop the robot
```

Cooperation and coordination among robotic platforms is a major research area, and quadruped robots have been examined as cooperating platforms for transporting objects. In one project, **implicit communication-based transport** was used to achieve cooperation, with each robot using only its own sensors to estimate the state of a task [Aiyama et. al]. Neither quadruped robot had a direct means of a communicating with the other; only by observing the behavior of the other could a robot decide how it should move in response (just as two human furniture movers might coordinate their motion while moving a heavy sofa). The technique, while applied to quadruped robots, may be employed to achieve certain types of cooperation by any type of robot (or robot/human) combination. Bipedal humanoid furniture movers may be one such commercial application.

The Korea Institute of Science and Technology developed a **centaur robot** called, naturally, CENTAUR. It consists of a humanoid head with stereo vision, two arms and hands, a trunk, four legs, and 37 degrees of freedom (DOF). The upper body has 25 DOF (1 DOF mouth, 2 DOF neck, 2 DOF trunk, two 7 DOF arms and two 3 DOF hands) and the four-legged lower body has 12 DOF. The main objective of the research is to develop a complete motion planning algorithm able to generate safe and thorough human-like motion [Kim, et.al.].

In summary, **quadruped robot locomotion** is reasonable well-understood (if not optimized for all sorts of terrain and environmental conditions) and ready for near-term development into fieldable systems. However, as with other forms of legged robots, none has as yet been demonstrated with high-level cognition or situational awareness.

8.4 Bipedal Humanoid Robots

As previously described, there are a number of commercially available humanoid robots. They **lack situational awareness**, do not yet duplicate human mobility (especially on irregular surface), and lack the dexterity of human arms and hands. While there is ongoing research to improve bipedal locomotion and arm and hand performance, there is little, if any, to improve humanoid robot cognition.

Waseda University in Japan has studied bipedal walking robots since 1966, including dynamic complete walking, walking under an unknown external force, dynamic turning, dynamic walking while adapting to an unknown, uneven surface, and other research [Yamaguchi, et. al.]. Human walking functionality and behavior was analyzed with the goal of allowing humanoid robots to share the same space, perceptions, and behaviors as people. Human locomotive activity was found to involve the whole body (lower and upper limbs and trunk) in a cooperative and dynamic way. Research was then focused on exploring similar **whole-body cooperative motion** in humanoid robots. Algorithms were developed and showed improved effectiveness in walking control (such as trunk-hip cooperative compensation motion). Another research project used a simulated humanoid robot (based on a physical robot) to experiment with a whole-body motion controller, which included biped locomotion, dynamic balance control, and collision avoidance [Nakamura, et. al.].

Control algorithms for dynamic legged locomotion, and comparisons among different kinds of legged motion (e.g., quadruped trot and bound, biped run, kangaroo hop, etc.) have been examined for simulated and physical animals and robots [Raibert and Hodgins]. It was found that physically realistic motion does not necessarily look “natural.” Physical realism does not require the smoothness and coordination exhibited by animal motion. The robot motion appeared more natural after increasing the compliance of the actuators; and the addition of constraints, to minimize energy expenditure, for example, should also enhance the natural appearance of the motion.

As in the case of hexapod robots, **genetic algorithms**, developed in a simulator, have been used to evolve the walking ability of a physical bipedal humanoid robot [Ziegler, et. al.]. Other researchers [Wolff and Nordin] are also employing genetic algorithms as the method for getting humanoid robots to **adapt** to complex human environments. The Wolff and Nordin hypothesis is that even slight physical distinctions (adaptive defects) can have significant adverse consequences. For example, left-handed people have a greater mortality rate than right-handed people in a world of right-handed artifacts because their left-handedness leads to a greater propensity for accidents. Robots, in general, are even more different than left-handed people in a right-handed world and thus even more prone to mishaps – unless they can be made to adapt better; hence the need for genetic algorithms or other learning tools.) The fitness scores for the genetic algorithms were evaluated automatically on the robot based on information from the robot's sensors, including its vision system. The evolutionarily-developed algorithm improved the manually-developed set of gait parameter values in that the robot moved more robustly and in a straighter path. Each evolutionary experiment – running the genetic algorithms in simulated robots and then implementing the surviving successful algorithm in a physical humanoid robot – took about 5 hours. The exercises to evolve efficient gaits, performed over a period of 6 months, took a toll on the physical robot's hardware, which required extensive maintenance. **Genetic programming** was combined with **sensor-based (infrared vision) locomotion** controllers to allow the humanoid robot to learn self-locomotion for movement in different directions, and by superposition of different path solution candidates, to follow an arbitrary path [Hedman, et. al.]. Genetic algorithms were successfully used to synthesize humanoid gaits for stair climbing based on minimizing energy and torque change [Capi, et. al.].

Wolff and Nordin conclude that **evolutionary programming is superior** to traditional robot control programming for achieving adaptive behavior. The conventional approach to robot control, by comparison, derives an internal geometric model of the system, such as for leg trajectories, and calculates the inverse kinematics. This is computationally expensive and requires "fine tuning" several parameters in the equations. While this approach is satisfactory for stationary industrial robots, it is less appropriate for legged mobile, where the model of the system is complex and difficult to derive, and model-based calculations for actuator commands may require excessive time for rapid reactive tasks. The usual justification for expert systems or evolutionary programming in machine intelligence applies in this case, i.e., the humanoid robot must be able to **cope with the unexpected** and adapt quickly in a dynamic, complex human environment in which the programmer cannot foresee all contingencies.

Genetic algorithms, however, may not be suitable for real-time situations. **Neural networks** have been examined as a method for generating an appropriate gait based on information received from the robot's visual system [Capi, et. al.]. The real-time gait generation would allow the robot to adapt quickly to an unknown environment, including those with difficult surfaces. In experiments, the optimal gait was generated based on the step length and step time. But walking was limited to normal walking and movement up stairs. Future research will include real-time gait generation for movement down stairs, overcoming obstacles, creeping, and other types of movement.

In other research, a mathematical method was developed for generating autonomous, dynamically stable biped motion that is **behaviorally close to that of human motion** [Denk and Schmidt]. The premise is that an autonomous bipedal robot must be able to adapt its gait pattern appropriately to the environmental situation in order to avoid or overcome the obstacles it encounters. A typical approach is to compute, offline, a set of stable walking primitives for steps with different parameters and then store them in a database. While the humanoid robot is walking, it can then select and concatenate appropriate walking primitives to create a suitable situation-dependent walking pattern. The synthesis of the walking primitives may be simplified by prescribing time-dependent trajectories for selected body parts. The suitability of the trajectories then depends on the programmer's skill and knowledge of human gait behavior. Denk and Schmidt explored an alternative method for synthesizing dynamically stable walking primitives with **three gait phases**: pre-swing, swing, and heel-contact. Only step-length, step-width, and temporal succession of the gait phases are needed to specify the humanoid robot's desired motion. The resulting walking primitive is the solution of a multi-phase optimal control problem minimizing the absolute mechanical power consumption in the biped's joints. Other constraints to ensure feasibility of the trajectory include zero moment point and friction conditions, as well as bounds on joint angles and control torques. Optimization of bipedal control is then obtained conventionally in the form of a numerical solution to a **nonlinear programming** problem. Another study [Ibidapo-Obe and Alonge] minimized the deviation of a simulated bipedal robot from a linear path using variations of parameters associated with *gait functions*. The motion of each leg member was simulated relative to adjoining members to select suitable combinations of parameters from the geometry. The simulations were formulated by deriving equations to describe the details of human motion, including lower limb coordinates, velocity and acceleration at the joints, gaits, foot, knee, and hip motion, velocity of the upper extremity, and implications of posture to the function equations.

In the Japanese ESYS humanoid robot project, begun in 1996, several humanoid robots were built to experiment with four **biped locomotion control strategies** [Furuta, et. al.]. All of the control strategies involved the calculation of reference angles of the robot's joints for a selected gait pattern. The computed reference angles were used by servo controller units with local angle feedback to actuate the robot's joints. The coordinated actuation of the appropriate joints generated the dynamic walking locomotion of the robot, including starting, stopping, accelerating, decelerating, and turning. As an example, one of the control strategies consisted of the biped robots' use of multiple-link virtual inverted pendulum models. In one biomimetic approach to developing human-like control architectures for humanoid robots, mammalian **sensory-motor interfaces** between the cortex and spinal cord are being examined to develop functionally equivalent analogs to serve in a humanoid robot motor system [Giszter, et. al.].

There have been experiments with **vision** as a means for **guiding legged robots** in unstructured environments, especially tailored to their constraints and requirements [Martinez and Torras]. Biomimetic gaze stabilization [Shibata and Schaal] and vision-based adaptive and interactive behaviors, such as control of a bipedal robot's balance on irregular surfaces, have also been studied [Inaba et. al.]. Visual and acoustic cues, integrated in a binocular head, can used to control the orienting behavior and direction of motion of a humanoid robot [Natale, et. al.]. Vision-guided (or *perception-guided*) walking around obstacles has been demonstrated [Denk, et. al.]. The research employed a hierarchical architecture for a **vision-based guidance** system, which included an environmental map, a scene analysis module, a view direction control module, and a step sequence planning module. A **stereo vision algorithm** was developed which provided the robot information about rectangular obstacles. Further research is focusing on the robustness of the visual estimation techniques employed.

To extend the ability of humanoid robots to use tools and enhance its ability to move, experiments were conducted to allow a humanoid robot to operate a **scooter** (similar to a child's scooter) with foot propulsion. The relationships between the robot's body, the tool, and the environment are difficult to solve analytically. The robot should have an ability to adapt and learn to allow it to adjust its posture and dynamics (such as foot motion) to the scooter and environment [Kakiuchi et. al.].

Research has examined a technique known as ***robot fostering***, where skills are transferred to robots through close interaction with humans [Stoica]. This is in contrast to the extremes of achieving robot behavior by either depending mainly on a human's programming for the robot's behavior (and having to foresee all contingencies) or giving the robot a few learning algorithms and sending it into the world to learn everything on its own. The fostering technique is applicable to all forms of robots, but it is most natural where the interaction is between humans and humanoid robots. **Fostering** includes:

- ☐ Humans demonstrating behaviors to robots who then imitate them (e.g., duplicating human arm or leg positions and movement)
- ☐ Robots demonstrating behaviors to robots who then imitate them
- ☐ Humans reinforcing robot behavior through bodily positions and movement
- ☐ Humans providing collaboration and aid to robots in the context of learning experiments (e.g., giving the robot a helping hand or a walker while it is learning to walk)

The Waseda Bipedal Humanoid (WABIAN) robot used human motion through **hand contact** with the robot, as a form of dynamic human-robot interaction, to guide the robot in its walking [Takanishi et. al.].

A few years ago, achieving useful coordination between two factory robotic arms, to manipulate a work piece, for example, was considered advanced technology. **Arm/hand coordination** in a humanoid robot remains a difficult task, especially when it is guided by the robot's vision. There is ongoing research, in a number of laboratories, in arm and hand control for humanoid robots, and there has been progress. A full-bodied humanoid robot, with a real-time vision system, demonstrated the ability to perform **coordinated arm and leg motion** to reach for, and grasp, objects on a table. The robot, when sitting on a chair, could move to grasp an object that was out of reach by changing the upper body posture or standing for a longer reach [Inaba et. al.]. (The robot, however, did not have tactile sensors to sense when it was sitting on a chair). Subsequent research demonstrated **distributed tactile sensors** over a humanoid robot, including hands, fingers, and other "skin" areas [Tajima, et. al.]. The two types of tactile sensors consisted of (1) a less accurate, but wide area, multi-valued touch switch for torso surfaces, and (2) a more accurate, more flexible, and softer conductive gel tactile sensor for geometrically complicated surfaces.

Adonis, an experimental physically simulated humanoid robot torso, demonstrated the *Macarena* dance (largely involving arm and hand motions) to compare two **control techniques** to each other and to human performance [Mataric, et. al.]. The Macarena is a well-defined task that can be precisely specified and evaluated relative to quantitative specifications and qualitative aesthetic judgment as a human performance. One of the two control techniques in the experiment is based on joint-space torques and the other on convergent force fields applied to the hands. A research goal is to develop a control architecture that, in a modular approach, allows various movement primitives (perhaps from different users) to be combined into a versatile and general system for complex, dynamic humanoid motion.

Humanoid platforms at the University of Massachusetts have been used to develop **haptic and visual perception** for reaching and grasping [Coelho et. al.]. The University of Tokyo developed a humanoid upper body able to dribble a bouncing ball, catch a thrown ball, and grope and grasp unknown objects. The arm/hand system is lightweight, with most of the motors built into the arms and torso [Swinson]. **Imitation** (the ability to repeat an observed behavior and learn new skills) is a biologically based process that has been explored as a means of instilling human-type arm movements in humanoid robots [Pomplun and Mataric].

8.4.1 Humanoid Robot Cognition

The appropriate mechanical engineering of legged robots is critical to their ability to walk or run on a variety of surfaces, especially irregular ones. But to perform with (supervised) autonomy, the legged robots – and especially humanoid robots – also need **situational awareness** and the ability to learn, adapt, and make appropriate choices when confronted with threats and opportunities. There are a number of ongoing projects, and various approaches, to develop autonomous intelligent robots regardless of their means of mobility. The NIST 4D/RCS autonomous intelligent control system architecture, for example, is applicable to robotic platforms of all types, whether they have propellers, wheels, tracks, or legs. Some research in cognition, however, is oriented specifically toward humanoid robots.

The label *cognitive developmental robotics* (CDR) has been used to describe a “new” principle for the design of humanoid robots [Asada, et. al.]. The focus of CDR, which is still incomplete in its formulation, is to comprehend the cognitive developmental processes needed by intelligent robots and the means to implement cognition in robots. Physical robots (not just simulated ones) are important because perception and action are considered to be inseparable and tightly coupled. The design of the CDR is centered on:

- ☐ An **embedded structure** in the robot that permits the robot to interact with environment
    - Has an ability to learn and develop
    - Allows new information to emerge from within the robot
- ☐ A **social environment** that supports the development of cognitive processes

Developmental approaches in CDR include **robot shaping** or learning from easy missions (LEM) which can be used to accelerate learning. The robot starts close to the goal state in the state space and is gradually moved further from the goal state as learning progresses. Defined metrics are evaluated to determine when the robot should be introduced to a more difficult learning situation. The process is similar to the way children are taught with age-appropriate environments, where the complexity of the environment is altered and aligned with the developmental stage of the child (robot). A metric to evaluate the **complexity of the environment** is defined in terms of the relationship between the robot’s self-induced motor commands and changes in sensory input. For a humanoid robot to behave intelligently, the complexity of its internal representation should mirror that of the environment [Asada, et. al.]. This is similar to Ashby's Law of Requisite Variety [Ashby], that only variety (the number of distinguishable states of a system) can destroy variety. That is, any control system should be able to generate at least the number of states that can be generated by the system it controls. Control can be imposed on a system either by constraining the variety of the system (a "meat axe" approach) or having a suitably sophisticated control system able to generate sufficient variety. For example, a humanoid robot may be physically constrained from sitting on any chair (if its knee joints could not bend sufficiently, for example), lest it sit on – and squash – a person already occupying the chair; or it may have a the sensing and processing ability to perceive when a chair is already occupied and know not to sit on it. While the CDR approach is to cognition developed, it has not yet been implemented on a physical humanoid robot.

Research on **behavioral-based robot mobility**, with reactive architectures (such as the subsumption architecture), is being extended from emulating insect-level behavior to human-level behavior [Brooks, RAS 20]. In the subsumption architecture, there is no world model filled with objects and relationships, nor are there explicit representations of beliefs, desires, and intentions. But insect-robot behavior cannot be simply extrapolated into humanoid-robot behavior, nor reaction mapped into cognition. Humanoid robots, as cognitive robots (*cognobotics*), require a fundamentally different approach to achieve complex human-like behavior [Brooks]. The nature of the interactions between humans and humanoid robots are especially important, and the humanoid robot should be designed (as in research with MIT's Cog robot) so that humans perceive that the human/robot semiotic interactions, whether with speech or body language, are natural.

There is a growing conjecture in the humanoid research community that **learning through imitation** (*imitation learning*) may be a key approach to developing autonomous humanoid robots [Schaal], although the learning ability of current robots is not yet that of a two year old child. Gradations and types of robot imitative behavior have been defined [Breazeal and Scassellati], where basic imitative behavior is simply the ability of a robot to replicate the movement of a demonstrator. *True imitation* is defined as the ability of a robot to learn a novel task, where it acquires both the goal and the manner of achieving the goal from the demonstration.

An architecture based on a biologically inspired, **neurological** (connectionist) model of visuo-motor processing is being examined for humanoid robot learning through imitation [Billard and Mataric]. The model consists of modules that are high-level abstractions of the spinal cord, the primary and pre-motor cortex, the cerebellum, and the temporal cortex. There are three major parts divided into **seven modules**:

- Learning System
    - Drive module
    - Supplementary motor module
    - Premotor cortex module
- Visual System
    - Attention module
    - Temporal cortex module

- ☐ Motor Control System
  - o Motor control module
  - o Spinal cord module

The research goal is to develop a complete architecture for learning by imitation in a humanoid robot. The result of the experiments was a successful demonstration, albeit a first approximation, of imitative learning. The architecture was validated in a mechanical simulation of a pair of high degree of freedom imitator-imitatee humanoids for learning three types of movement sequences.

In one research example, a real-time **vision system** allows a humanoid robot to learn from, and interact with, humans [Ude, et. al.]. The vision system uses shape and color, in conjunction with a probabilistic approach to tracking objects, to locate objects in the field of view. Various techniques (such as windowing and masking) are used for faster image processing. This perception system is coupled to the motors controlling the humanoid robot's effectors. The robot can, through visual observation of its human instructor, **mimic human hand and head motion** in real-time.

In another approach, a method of **visual search and attention** is used to shift its computational resources and exploratory behavior toward objects in the environment that are of greater immediate importance. The method combines vision processing techniques (e.g., feature detection, depth and color perception, and perceptual classifiers, such as face detectors) with a motivational and behavioral model. If, for example, the robot's task requires interaction with a person, the motivational module increases the weight (importance) of face detection, which initiates the face detection module for vision processing [Adams, et. al.].

The Intelligent Soft-Arm Control (ISAC) robot is designed to work with a human partner or assistant, so it must **interact with people robustly** and communicate its needs and abilities in a natural way [Kawamura, et. al.]. Researchers are developing a flexible, multi-agent based architecture, with short and long-term memory, to allow the robot to learn, recognize individuals, and adapt its behavior accordingly. Initial demonstrations showed that the robot could acknowledge a user's presence and respond to the user based on its current situation and activity. The robot could process the intentions of humans, resolve them with its own intentions and abilities, and communicate to a user if there is a problem with the user's request that the robot perform a task (such as apologizing for being busy, if the user interrupts the robot in a higher priority task).

Imitation learning links the perception of movement to the movement of the robot's effector (such as leg, arm, or hand) movement. The movement is synthesized by coupling sequences of primitive movements generated by modular motor controllers. **Research objectives** in the study of imitation learning include understanding efficient motor learning, the functional relationships between perception and action, and the parallels and differences between biological and computational approaches to imitation. **Research issues** in imitation learning ([Schaal] and [Breazeal and Scassellati]) include:

☐ Determining how representations of the movement of others in visual input can be used to automate movement in a humanoid robot
☐ Determining whether there exists a basic set of primitives to initialize imitation learning and the complexity of the most elementary primitives in the set
☐ Determining whether new movement primitives can be learned and old primitives combined to form higher level primitives
☐ Determining how to recognize and sequence movement primitives
☐ Determining whether the motor system can be used for movement recognition, as well as movement generation, and how to represent movement to allow this dual use of the motor system
☐ Determining whether movement primitives can be, simultaneously, predictive forward models (e.g., mathematical models that predict the time evolution of dynamic systems)
☐ Determining wow the intention of a demonstrated movement can be recognized and converted to the imitator's goal
☐ Determining whether a robot can have the ability to infer the ultimate intent of behavior so that it can imitate the goal of an action rather than the specific act
☐ Determining from whom the robot should learn
☐ Determining when imitative learning is appropriate
☐ Determining whether robots can use social interactions to enhance learning
☐ Determining whether robots should have the ability to question instructors to enhance learning
☐ Determining how a robot should recognize and respond to actions it cannot (or should not) physically imitate (e.g., the instructor sneezes or scratches an itch while showing the robot how to dismantle a mine)

Ultimately, socially adept humanoid robots must be able to detect and understand natural **human cues**, social conventions, and semiotics, so that people do not need special training to interact with the robots (and the robots may also communicate efficiently with each other using common body language). **Anthropopathetic** robots are those that can foster and maintain emotional relationships with humans, able to perceive and respond to human emotion, as well as having an emotional system modeled after humans such that an actual emotional state (and not just a superficial outward expression of emotion) permeates their control architecture and influences their behavior [Swinson].

Empathy is necessary for the complex social interactions of higher animals, including humans. With empathy, a person projects his or her own personality into the personality of another in order to better understand the person's motivations, thoughts, beliefs, desires, perceptions, emotions, and behavior. This process is sometimes flawed, leading to intentional or unintentional misunderstandings, or misleading and fraudulent behavior (which animals other than humans also perpetrate on one another); hence the plethora of lawyers.

However, it may difficult or impossible for robots, even if they are deemed intelligent (i.e., have the ability to make appropriate choices), to consistently make human-like choices. Research on the functioning of the human brain indicates that biochemically-driven human **emotion** may be closely coupled with rationality in the human decision-making process [Damasio]. It is hypothesized that an *emotion* (a change in body state in response to an external stimulus) triggers a *feeling* (the representation in the brain of that change as well as specific mental images). Trembling causes the sensation of fear, not the usually assumed converse. People who have suffered physiological damage to emotional sources in the brain's frontal lobe, but whose IQ scores are high, tend to make poor decisions. A purely rational humanoid robot, without biochemically-derived empathy, may be able to make "intelligent" decisions but not human-like decisions or not exhibit human-like behavior (except perhaps that of sociopathic humans). It may be possible, however, for empathy to be simulated in robots (as a sage once said: "If you can fake sincerity, you have it made").

Research is addressing the question of whether humanoid robots can acquire human-like cognition, like human infants, through **interaction** with their physical and social environments [Ziemke]. That is: could a humanoid robot develop a humanoid *Umwelt* (the environment as it is perceived by the entities inhabiting it)? Could a humanoid robot's semiotic processes become intrinsically meaningful to the robot, so that its mind becomes an actual mind and not merely a model of a mind? Might a humanoid robot have ethics [Harbron]? The Kismet humanoid upper body at MIT is being "raised" as if in child development, with an attempt to have it learn to become socially adept through communication and interaction with people [Overby]. The robot's facial expressions are intended to encourage people to interact with it.

There are even **theological implications** being contemplated by humanoid robot researchers – and the claim that humanoid robot development, especially MIT's Cog project, can be enriched by theological dialogue and insight [Foerst], [Reich]. This approach features an epistemological framework that emphasizes the symbolic nature of reality. The essence of a human may lie not only be in brains or body, but perhaps (even primarily) in social interactions [Foerst]. Perhaps the relationship between human and robot will have implications for understanding the relationship between God and human [Gerhart and Russell].

Whether or not the humanoid robot has actual cognition – or it just perceived as such by human observers – the robot should move appropriately to **replicate human behavior** and thereby facilitate robot/human interactions. The robot's visual system and eye motions should be smooth, for example, capable of saccades, smooth pursuit, vergence, and coordinating the head and eyes through modeling of the human vestibule-ocular reflex, as is the case for MIT's Cog robot [Swinson]. Research into the ethological (i.e., the study of the characteristic behavior of animals) and emotional basis for human/robot interactions is critically important for entertainment robots [Arkin, et. al.], but will facilitate human/humanoid interactions for all applications, including military missions.

An understanding of the psychology of humanoid robots, as well as humans, is needed to incorporate high-fidelity ethological models of behavior into the system and provide a basis for people and robots to relate in predictable ways to each other. A goal is to be able to generate motivational behavior (e.g., emotion) that supports human conceptions of animal behavior in order to nurture a **natural bonding** between the human and the humanoid or other legged robot, such as a canine [Arkin, et. al.]. Ethological studies have led to behavioral models of the dog, which have been mapped into a behavior-based architecture (*emotionally grounded* – or EGO – architecture) of the Sony Aibo quadruped robot. The **EGO architecture** allows the robot to learn new objects and associate their effect on internal motivational and emotional variables that generate instructions of how the robot should behave in the presence of these objects. The EGO architecture was extended by Sony from the Aibo to the humanoid robot, SDR-4X, which has some perception capabilities (e.g., face detection, identification, and stereo vision with obstacle avoidance. Future research will incorporate speech and dialogue ability into the robot, to allow it to understand the meaning of the human's words in relation to the humanoid robot's perceptions, behaviors, capabilities, and needs [Arkin, et. al.].

To **replicate lifelike human behavior**, for example, the humanoid robots should be able to [Swinson]:

☐ Overlap motions in performing tasks (e.g., reaching and grabbing), because this is the way people move
☐ Follow through with additional motion once the task is completed (e.g., grasping an object) and not abruptly stop
☐ Anticipate an action by preparing for it the way people do
☐ Move generally in arcs, because most human body movements are in curved paths
☐ Display ambient motion, because human bodies are rarely completely still
☐ Ease in and out of a movement, because human movements begin gradually, then accelerate before slowing again

For sheer **physical flexibility**, consider the Morph3 humanoid robot, built by the Japanese Science and Technology Corp. It has 28 freely moving joints in a "muscular" humanoid body and is able to perform human-type stretching exercises, such as spreading its legs and touching its toes.

Some researchers expect that **human-like responsive behavior** can emerge only through a "richly integrated" humanoid robot system [Cheng, et. al.]. A humanoid upper body is being used to examine this view, where the **richly integrated system** includes active, real-time stereo vision, binaural (spatial) hearing, proprioceptive systems, and high-performance motor control systems. Experiments are being conducted with the humanoid robot in the context of continuous interaction, active and passive, with its environment and humans. The research is focusing on the ability of the robot to interact with a continuum of stimuli and produce meaningful behavior in response. The control technique being developed is very responsive and provides a system that is adaptable through redundancy, and is flexible. The humanoid upper body has demonstrated the ability to mimic the upper body motion of a person, track a sound source with spatial orientation, and be compliant to physical handling.

Other research is directed toward developing a mechanism that would a humanoid robot to learn **representations of high level tasks**, based on the robot's underlying capabilities (as opposed to the conventional approach of teaching robots to perform tasks by presenting demonstrations of the tasks). The research goal is to enable a robot to automatically build a controller that achieves a particular task from the experience it had while interacting with a human [Nicolescu and Mataric].

In terms of artificial intelligence, humanoid robots may be perceived, by humans, as having human-like behavior whether the behavior is a product of *strong AI* or *weak AI*. **Strong**

AI asserts that it is possible, one way or another, to duplicate human intelligence in machines. **Weak AI** asserts that human intelligence can only be simulated in machines, creating an illusion of intelligence. In the strong case, the machine is intelligent in the sense that it is able to make appropriate decisions as evaluated by objective metrics. In the weak case, the robot displays attributes that facilitate or promote the interpretation, by human observers, that it is intelligent [Duffy]. **Social interactions** between humans and humanoids would be acceptably anthropomorphic in either case, but the robot's ability to be effective in solving real-world problems depends on it mastering strong AI, not merely the tricks of weak AI.

Small (45 cm high) **humanoid robot dolls** (*Robota* robots), with different ethnic and racial characteristics, are being used experimentally to investigate the benefits of their **social interactions** with normal and disabled children, including those with autism. The small humanoid robots have 3 superimposed computer boards that drive 6 motor outputs, 24 sensor entries (16 analog and 8 digital) and sensors, including 4 infrared emitters/receivers, 2 light detectors, 1 video camera, 2 pyroelectric sensors, 6 switches, and 2 electromagnets. Linked to a PC or PocketPC, a robot can perform image processing and speech processing and synthesis [Billard].

The usefulness of **sentience** (including emotion as well as perception) in humanoid robots is believed, by many researchers, to be important in direct proportion to the proximity of the robots to humans while performing their tasks [*Sentience in Robots: Applications and Challenges*]. For example, robots nursing the elderly should have sentience, or at least semi-sentience, while sentience would likely be a disadvantage for a lone robot tending a space station.

8.5 Summary of the State of the Technology

In recent years there has been **significant progress** in the technology of bipedal humanoid and other legged robots (primarily hexapods and quadrupeds). Teleoperation (and telepresence) of legged robots is feasible in the near-term and militarily useful. A number of tools, including genetic algorithms, neural networks, expert systems, vision-based walking, and various kinds of control algorithms, are being developed for optimal gait control. Many of these techniques will enable humanoid robots to learn complex tasks in uncertain environments without the need for programmers to foresee every contingency. Methods for intelligent control and robot cognition are improving. And humanoid robots are becoming more lifelike in their movement and ability to interact with humans. Nevertheless, **more progress** is needed for humanoid robots to be able to perform a variety of military missions. For 21st century humanoid and legged robots, the state of technology in 2003 is the equivalent of the state of automotive technology in 1903. This is not necessarily discouraging, given the rapid technological and social progress of the automobile over the first two decades of the 20th century – and the reduction in cost. While the autonomous humanoid robot is far more complex than the 1903 automobile, the 2003 technology infrastructure is also comparably more advanced than its 1903 counterpart. With sufficient user demand, the humanoid robot can be elevated to competence like the Model T Ford, where the 239 cars that were sold in 1908 increased to more than a million cars sold in 1927. And just as World War I accelerated automotive technology, the war on terrorists will accelerate the development of humanoid robot technology.

9.0 ROADMAP

As we have seen, there is pervasive research and development of humanoid and legged robots, albeit scattered worldwide. While Japanese humanoid robots excel in bipedal **locomotion** and can walk smoothly and climb stairs, they are insufficiently robust and flexible for most real-world applications. Their upper body, arm, and hand abilities are also weak and ineffectual. While these humanoid robots are intended, ultimately, for such commercial applications as patient care and household chores, they have neither **situational awareness** nor a useful level of **autonomous intelligence**. The U.S. has been in the forefront of research in sensors, sensor processing, autonomous intelligent control systems, and human/machine interfaces, all of which can be applied to the development of advanced humanoid and other legged robots suitable for military applications.

It is generally important for developers of military technology and systems to identify **potential users** who want what they are developing, lest their earnest projects disappear forever into a sinkhole. But it is often difficult to educate prospective users about novel technology and convince them of the benefits of something they never seen before. However, the military units dedicated to Explosive Ordnance Disposal have had many years of experience with robots. Typically, EOD robots are purely teleoperated wheeled or tracked platforms with a robotic arm and end effector able to manipulate suspicious ordnance.

Recently the U.S. Army's EOD Technical Detachment at Indianhead, Maryland, issued the U.S. military's first known **Mission Needs Statement for a humanoid robot**, as shown in **Figure 9-1**. And EOD personnel, whom we contacted, are eager to cooperate with a potential DARPA-sponsored project to develop a humanoid robot that will satisfy their needs. (Note that the most promising application for humanoid robots in our survey of users was countermine operations). While the **MOUT scenario** seems to be an especially compelling context in which to introduce the military to the worth of humanoid robots, the **EOD scenario** also makes a strong case for humanoid robots – and the demand pull of the user makes it more convincing than would technology push by itself. Of course, an EOD scenario can be devised *within* a MOUT environment to demonstrate the military worth of humanoid robots – with twice the impact.

The **prospective EOD users** would like a humanoid to be able perform certain functions, some of which may be somewhat difficult to accomplish in the near term (e.g., jumping 3 feet from a hovering helicopter onto soft soil). But they are willing to compromise and can work with humanoid robots that are able to satisfy at least some (if not all) of their needs. They will provide EOD personnel to help guide a development project from the user perspective, as well as facilities for test and evaluation. Most importantly, the EOD community offers immediate **credibility** – and a home – for a project to develop humanoid robots (and perhaps quadruped robots as well). Along with countermine and unexploded ordnance applications, the EOD mission also encompasses **counter-terrorism and homeland defense**, which includes civil law enforcement users of EOD equipment. We can assemble a **large community of stakeholders** to support the development of humanoid robots.

Figure 9-1: EOD Mission Needs Statement

NOTIONAL CONCEPT #5-03: *HUMANOID ROBOT*

STATEMENT OF NEED: A need exists for a robotic platform that is capable of climbing narrow stairs, climbing ladders, opening doors/hatches, and self-loading itself for transport. There is currently no capability to examine devices placed in locations that require climbing, such as water towers, ships' holds, or roofs. The humanoid robot would be capable of climbing both ship and land-based ladders. A humanoid robot would alleviate a need for the robot to be light for transportation, since it would be able to stow itself into an EOD response vehicle. A humanoid robot would also be capable of emplacing a disrupter tool or x-ray rather than the current methodology of mounting the disrupter on the tracked or wheeled robot.

THREAT: All IEDs and UXOs both foreign and domestic.

INADEQUACIES OF CURRENT SYSTEMS: Currently the services use tracked or wheeled robots. The current systems are heavy, weighing several hundred, if not thousands, of pounds, and are not capable of traversing all types of terrain or climbing ladder. The weight of these robots is important because personnel are expected to load the robot into a transport vehicle. The tracked and wheeled robots also move slowly and are expensive to operate. They have limited capability to emplace and aim a disrupter and no capability if the device is on a tower or roof.

PROPOSED APPROACH: This effort should examine if any COTS humanoid robots currently available that can be transitioned to EOD use. The pursued technology should leverage the "Land Warrior" type of control mechanism. Ideally, the hardened robot should be capable of a 3 foot jump/fall from a hovering helicopter onto soft soil. The robots gripper mechanisms should be capable of grasping the components of all current disrupters for assembly and they should have operator feedback sensitivity. The robot should have visual and auditory feedback capability. The robot should also be capable of carrying the EOD tools or X-ray down to the suspect item. The robot must be capable of being decontaminated. The robot must be able to self right itself should it fall or become knocked over. It should also have the capability of running a self diagnostic/prognostic. The robot should be able to operate in the temperature range of -10F -- + 100F for a minimum of 2 hours.

CURRENT EXAMPLES OF THIS TECHNOLGY:_Four known examples of this technology are: Sony SDR-4X, Honda Asimo, Fujitsu HOAP-1, and Dr. Robot (manufacturer unknown)

POC: LTC Bob Klimczak, U.S. Army EOD Technical Detachment, 2008 Stump Neck Rd., Indian Head, MD 20640. Phone 301 744-6820. e-mail robert.klimczak@us.army.mil

As we have seen, there are a number of research and development projects focused specifically on humanoid and legged robots. There are also projects to develop other kinds of robotic platforms, such as the Future Combat System, Tactical Mobile Robot, Mars Rover, and Demo III, where the technology and subsystems are often relevant to legged robots. **Figure 9-2** shows a rough characterization of the **state of bipedal humanoid robot technology**. The figure lists the functional robotic systems (in the first column) and their associated subsystems (in the second column), as previously described. The **three cases** represented in the final three columns are: teleoperated humanoid robots (which may be employed in various missions); autonomous humanoid robots for EOD missions; and autonomous humanoid robots for MOUT missions. The **color coding** of the systems and subsystems has no significance other than for convenient visualization of the grouping of the systems with their subsystems. However, the **color coding** in the columns for the three mission cases represents the **Technology Readiness Levels** (TRL) of the subsystems for those missions.

The **TRL are defined** by the Army Tank Automotive Command as:

☐ **TRL 1:** Basic principles observed and reported
☐ **TRL 2:** Technology concept and/or application formulated
☐ **TRL 3:** Analytical and experimental critical functions and/or characteristic proof of concept
☐ **TRL 4:** Component and/or breadboard validation in laboratory environment
☐ **TRL 5:** Component and/or breadboard validation in relevant environment
☐ **TRL 6:** System/subsystem model or prototype demonstration in a relevant environment
☐ **TRL 7:** System prototype demonstration in an operational environment
☐ **TRL 8:** Actual system completed and "flight qualified" through test and demonstration
☐ **TRL 9:** Actual system "flight proven" through successful mission operations

The **color coding** of **Figure 9-2** is our representation and aggregation of the TRL as:

☐ Red: TRL 1 to TRL 3
☐ Yellow: TRL 4 to TRL 6
☐ Green: TRL 7 to TRL 9

The TRL coding in the figure refers to technology that is suitable for the application under consideration, whatever the origins of the technology (i.e., the technology need not have been developed specifically for humanoid robots). Of course, there is more technology that is available for teleoperated humanoid robots (which may perform a variety of missions) than is available for autonomous EOD or MOUT missions; and much of that technology has already been demonstrated in the past for teleoperated robotic vehicles. The **control system architecture** is deemed to be green (at least TRL 7) for all the cases, based on the performance of the 4D/RCS in Demo III. Some of the subsystems are more ready for teleoperation (such as sensor processing) than for autonomy, because teleoperation allows the human operator to do what technology cannot. In general, the **EOD mission** has higher TRL scores than the MOUT mission because it generally will take place in a constrained environment with well-defined tasks, and under close supervision by a human EOD expert.

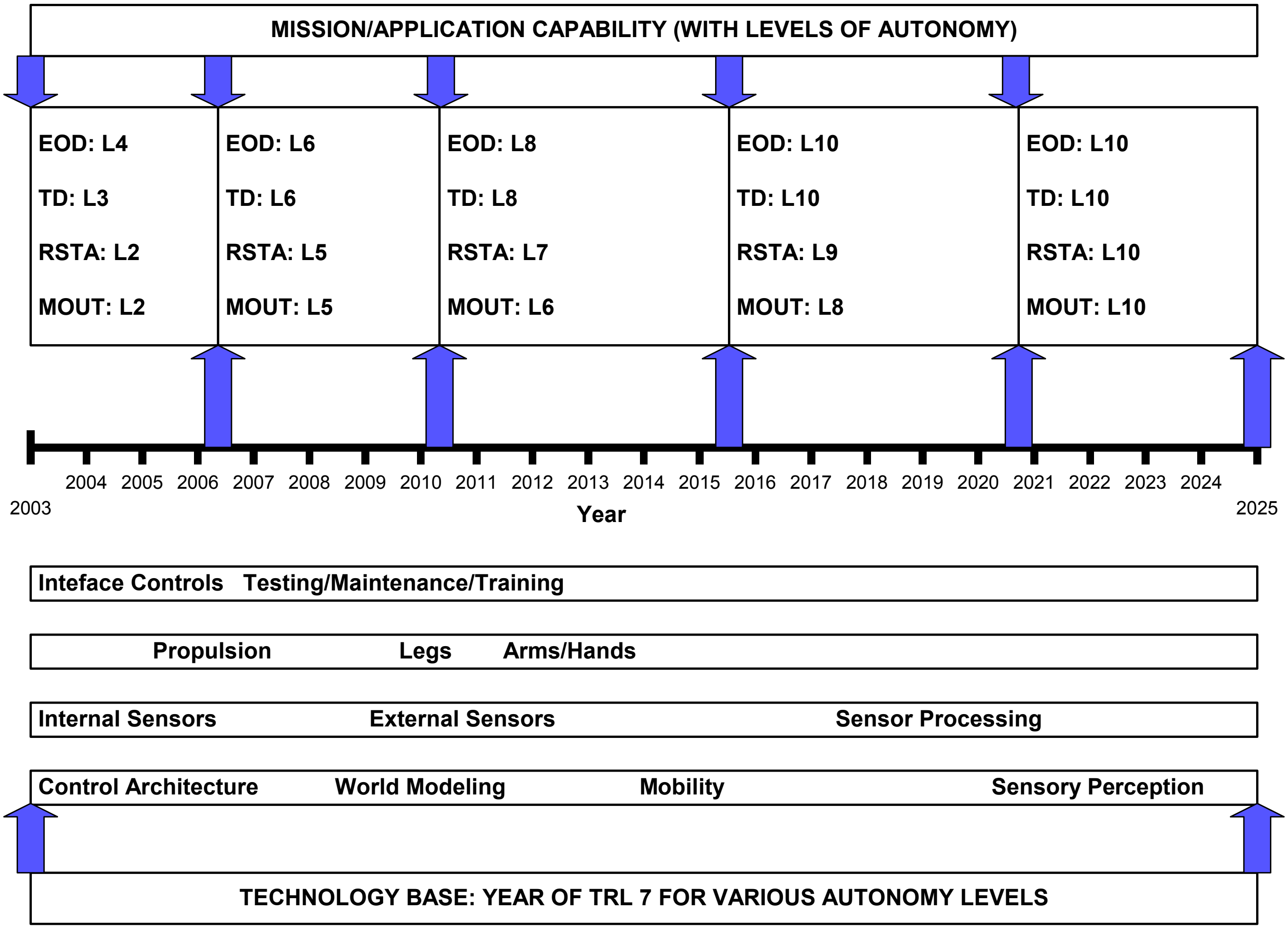
Figure 9-2: Humanoid or Legged Robot TRL for Teleoperation, EOD and MOUT

[Functional Decomposition]		Teleoperation	EOD	MOUT
Control Systems	Architecture	🟩	🟩	🟩
	Software Tools	🟨	🟥	🟥
	Perception	🟩	🟨	🟥
	Databases & World Modeling	🟩	🟥	🟥
	Internal & External Comm.	🟨	🟩	🟨
		🟨	🟨	🟥
	e Architecture	🟩	🟩	🟨
Sensor Systems	Internal & External Sensors	🟨	🟨	🟨
	Sensor Processing	🟩	🟨	🟥
	Architecture	🟩	🟨	🟨
Effector Systems	Platform & Mobility Design	🟨	🟨	🟥
	Structural Dynamics/ Kinematics	🟨	🟨	🟥
	Manipulators & End Effectors	🟨	🟨	🟥
	Systems	🟨	🟨	🟨
Human	Controls & Displays	🟨	🟨	🟨
		🟨	🟨	🟥
	Maintenance & Support	🟨	🟨	🟥
		🟨	🟨	🟥

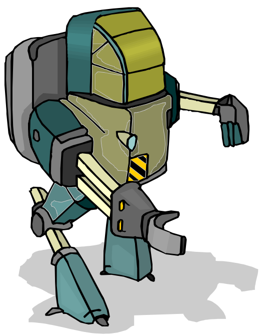
A **short-term roadmap** for developing a humanoid robot for the EOD mission includes:

- ☐ Monitor ongoing progress in humanoid and legged **robot research and development** in university and government laboratories worldwide
    - Literature, conferences, on-line, and direct conversations with researchers
    - Focus on technology below TRL 7
- ☐ Define the user's **functional requirements** in conjunction with the U.S. Army EOD Technical Detachment at Indianhead, Maryland
    - Design realistic **scenarios** in which useful EOD mission can be accomplished by a near-term prototype humanoid robot
- ☐ Use **Quality Function Deployment** to relate the user's needs to the design of a humanoid robot
    - Generate and evaluate functional requirements and solution alternatives using the Quality Function Deployment method (QFD) by specifying the user's functional requirements (*wants* and *needs*) explicitly and with the graphic conventions of the QFD. Compare requirements, systematically and graphically, with prospective technologies, systems, components, or services able to satisfy the requirements. Using QFD, construct one or more matrices (*quality tables*), the first matrix being the House of Quality (HOQ), which represents the voice of the customer
- ☐ Employ **multifunctional/multidisciplinary design optimization** (MDO) procedures and tools to design a humanoid robot
    - MDO is a body of methods and techniques (including machine intelligence and simulation tools) for the design of complex engineering systems and subsystems that coherently exploits the synergism of mutually interacting phenomena [from a NASA definition]
    - MDO is used extensively by NASA in the design of complex aerospace vehicles and it would be suitable for the design of complex humanoid robots
- ☐ Select a **commercially-available** humanoid robot as a basic platform for a **near-term demonstration**, if it sufficiently *feasible* to satisfy the defined user requirements
    - Integrate a suitable control system, such as the 4D/RCS, able to provide teleoperation and autonomous intelligent control
    - Integrate a suitable power source, such as an internal combustion engine or fuel cells, to replace the battery power of a commercial humanoid robot
    - Integrate additional sensors, such as a ladar, onto the humanoid robot as needed
- ☐ Perform ongoing **technology assessments and risk mitigation analyses** of the humanoid robot technologies, subsystems, and system to ensure that the robot will perform as expected in the context of the user's functional requirements and mission scenario
    - Employ the Risk Breakdown Structure (RBS) method, which involves a hierarchical structuring of risks on a project, to identify, assess, and mitigate risks, as well as using the risk assessment matrix tools favored by DOD
- ☐ Design (or adapt) models and **simulations** for the humanoid robot
    - Integrate the control system with the simulation
    - Develop and test the control system software in the simulator
- ☐ Design a **field test** to validate the simulated robot's performance with the physical robot
- ☐ **Demonstrate** the physical humanoid robot performing the selected EOD tasks

Figure 9-3: ROADMAP FOR HUMANOID/LEGGED TECHNOLOGY AND PERFORMANCE



EOD: L4	EOD: L6	EOD: L8	EOD: L10	EOD: L10
TD: L3	TD: L6	TD: L8	TD: L10	TD: L10
RSTA: L2	RSTA: L5	RSTA: L7	RSTA: L9	RSTA: L10
MOUT: L2	MOUT: L5	MOUT: L6	MOUT: L8	MOUT: L10



The illustration of a **longer-term roadmap** in **Figure 9-3** shows a timeline from 2003 to 2025. We selected, as representative, three humanoid or legged robot military missions or applications chosen as particularly desirable by the experts or users in their respective surveys. The missions are: Explosive Ordnance Disposal or countermine (EOD); Target Designation (TD); Reconnaissance, Surveillance, Target Acquisition (RSTA); and Military Operations in Urban Terrain (MOUT). Over time, each mission can be accomplished by humanoid (or legged hybrids, etc.) robots with increasing autonomy as allowed by the technology base. The levels of autonomy are characterized by the defined nomenclature of the FCS program, as shown previously in **Table 7-1**. For example, the Level 4 (L4) characterization of autonomy means that the humanoid (or other legged robot) has knowledge of the local environment and suitable perception from the sensor suite, can negotiate simple environments, but still requires operator intervention. While the FCS levels of autonomy were defined originally for robotic *vehicles*, they can be adapted readily for *legged* robots. The widths of the boxes (that enclose the missions shown in **Figure 9-3**) represent time intervals; the capabilities predicted in each box will be achieved by the end of each interval. The roadmap assumes continuous and appropriate support for development and demonstration of the technology and systems.

For example, with a development program beginning in 2003, the EOD mission could be demonstrated at autonomy Level 4 (L4) by 2006, while the TD mission could be demonstrated at L3 in 2006, and the RSTA and MOUT missions at L2. The demonstrations could be at TRL 6 or higher. We are characterizing the levels of autonomy in the roadmap only for humanoid or other legged robots, which may differ in the timeline from autonomy levels achievable by robotic vehicles. The figure depicts the evolution of autonomy for each selected mission. Humanoid robots able to perform the EOD/countermine mission evolve faster toward full autonomy (L10) than, for example, the MOUT mission, because the EOD environments and objects of interest are simpler and less numerous. EOD humanoid robots, according to our forecast, achieve L6 by 2010, L8 by 2015, and L10 by 2020. All of the selected missions achieve L10 by 2025.

We emphasize that **each level of autonomy** (or semi and supervised autonomy), even a lower one, represents **militarily useful capabilities**, depending mainly on how the robots are employed. For example, an EOD or RSTA humanoid robot at autonomy Level 2 (L2), where the robot is teleoperated but has state knowledge, inserts a machine in harm's way, instead of a person, and allows the machine to interact with the environment, threats, and opportunities in a humanoid form. There is **military worth** all along the timeline.

Figure 9-3 also depicts the **technology base** that supports the evolving development of autonomous intelligent humanoid and legged robots. As in the previous function decomposition, the technology base is divided into: control systems, sensor systems, effector systems, and human/machine interfaces. For each case, it is a high level of technology achievement that is represented in the figure. We assume that the technology is at TRL 7 for the most difficult and stressing of the missions (such as MOUT). The control system architecture, for example, can be largely accomplished (at TRL 7) by 2006 or so, while sensory perception won't be fully achieved until 2021 or later. A technology, for example, may be sufficient for a TRL 6 demonstration of an EOD robot, but not a RSTA robot.

In the figure, note that we are assuming TRL 6 for the humanoid systems, but TRL 7 for the underlying technologies; this provides a better probability of success for system demonstrations. The technologies may achieve TRL 7 before they are incorporated into humanoid platforms because they have been demonstrated, in an operational environment, as part of a robotic vehicle.

Humanoid robots may have sufficient legged mobility to perform EOD missions by 2006, but their legged mobility (which depends on the engineering design of the legged system as well as the intelligent control of that system) won't allow then to scramble with human (or better) speed and dexterity over city rubble and through buildings until about 2015. If a technology is developed successfully and integrated into humanoid robots, it does not mean that further improvements and refinements cannot take place over time (although the technology improvement process is not represented in the figure). For example, a suitable propulsion system (one that is at TRL 7 for the most stressing mission) could be incorporated into a humanoid robot by 2006 (using, perhaps, a small heavy fuel engine developed as the propulsion system for small UAVs). While small engine technology will continue to be improved over time, it will have sufficient military worth for humanoid robot applications before the end of this decade.

It is feasible – and sensible – to begin a humanoid (and other legged) robot program for military applications immediately, where products with great military (and civilian) worth will become available within this decade; and where fully autonomous humanoid robots, with human-like physical strength and agility and advanced cognitive abilities, will be operational in a little more than two decades.

APPENDIX A: PROSPECTIVE AND ACTUAL SURVEY EXPERTS

(PARTICIPANTS ARE SHOWN IN *ITALICS*)

Albus, James
Intelligent Systems Division
National Institute of Standards and Technology
301-975-3418
james.albus@nist.gov

Arkin, Ronald
College of Computing
Georgia Institute of Technology
404-894-8209
arkin@cc.gatech.edu

Asada, Harry
Massachusetts Institute of Technology
asada@mit.edu

Atkeson, Chris
Robotics Institute
Carnegie Mellon University (CMU)
412-681-8354
cga@cmu.edu

Bekey, George
University of Southern California
bekey@usc.edu

Bosworth, Joe
Personal Robot Technologies, Inc.
413-684-0850
jbosw@earthlink.net

Book, Wayne
Dept. of Mechanical Engineering
Georgia Institute of Technology
wayne.book@me.gatech.edu

Breazeal, Cynthia
Artificial Intelligence Laboratory
Massachusetts Institute of Technology
Cynthia@ai.mit.edu

Brooks, Rodney
Artificial Intelligence Laboratory
Massachusetts Institute of Technology (MIT)
617-253-5223
brooks@ai.mit.edu

Brown, Constant
General Robotics Inc.
cbrown@generalrobotics.com

Browning, Brett
CMU
412-268-6021
brettb@cs.cmu.edu

Bruemmer, David
Idaho National Engineering Laboratory
bruedj@inel.gov

Cerny, Jeff
Army & Missile Research, Development & Engineering Center (AMRDEC)
US Army Aviation and Missile Command (AMCOM)
256-876-2607
jeff.cerny@rdec.redstone.army.mil

Charuhas, Thomas
Anybots, Inc.
650-248-9341
thomas@anybots.com

Chun, Wendell
Lockheed Martin Corp.
303-971-7945
Wendell.h.chun@lmco.com

Crane, Carl
University of Florida
352-392-9461
ccrane.ufl.edu

Culbert, Chris
NASA Johnson Space Center (JSC)
281-483-8080
chris.culbert@jsc.nasa.gov

DiAntonio, Steve
Robotics Institute
Carnegie Mellon University (CMU)
sda@rec.ri.cmu.edu

Dietsch, Jeanne
Active Media Research Inc.
research@activmediaresearch.com

Dobell, Colin
Inuktun Inc.
cdobell@inuktun.com

Doty, Keith
Mekatronix Inc.
doty@mekatronix.com

Drobot, Adam
SAIC
drobota@saic.com

Dubowsky, Steve
Massachusetts Institute of Technology
dubowsky@mit.edu

Finkelstein, Robert
Robotic Technology Inc.
301-983-4194
robertfinkelstein@compuserve.com

Foley, Joe
Aerospace and Engineering Division
Jackson & Tull
jfoley@jnt.com

Giovanetti, Anthony
United Defense, LP
anthony_giovenetti@udlp.com

Greiner, Helen
iRobot
info@irobot.com

Grupen, Roderic
Computer Science Dept.
University of Massachusetts, Amherst
413-545-3280
grupen@cs.umass.edu

Jacobsen, Steve
Sarcos, Inc.
s.jacobsen@sarcos.com

Juberts, Maris
Intelligent Systems Division
National Institute of Standards and Technology
juberts@cme.nist.gov

Kawamura, Kazuhiko
Vanderbilt University
kawamura@vuse.vanderbilt.edu

Kazerooni, Homayoon
Dept. of Mechanical Engineering
University of California, Berkley
kazeroon@me.berkley.edu

Khatib, Oussama
Dept. of Computer Science
Stanford University
650-723-9753
khatib@cs.stanford.edu

Khosla, Pradeep
Carnegie Mellon University
pkk@ece.cmu.edu

Kortenkamp, David
NASA Johnson Space Center
korten@smtp.traclabs.com

Kumar, Vijay
University of Pennsylvania
kumar@grip.cis.upenn.edu

Lavery, Dave
NASA Hq.
dlavery@hq.nasa.gov

Lay, Keith
Robotics Dept
Caterpillar Corp.
laynk@cat.com

Lee, George
Purdue University
csglee@purdue.edu

Leifer, Larry
Stanford University
leifer@cdr.stanford.edu

Mahadevan, Sridhar
Computer Science Dept.
University of Massachusetts
mahadeva@cs.umass.edu

Mandelbaum, Robert
Sarnoff Laboratory
mandelbaum@sarnoff.com

Mataric Maja
USC Robotics Research Laboratory
Computer Science Dept. & Neuroscience Program
University of Southern California
213-740-5420
mataric@usc.edu

Meyrowitz, Alan
Artificial Intelligence Center
Naval Research Laboratory
alanm@aic.nrl.navy.mil

Moravec, Hans
Computer Science Dept.
Carnegie Mellon University
hpm@cs.cmu.edu

More, Grinnell
iRobot
gm@irobot.com

Murphy, Robin
Dept. of Computer Science
University of South Florida
Murphy@csee.usf.edu

Norman, Christopher
iRobot Corp.
781-345-0200
Norman@irobot.com

Orin, David
Dept. of Electrical Engineering
Ohio State University
614-292-3064
orin.1@osu.edu

Paluska, Daniel
Yobotics, Inc.
617-504-9619
leinad@yobotics.com

Peters, Alan
Vanderbilt University
Rap2@vuse.vanderbilt.edu

Pratt, Jerry
Institute for Human and Machine Cognition
University of West Florida
850-202-4481
jpratt@ai.uwf.edu

Rumpf, Richard
Rumpf & Associates
drumpf@rumpfassociates.com

Savely, Robert
NASA JSC
281-483-8105
robert.t.savely@nasa.gov

Schaal, Stefan
University of Southern California
213-740-9418
sschaal@usc.edu

Shaker, Steven
Evidence Based Research, Inc.
703-287-0305
shaker@ebrinc.com

Shanker, Sastry
University of California, Berkely
sastry@eecs.berkely.edu

Simonds, Todd
Redzone Robotics
jtodd@redzone.com

Spencer, Martin
Gecko Systems Inc.
mspencer@geckosystems.com

Stavridou, Victoria
Computer Science Laboratory
SRI International
Victoria@sdl.sri.com

Stentz, Tony
Carnegie Mellon University
tony+@cmu.edu

Swinson, Mark
Sandia National Laboratories
505-845-9642
mlswins@sandia.gov

Thorpe, Charles
Robotics Institute
Carnegie Mellon University
Thorpe@ri.cmu.edu

Toscano, Mike
Office of the Secretary of Defense
michael.toscano@osd.mil

Van Atta, Richard
Institute for Defense Analysis
703-845-2318
rvanatta@ida.org

Volpe, Richard
Jet Propulsion Laboratory
NASA
volpe@jpl.nasa.gov

Voyles, Richard
Dept. of Computer Science
University of Minnesota
612-625-8306
voyles@cs.umn.edu

Wade, Robert
Software Engineering Directorate
Army & Missile Research, Development & Engineering Center (AMRDEC)
US Army Aviation and Missile Command (AMCOM)
robert.wade@sed.redstone.army.mil

Waldron, Ken
Stanford University
Waldron@cdr.stanford.edu

Whittaker, Red
Robotics Institute
Carnegie Mellon University
red@ri.cmu.edu

Wilcox, Brian
Jet Propulsion Laboratory
NASA
brian.h.wilcox.nasa.gov

Will, Peter
Information Sciences Institute
University of Southern California
will@isi.edu

Xiao, Jing
Intelligent, Multimedia, and Interactive Systems Lab
College of Information Technology
University of North Carolina, Charlotte
xiao@uncc.edu

Yim, Mark
Palo Alto Research Center
650-812-4806
yim@parc.com

Young, Suzy
Army & Missile Research, Development & Engineering Center (AMRDEC)
US Army Aviation and Missile Command (AMCOM)
256-876-3336
suzy.young@rdec.redstone.army.mil

Yun, Xiaoping
Department of Electrical and Computer Engineering
Naval Post Graduate School
yun@nps.navy.mil

APPENDIX B:

SURVEY FORM
FOR SURVEY OF ROBOT EXPERTS

SURVEY ON HUMANOID ROBOTS

BACKGROUND

Robotic Technology Inc. (RTI) is performing a study for the Defense Advanced Research Projects Agency (DARPA) concerning a technology assessment of **bipedal humanoid robots** and other legged robots. DARPA (Dr. Alan Rudolph, DSO Program Manager) is interested in determining whether humanoid (and other legged robots) are technologically and economically feasible and can serve as tactically useful military systems. The results of this study may lead to DARPA support for the development of humanoid robots for military applications.

There are a number of ongoing programs in the Department of Defense (DOD) for the development of combat robotics, but they emphasize the development wheeled or tracked vehicle platforms, not humanoid robots. But the world of **artifacts** is designed by humans for humans – such as tools, buildings, and vehicles. A humanoid robot, with biped legs, dexterous arms and hands, and sufficient intelligence, could function smoothly in that world. In the **natural environment**, military wheeled and tracked vehicles can operate on about 30% to 50% of the earth's land surface. Legged organisms and machines, including bipedal humanoids, can travel over nearly the entire land surface. Current developmental humanoid robots do not yet have cognition and situational awareness, so they are limited in their autonomous interaction with the environment (as well as lacking human-like proficiency in their basic motions). This **technology assessment** will examine their prospective military worth and the feasibility of achieving militarily useful behavior in the near to far term (e.g., years 2003 - 2030), and, if humanoid robots are worthwhile, to provide a technology roadmap for reducing developmental risk and eliminating technology gaps.

This survey is part of the overall study. We will also request **interviews** with some of the recipients of this survey in order to explore key issues in greater depth. You were selected to receive this survey because we understand that your experience is relevant to this topic; if it is not, we apologize for any inconvenience. We and DARPA appreciate your participation in this survey, and **you will receive a summary of the results** as an incentive for sharing your experiences and opinions.

Please rely on your own **knowledge, experience, and opinions** to answer the survey questions. **Please complete the survey and email (preferable), snail-mail, or fax it to:**

Dr. Robert Finkelstein
Robotic Technology Inc.
11424 Palatine Drive
Potomac, Maryland 20854-1451 USA
(301)-983-4194 Voice
(301)-983-3921 Fax
RobertFinkelstein@compuserve.com

Thank you very much for your help.

EXPERT SURVEY ON HUMANOID ROBOTS

Last Name____ First____________________

Organization____

Address ____

____

Phone________________________ Email _______________________________________

(1) Please summarize your experience relevant to robotics or humanoid robotics technology:

(2) In your opinion, characterize the **current state of technology** for the successfully development of military humanoid robots. Please place an "X" on the appropriate position along the scale:

/---------/---------/---------/---------/---------/---------/---------/---------/---------/--------/
0 1 2 3 4 5 6 7 8 9 10
Poor Satisfactory Excellent

Comments (if any):

(3) By what **year** will humanoid robot **technology** be **at least satisfactory** for the successful development of supervised autonomous military humanoid robots? Please place an "X" on the appropriate position along the scale:

/---------/---------/---------/---------/---------/---------/---------/---------/---------/--------/
2003 05 07 09 11 13 15 17 19 21 >21
Year

Comments (if any):

(4) What is your expectation of the U.S. military's use of supervised autonomous humanoid robots by **2020**? Please place an "X" on the appropriate position along the scale:

/---------/---------/---------/---------/---------/---------/---------/---------/---------/--------/
0 1 2 3 4 5 6 7 8 9 10
Not in Use Used in Several Applications Ubiquitous in the Military

Comments (if any):

(5) Which humanoid robot **applications**, **missions,** or **combat functions** (not all mutually exclusive) are **most promising** for the U.S. military? Please score each of the choices, from 1 (most promising) to 15 (least promising):

Reconnaissance, Surveillance, Target Acquisition (RSTA) ______
Driving or Piloting Vehicles ______
Infantry (e.g., Operating Small Arms) ______
Operating Direct Fire Weapons (e.g., Tank/Antitank) ______
Operating Indirect Fire Weapons (e.g., Artillery) ______
Military Operations in Urban Areas ______
Countermine Operations ______
Target Designation (e.g., with laser designators) ______
Logistics/Material Handling ______
Air Defense ______
Special Forces/Counter-Terrorism ______
Satellite Operations/Space Exploration ______
Other (Explain) ______

Comments (if any):

(6) By what **year** will humanoid robots have a significant impact on **the U.S. military** (e.g., commonly performing functions and missions)? Please insert your estimate of the year for each case below:

Optimistic Year ___________
Pessimistic Year __________
Most Likely Year _________

Comments (if any):

(7) Considering all types of **legged supervised autonomous robots**, which are potentially the **most useful** to the U.S. military. Please rank the alternatives from 1 (the most important) to 5 (the least important):

Bipedal humanoid __________
Bipedal non-humanoid __________
Quadruped __________
Hexapod __________
Hybrids (e.g., quadruped with arms, etc.) __________

Comments (if any):

(8) Considering all types of supervised **legged autonomous robots**, which are potentially the **most difficult** to develop into useful systems for the U.S. military. Please rank the alternatives from 1 (the most difficult) to 5 (the least difficult):

Bipedal humanoid __________
Bipedal non-humanoid __________
Quadruped __________
Hexapod __________
Hybrids (e.g., quadruped with arms) __________

Comments (if any):

(9) What is your estimate of **the cost** (in today's dollars) of a militarily useful supervised autonomous **humanoid** robot by **2020**? Please insert your estimate of the unit cost (in dollars) for each case below:

Optimistic cost ______________
Pessimistic cost ______________
Most likely cost ______________

Comments (if any):

(10) What is your estimate of **the cost** (in today's dollars) of a militarily useful supervised autonomous **quadruped or hexapod** robot by **2020**? Please insert your estimate of the unit cost (in dollars) for each case below:

Optimistic cost ______________
Pessimistic cost ______________
Most likely cost ______________

Comments (if any):

(10) Which **key technologies** need the most research and development in order to achieve significant improvements in supervised autonomous humanoid robotics? Please score each of the choices from 1 (needs the **most** R&D) to 11 (needs the **least** R&D):

Sensors _______________
Sensor processing _______________
Computer software _______________
Software tools _______________
Control system architectures _______________
Databases and world modeling _______________
Bipedal leg control/balance/mobility _______________
Arms and end effectors _______________
Computer hardware and hardware architecture _______________
Propulsion and energy systems _______________
Human/Robot interfaces _______________
Other (please describe) _______________

Comments (if any):

(11) By which **year** will supervised autonomous humanoid robots be able to demonstrate ***all*** of the following example behaviors: **(1) manipulation:** load, aim, and shoot a rifle; unlock a door with a key; collect environmental samples; disable explosives; cut the pant leg of a wounded soldier and apply appropriate pressure to a wound; **(2) perception and cognition:** locate and map suitable foot placement; **(3) dynamics:** compute posture and balance; **(4) legs:** carry loads of practical size and weight over uneven terrain. (Please place an "X" on the appropriate position along the scale)?

/---------/---------/---------/---------/---------/---------/---------/---------/---------/--------/
2004 06 08 10 12 14 16 18 20 22 >22
Year

Comments (if any):

(12) By which **year** will supervised autonomous humanoid robots be able to demonstrate ***all*** of the following example behaviors: **(1) manipulation:** pick up and carry a wounded soldier to safety; give injections and IVs to the wounded; apply telemedicine intervention; change a tire; **(2) perception and cognition:** detect, classify, and track moving objects, including humans and vehicles; interact safely with humans; **(3) dynamics:** run, jump, and crawl; fall safely and get up; **(4) legs:** operate in an outdoor urban environment with tactical posture and gait. (Please place an "X" on the appropriate position along the scale)?

/---------/---------/---------/---------/---------/---------/---------/---------/---------/--------/
2004 06 08 10 12 14 16 18 20 22 >22
Year

Comments (if any):

(13) By which **year** will supervised autonomous humanoid robots be able to demonstrate ***all*** of the following example behaviors: **(1) manipulation:** rescue victims from rubble and wreckage; suture wounds; **(2) perception and cognition:** analyze many tactical and other situations, solve problems, and devise solutions; **(3) dynamics:** climb, rappel, and parachute; **(4) legs:** operate in an outdoor urban environment with tactical posture and gait. (Please place an "X" on the appropriate position along the scale)?

/---------/---------/---------/---------/---------/---------/---------/---------/---------/--------/
2004 06 08 10 12 14 16 18 20 22 >22
Year

Comments (if any):

(14) What minimum level of autonomy is needed for most practical militarily applications of humanoid or other legged robots? Please place an “X” on the appropriate position along the scale:

```
  /---------/---------/---------/---------/---------/---------/---------/---------/---------/--------/
  0         1         2         3         4         5         6         7         8         9        10
Full Teleoperation                  Semi-Autonomy                              Full Autonomy
```

Comments (if any):

(15) In your opinion, what is needed for the successful development of tactically useful, military humanoid robots? Please respond below:

(16) Additional comments (if any):

APPENDIX C:

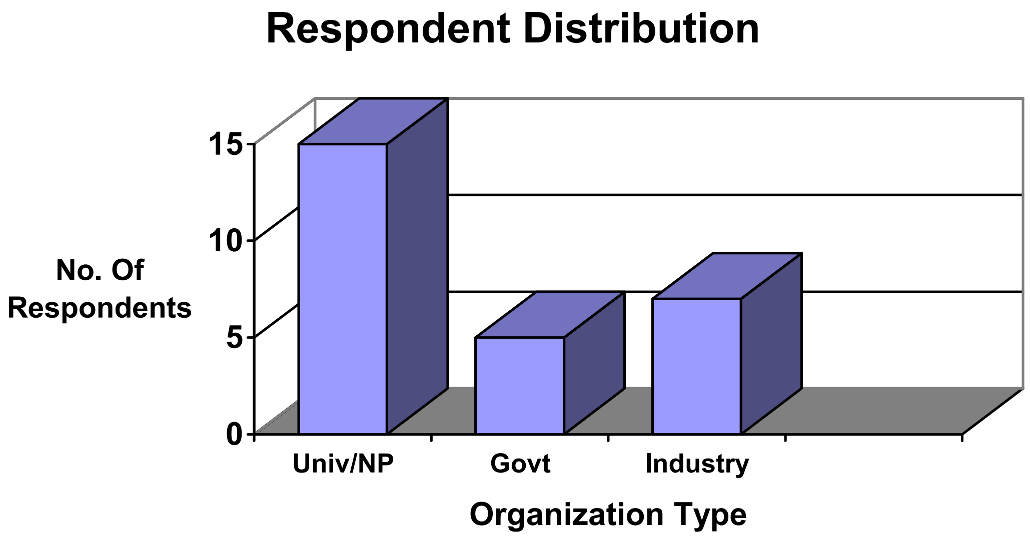
AGGREGATED EXPERT SURVEY RESULTS

EXPERT SURVEY ON HUMANOID ROBOTS: RESULTS

Number of survey recipients: 66
Number of respondents (survey population): 27 (including 1 received too late for use in computations, but with comments incorporated)
Percentage of completed surveys: 41%

[A 41% survey return is considered excellent].

Respondent Distribution: (University/Non-Profit, Government, Industry)



(1) Please summarize your experience relevant to robotics or humanoid robotics technology: [The following are verbatim or edited responses].

- ☐ *I was Chief of Intelligent Systems Division at NIST for 23 years; Author of: "Engineering of Mind: An Introduction to the Science of Intelligent Systems," Wiley 2001; "Brains, Behavior, and Robotics," (BYTE/McGraw-Hill, 1981); "Designer of control system architecture for NBS Automated Manufacturing Research Facility; Author of over 180 articles in scientific and professional journals and conference proceedings; Inventor of CMAC neural net; Developer of well known theory of Cerebellar Function; Developer of 4D/RCS architecture for unmanned vehicle systems.*

- ☐ *I have conducted extensive robotics research (see www.cc.gatech.edu/ai/robot-lab), and served as a research as a consultant to Sony Corporation on humanoid robots (SDR), and conducted funded research on the Honda P3 humanoid robot.*

☐ *I have programmed a number of robots, including an upper body humanoid robot, to do challenging dynamic tasks, including juggling and fast manipulation. (Please see www.cc.gatech.edu/fac/Chris.Atkeson for more information, and please see (http://www-2.cs.cmu.edu/~cga/mars/ for support information for a recent DARPA MARS proposal).*

☐ *I founded the RB Robot Corporation in Golden, Colorado, as well at the National Personal Robot Association (NPRA) in the early 1980s, plus the International Personal Robot Congress (IPRC) conference held in Albuquerque in 1984.*

☐ *I have been developing mobile robots since 1984 and, since 1993, have led the first US effort in building humanoid robots. Our Cog and Kismet robots have been at the forefront of humanoid robots since then.*

☐ *Some of my early research experiences focused on 6-legged walking platforms. More recently I have had some use with the Sony AIBO platform (a quadruped). I would like in the future to use the Sony humanoid (or something equivalent) when it becomes available*

☐ *I am working on the MAV UAV controller with DARPA now as it interfaces with the Land Warrior. I am also working with Ft. Benning on Robotics. I was the Deputy PM in the UGV Joint Program Office. (And I agree with statement above about the limitations of wheel and tracks).*

☐ *We are designing a general purpose biped humanoid robot for military, industrial and (eventually) consumer use. We have built a prototype biped robot, but we will focus on software in the long term, partnering with more adept hardware designers in the future.*

☐ *I have been involved with such projects as: the Walking Beam frame walker, Intelligent Task Automation, Stereo-head mounted displays, Flight Telerobotic Servicer, NOSC Greenman refurbishment, exoskeletons for manipulator control, biped walking for paraplegics, stereo head with 4 dof for humanoids, scene classification, scene registration, neural network for classification, and coordinated dual manipulator systems.*

☐ *I have worked in the area of autonomously navigating vehicles for over ten years in support of the efforts at the Air Force Research Lab at Tyndall AFB. I have worked in the areas of path planning, position systems, vehicle control, obstacle avoidance, and architecture design.*

☐ *I manage the Robotics Systems Technology Group at Johnson Space Center. We focus on developing advanced robotic technology that can directly interact with humans to perform space operations. We have developed numerous robots, the most relevant being Robonaut, a fully humanoid upper torso that has successfully demonstrated the ability to use almost every tool in the astronaut tool chest.*

- ☐ *I have been president of a robotic company since 1985 and have managed dozens of robotics (unmanned vehicles) projects. I have been involved with combat robotics (especially studies and analyses) since 1977.*

- ☐ *I have 20 years of experience with hardware and the control of dexterous prehensile effectors, several integrated platforms for studying manual dexterity, as well as experience with 4-legged walking platforms.*

- ☐ *I have worked over the past 20 years in autonomous robots, human-centered robotics, human-friendly robot design, dynamic simulations, and haptic interactions. The exploration in this research ranges from the autonomous ability of a robot to cooperate with a human, to the haptic interaction of a user with an animated character, virtual prototype, or surgical instrument.*

- ☐ *My laboratory has been conducting research into humanoid control and learning since 1995. Our approach is based on the notion of movement primitives, for structuring and modularizing control, as well as facilitating movement perception, classification, understanding, and learning. The work is based on two lines of neuroscience evidence, one supporting such additive and composable movement primitives, and the other supporting mirror neurons, of a key rule in learning by imitation. Our work in humanoid learning has focused on using the notion of primitives as a substrate for mapping observed movements onto the existing repertoire and then expanding the known repertoire in a generative fashion, through imitation and rehearsal. We have demonstrated effective upper-body movement learning on humanoids, with anywhere from 20 degrees of freedom (DOF) to, most recently, over 100 DOF in a full body. We are also applying our model to real-time control of multi-humanoid interaction, addressing domains such as task-learning and teaching, and real-time assistance as well as sparring.*

- ☐ *I have worked on military UGVs for seven years. This experience includes large vehicles for demining operations, including mechanical and software design of systems that autonomously processed mine fields with detection systems or remediation equipment such as flails. On these systems I performed mechanical design of highly dexterous manipulators, hydraulic power systems, pneumatic systems, demining flails, and various implements for demining. On software, I was the principle architect and developer for a new generation of controls taking advantage of the latest in technology for ruggedized, semi-autonomous control for mine-field operations. These systems were successfully deployed at military bases domestically and in Egypt and Jordan. I have worked on software control for the PackBot system, including communication software and head/neck control. I wrote the software for the Pyramid Exploration robot and iRobot's Unmanned Ground Combat Vehicle Prototype. Recently, I have worked on software control of bipedal walking machines and modeled these mechanisms in virtual environments.*

- ☐ *I have worked in the field of robotics for 30 years. Much of my work has been related to the development of legged machines. I was an investigator on the DARPA Adaptive*

Suspension Vehicle project at Ohio State in the 1980s and early 1990s. I worked on the control and simulation aspects of the project. I have been funded by NSF over the past more than 3 years, along with Ken Waldron of Stanford University, to develop a galloping machine. We are currently looking at rapid starts, stops, jumps, and turns of high-speed running vehicles.

- ☐ *I was lead electronic and mechanical engineer on the MIT Leg Lab robot M2, which was sponsored by DARPA. I have designed several Series Elastic Actuators which provide high fidelity force control in a small package. I have written code for computer simulations and real robots to control walking and similar actions. I am up to date with the current state of the art in the US, Europe and Japan.*

- ☐ *From 1994 to 2000, I designed, built, and controlled bipedal walking robots and bipedal simulations at the MIT Leg Laboratory (www.ai.mit.edu/projects/leglab). There I built Spring Flamingo, a planar bipedal walking robot that can walk up to 1.25 meters per second and traverse rolling terrain without prior knowledge of the terrain. From 2000 to 2002, I worked at Yobotics, Inc. (www.yobotics.com), a startup I co-founded with 3 other Leg Lab graduates. There I did human walking simulation development as a consultant to Boston Dynamics, and also worked on the RoboWalker exoskeleton. In April 2002, I joined the Institute for Human and Machine Cognition in Pensacola, FL. Here I am setting up a lab for research on legged robots, modeling of human gait, and human amplification.*

- ☐ *I serve as the Chief Scientist in the Automation, Robotics, and Simulation Division at NASA/JSC in Houston, Texas. I founded the Artificial Intelligence Lab in 1984 at the Johnson Space Center, and I am currently a PI on the DARPA MARS program as well as Chief Scientist for the Robonaut project.*

- ☐ *I am a market researcher and author who has focused extensively on unmanned systems and robotics systems, including that of humanoid robotics.*

- ☐ *I have more than twenty years in robotics research for military applications. My experience includes UGVs, UAVs, and exotic platforms such as hexapods and humanoids. I served as a DARPA PM and Office Director in information technology, especially as it relates to embedded software, distributed computing, and machine learning. Currently I serve as the deputy director of the Intelligent Systems and Robotics Center at Sandia.*

- ☐ *I have been involved in studies on military application of unmanned systems and various types of unattended sensor systems (such as in MOUT and in pursuit of elusive targets).*

- ☐ *I have twenty years of experience in the robotic field, including academic and industrial research and applications. I have designed mechanical and electrical hardware, control software, artificial intelligence software, and user interface software for both manipulators and mobile robots. The bulk of my experience is with manipulators, but I have also worked with wheeled mobile robots and legged systems.*

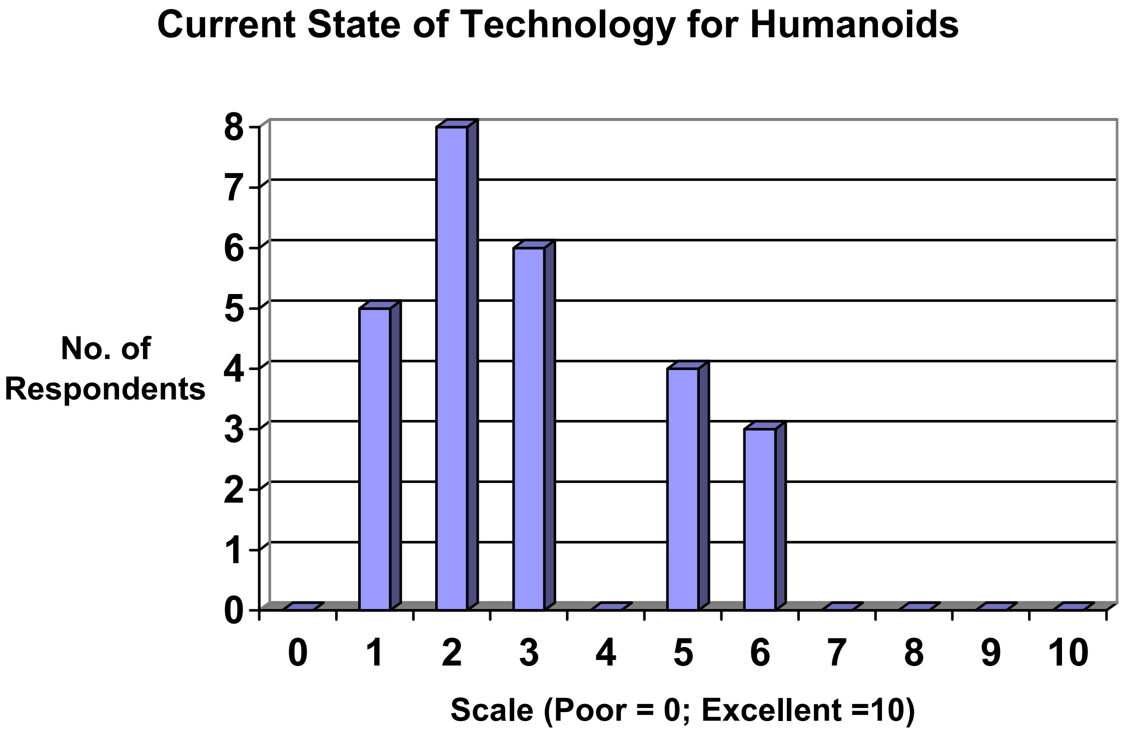
☐ *I have been developing modular robotics for 10 years. These robots have demonstrated a variety of tasks, including dozens of modes of locomotion, manipulation, and the use of tools designed for humans. In all of this survey, I will assume (unless otherwise stated,) humanoid means robots of human form with 2 legs, 2 arms, a head, and that runs self-powered and untethered.*

☐ *I am involved with the initial development and testing of military applications for unmanned systems, both air and ground, including the development of interoperability of systems and weaponization/operational techniques.*

(2) In your opinion, characterize the *current state of technology* for the successfully development of military humanoid robots. Please place an "X" on the appropriate position along the scale:

Results: Number of Respondents (n) = 26; **Mean (M) = 3.4**; Standard Deviation (Sta. Dev.) = 1.7; **Median ~ 3.0**; Mode = 2; Range = 1.5 – 6.5

/---------/---------/---------/---X-----/---------/---------/---------/---------/---------/--------/
0 1 2 3 4 5 6 7 8 9 10
Poor Satisfactory Excellent



Comments (if any): [The following are verbatim or edited responses].

☐ *The technology is weak or unproven in: (1) Perception; (2) Legs and artificial muscle (i.e., actuators with speed, strength/weight, and impedance characteristics similar to muscle); (3) Balance, posture, gait, and intelligent control capable of controlling a biped vehicle. These are the critical enabling technologies for humanoid robots.*

☐ *We do not have the basic technology for humanoid mobility, humanoid manipulation of objects and humanoid visual object recognition.*

☐ *I think humanoids are on the edge of being useful in a research environment, particularly the Sony humanoid. Most other humanoids, while capable of controlled walking, still lack the technological understanding to perform difficult activities robustly. I believe there is a great opportunity for research breakthroughs here. It would be a great shame, in my opinion, if those breakthroughs occur in other countries where there appears to be significantly more interest in supporting humanoid research than in the US.*

☐ *There is a need to work on the Human Interface for Humanoid Robots.*

☐ *There are very few teams focusing on this (humanoid robots) at the moment. The Japanese have had some success, but for very limited scenarios, and none in the military as far as we know. They have built some interesting hardware, but the software is not highly sophisticated. The difficult issues around teleoperation, autonomy, sensing, cognition and communication must be solved for the military arena.*

☐ *Much integration work needs to be done. Major concerns include the power source, actuator efficiency, and intelligent behavior.*

☐ *The technology has far to go for its ultimate fruition, but it is sufficient now to begin developing useful (within constrained missions) humanoid robots.*

☐ *I believe that it would take a "significant" initial investment in platform development, and then a likewise significant investment in control. The opportunity to leverage results from current robotics efforts at DARPA is excellent. There are strong groups (NASA-JSC, for example) that have significant pieces of a plausible system worked out already. Some new money together with effective leverage from existing pioneering work should produce field-able (not research) devices within 8 years.*

☐ *Some of the needed technologies are already in place – some others, e.g. mechanisms, perception, and power, are not quite ready.*

☐ *This is difficult to quantify because the semantics of this question can be interpreted in different ways. Bottom-line, we need to develop quite a bit of technology for military humanoid robots to be practical. One of the largest limitations in technology is energy density of power sources.*

☐ *The state of the technology is not too bad, but has been stagnate the last few years with little new work since M2. There are little pieces here and there, but no large scale integrated projects.*

☐ *The current state of the art in humanoid technology would not allow for the successful short-term deployment of humanoid robots in a military scenario. There is a lack in gait algorithms, power and actuation, sensing, and AI. For gait algorithms, there needs to be research on algorithms for better balance over cluttered terrain, better robustness to external pushes, algorithms for walk to run transitions, and algorithms for getting up from a fall. For power and actuation, we need high power to weight ratio low impedance force controllable actuators and high density power supplies. For sensing, we need better terrain sensing. For AI we need everything, and therefore my view is that any military robot should only be semi autonomous with a fairly high soldier to robot ratio. I know the military would like to see one soldier operate hundreds of robots, but I think 1 soldier to 2-5 robots is more realistic since teleoperation will be very important in many situations, and too difficult to automate completely. In these areas, therefore, I believe research on enhancing the capabilities of the soldier-robot combo is a more productive approach than trying to replace the capabilities that the soldier brings to the table.*

☐ *There has been excellent hardware (mechanics, computing) and software advances over the last few years, such that humanoid robots could become a successful tool for the military – if a focused research program could be initiated.*

☐ *Humanoid robots have a great deal of promise for the future, but the technology needs much more progress. It is competing not only against soldiers and manned systems, but with non humanoid unmanned systems and robots as well (including wheeled, tracked, flying and non bipedal systems).*

☐ *Clearly, the answer depends upon the application in mind. Those that favor manipulation over mobility are nearer term.*

☐ *This question is difficult to answer – the current state of actual technology is pretty rudimentary and not well suited for application in the military environment. But there is an unasked question (perhaps it is stated later) whether humanoid robots are needed and useful for mil applications —which applications, and by when. SUCCESSFUL development will only take place when real applications are defined and pursued.*

☐ *The current state of humanoid robots is very primitive relative to the demanding requirements of military applications. Self-contained power and dynamic locomotion are particular areas that must be addressed.*

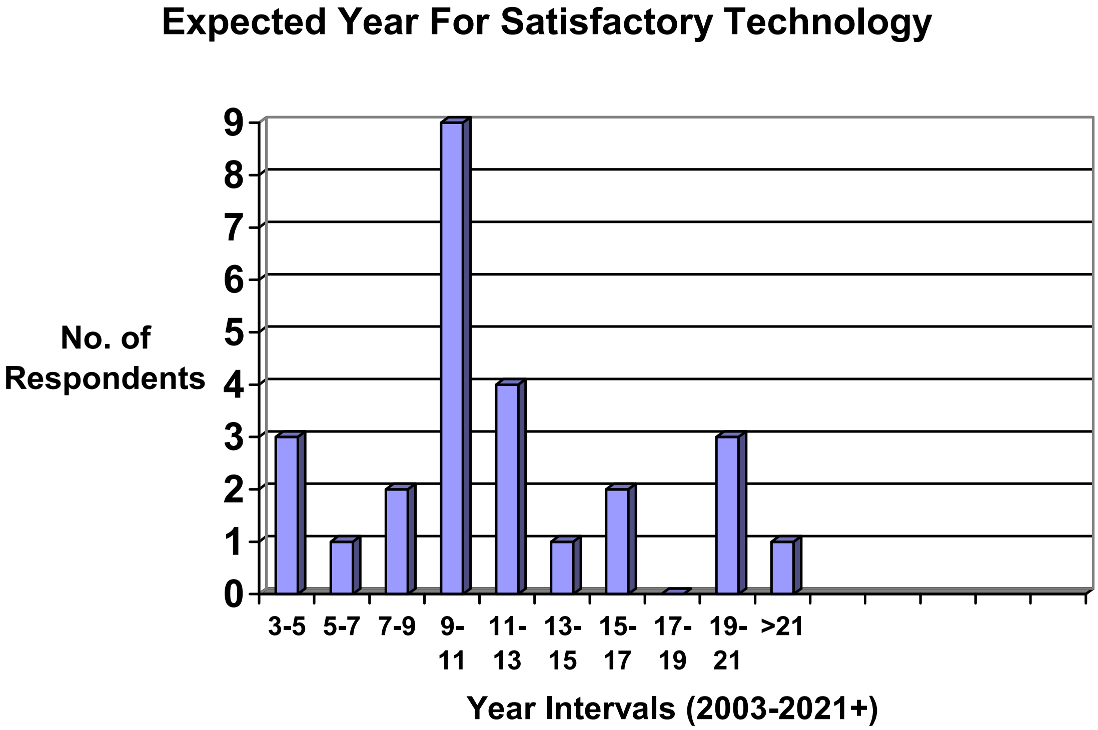
☐ *I believe the emphasis on humanoid robotics has been coming from Japan with the most recent efforts in entertainment (as the first near term application).*

☐ *Technology may be available, but not affordable, for military applications with limited survivability.*

(3) By what *year* will humanoid robot *technology* be *at least satisfactory* for the successful development of supervised autonomous military humanoid robots? Please place an "X" on the appropriate position along the scale:

Results: n = 26; **M = 2012**; Sta. Dev. = 5.1; **Median ~ 2011**; Mode = 2009 – 2011; Range = 2003 – 2022

/---------/---------/---------/---------/----X---/---------/---------/---------/---------/--------/
2003 05 07 09 11 13 15 17 19 21 >21
Year



Comments (if any): [The following are verbatim or edited responses].

- *This could happen sooner, with the right funding. My estimate is based on my current guess as to the likely funding profile.*

- *I make this prediction on the following basis: In 1984 I started building mobile robots when there were almost none elsewhere in the world. They were very primitive. In 2002 my company, iRobot, built the first robots to be deployed by the military in operational situations (in Afghanistan). By analogy, I started building humanoid robots in 1993, and 18 years later is 2011.*

☐ *This is assuming a broad effort targeting industry, to build hardware, and research institutions to focus on developing robust control, recovery, and learning mechanisms. The latter is necessary because programming a 30DOF robot is by no means trivial.*

☐ *The end effectors and sensors need to be developed. Humanoid robot development could be based on UGV and UAV efforts so far. There is a need to take the technology to the next level.*

☐ *We intend to have useful prototypes within 3 years, at which point it will be reasonable to start a development process for practical military products.*

☐ *There is no perfect system, but it is possible to get something to run within a year (sacrificing something: noise, duration, lifting capability, etc.). Asimov's android still a ways out.*

☐ *Useful humanoid robots can be fielded within 5 years, if their missions are well-defined. Humanoid robots can be integrated with the initial deployment of the Future Combat System (FCS), if their development starts now.*

☐ *A stable funding profile could demonstrate mobile and dexterous humanoids, and some degree of autonomy, within 5 years.*

☐ *The estimate depends on the level of effort devoted to the development of humanoid technology.*

☐ *This is highly dependent on funding level. Increases in funding could bring this point forward.*

☐ *Success will be dependent upon a sufficient investment of funds in the area.*

☐ *This is completely dependant on the amount of funding to be allocated in the next couple years.*

☐ *This depends heavily on the level of autonomy. For teleoperation, or simple waypoint navigation, I'd say we could do it by 2010 if there was large investment. For having a soldier to robot ratio of 1/10, I'd say 2020 or so could be possible, but it will require a highly trained, competent soldier. For a fully autonomous humanoid robot with satisfactory operation, I'd say perhaps 3000.*

☐ *Even under high level funding, development and research cycles take about 1-2 years, such that after 2-3 iterations of such cycles satisfying results should be available.*

☐ *Start off with some very select applications, in which the human form is advantageous over that of another robot configuration, and in which an autonomous system is beneficial, should be pursued. Care and thought should be made in targeting a specific application, and then slowly expanding it to more and greater applications.*

- *This is another classic "it depends." The investment will effect the maturity date by roughly a factor of two. That is, significant investment will halve the time when it will emerge (possibly outside the U.S.) without significant funding.*

- *This depends on what you want them to be able to do – the making of humanoid systems that are relatively unintelligent, that simply "walk perimeter defense" may be feasible within 5-7 years — but if you want them to do anything requiring independent action — with human-like reactions — that's way off.*

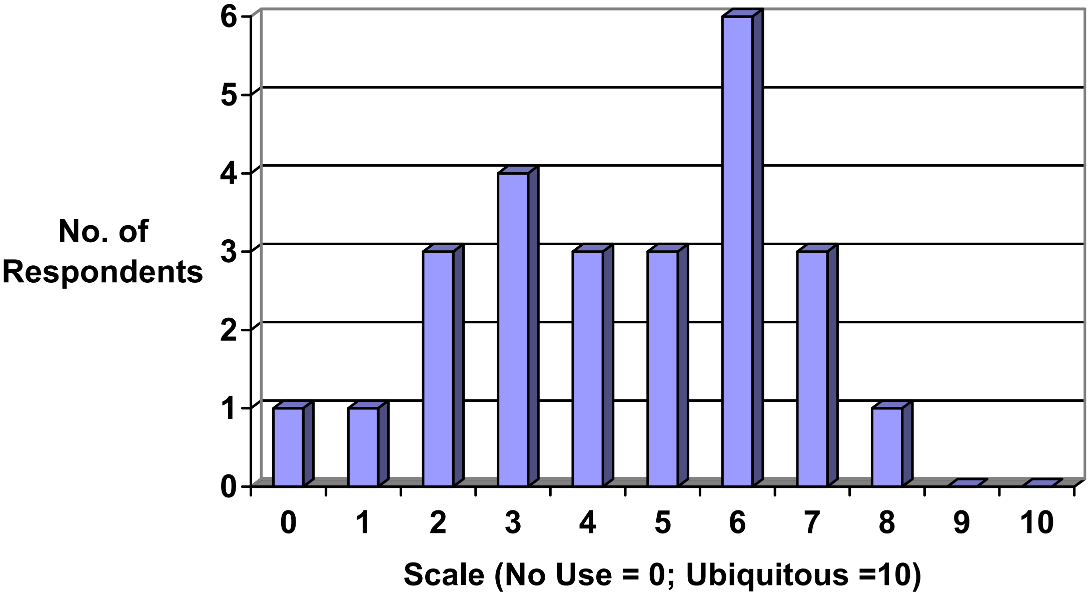
- *The general autonomy of robots is improving at a slow, but steady pace. Humanoid robots suffer from all the same drawbacks of intelligence and autonomy that other robots suffer and will ride that development wave. But humanoids have many key advantages in real-world scenarios. The first applications will be very simple, with shared autonomy (surveillance, recon), but their locomotive ability and adaptability will make them superior to wheeled vehicles.*

(4) What is your expectation of the U.S. military's use of supervised autonomous humanoid robots by *2020*? Please place an "X" on the appropriate position along the scale:

Results: Number of Respondents (n) = 25; **Mean (M) = 4.9**; Standard Deviation (Sta. Dev.) = 2.1; **Median ~ 5.0**; Mode = 6; Range = 0.5 – 8.0

/---------/---------/---------/---------/--------X/---------/---------/---------/---------/--------/
0 1 2 3 4 5 6 7 8 9 10
Not in Use Used in Several Applications Ubiquitous in the Military

Expected Military Use Of Humanoids By 2020



Comments (if any): [The following are verbatim or edited responses].

- ☐ *It will take many years after the technology is satisfactory for the benefit/cost ratio of humanoids to justify their inclusion into the military forces in a major way.*

- ☐ *I believe that as time progresses (provided we solve some of the key issues) humanoids will become increasingly prevalent in the military (and elsewhere). It will take some effort, though, to convince people that humanoids are useful – and this will take time.*

- ☐ *Humanoid robots will be used as a tool for manned forces.*

- ☐ *The proliferation will clearly depend on how well and reliably they work. If a humanoid robot can accomplish the majority of the tasks of a soldier, then there is no reason that the majority of soldiers won't be robots. I don't see people disagreeing about the possible uses; they are enormous. People are questioning whether the technology will work.*

- ☐ *Humanoid robots will not be widespread and ubiquitous, but they will have niche applications, such as the toaster or other multi-disciplinary system. These applications will define themselves.*

- ☐ *There should always be a place for traditional ground vehicles since there is still a large percentage of terrain that can be covered. Also advances in aerial systems may alleviate the need for an autonomous system to be "humanoid."*

- ☐ *Assuming development starts soon, and assuming "humanoid" also encompasses hybrids (e.g., a "Centaur" robot).*

- ☐ *I believe that the military will likely retain an interest in non-humanoid systems (those that fly or provide teleoperated reconnaissance) after humanoids are field-able.*

- ☐ *There are clearly many applications for supervised autonomous robots.*

- ☐ *I don't think the military will have any humanoid robots used in tactical environments by 2020. This is a great goal to word toward. Again, this is highly dependent on funding.*

- ☐ *I believe the following applications are possible and have potential benefit: (1) Target practice, because it will allow for more realistic training situations with the practice enemy (more automation could allow for live fire practice in realistic situations); (2) Tele-presence for recon; (3) Teleoperation for fighting in urban environments. I believe that military robots in general will be ubiquitous. They almost are already depending on what one would call a robot. The difficulty is that other types of robots (quadrupeds, tracked, hybrid, etc.) may have a better payoff than a humanoid and is what makes humanoid research a hard sell to those that want to immediately field the results of the research.*

☐ *Operating manned systems using a human configured (android) robot should be the initial applications.*

☐ *By 2020 the portable power problem should be well in hand, thus enabling fairly pervasive employment. This will be motivated, at least to some degree, by the use of Chem/Bio weapons by our adversaries as asymmetric weapon capabilities.*

☐ *Given the rate at which military has adopted UAVs, etc.: by 2020 you will likely have only an ACTD or an experiment and some close-hold use by special units.*

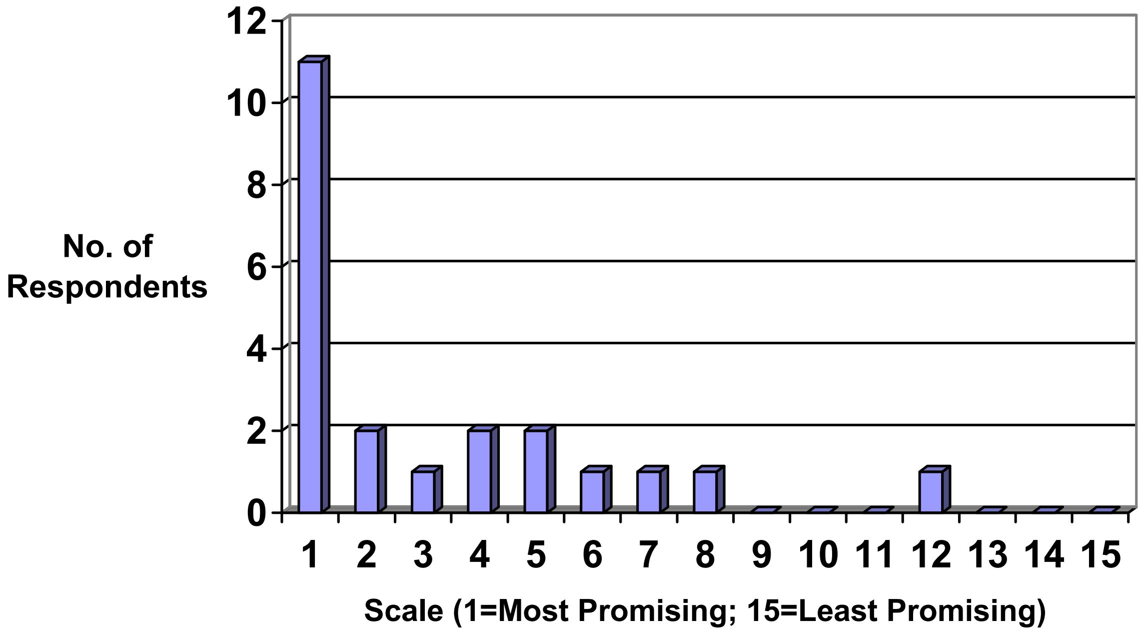
☐ *Technology will be ready early, but hardened systems will take several more years. By 2020, applications will still be limited, but they will be demonstrating their superiority and paving the way for more.*

☐ *Fielding/acquisition cycles dictate that appropriate technology is available and integration is feasible 10 years prior to First Unit Equipped. I think it would take 7 years to understand operational requirements and force structure implications.*

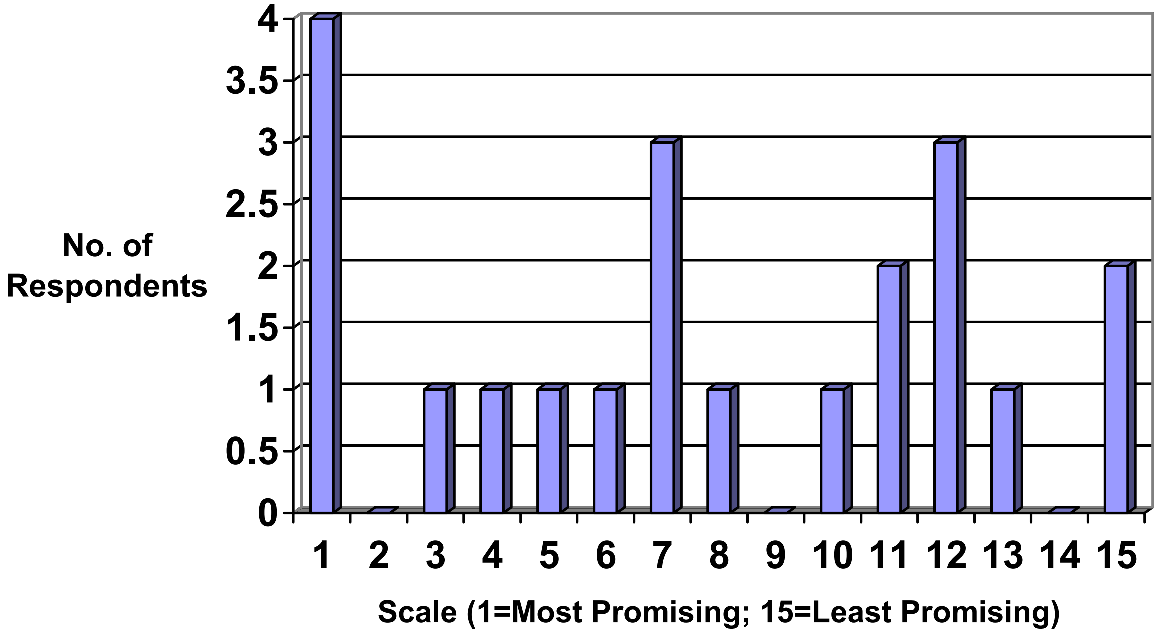
(5) Which humanoid robot *applications, missions*, or *combat functions* (not all mutually exclusive) are *most promising* for the U.S. military? Please score each of the choices, from 1 (most promising) to 15 (least promising):

		n	**Mean**	**Sta.D.**	**Med.**	**Rng.**
Reconnaissance, Surveillance, Target Acquisition (RSTA)	____	22	3.1	3.0	1.5	1-12
Driving or Piloting Vehicles	____	21	7.7	4.7	7.5	1-15
Infantry (e.g., Operating Small Arms)	____	21	6.1	4.0	5.0	1-14
Operating Direct Fire Weapons (e.g., Tank/Antitank)	____	22	8.4	3.6	8.5	1-15
Operating Indirect Fire Weapons (e.g., Artillery)	____	22	8.1	3.8	8.5	1-15
Military Operations in Urban Areas	____	22	3.3	3.4	1.5	1-11
Countermine Operations	____	22	6.8	4.5	5.0	2-15
Target Designation (e.g., with laser designators)	____	22	3.9	2.6	3.0	1 - 9
Logistics/Material Handling	____	22	5.8	4.0	5.5	1-11
Air Defense	____	18	8.9	3.8	8.0	1-11
Special Forces/Counter-Terrorism	____	22	5.8	4.2	4.5	1-14
Satellite Operations/Space Exploration	____	22	4.5	4.4	2.5	1-15
Other (Explain)	____	7	3.0	2.6	2.0	1 - 8

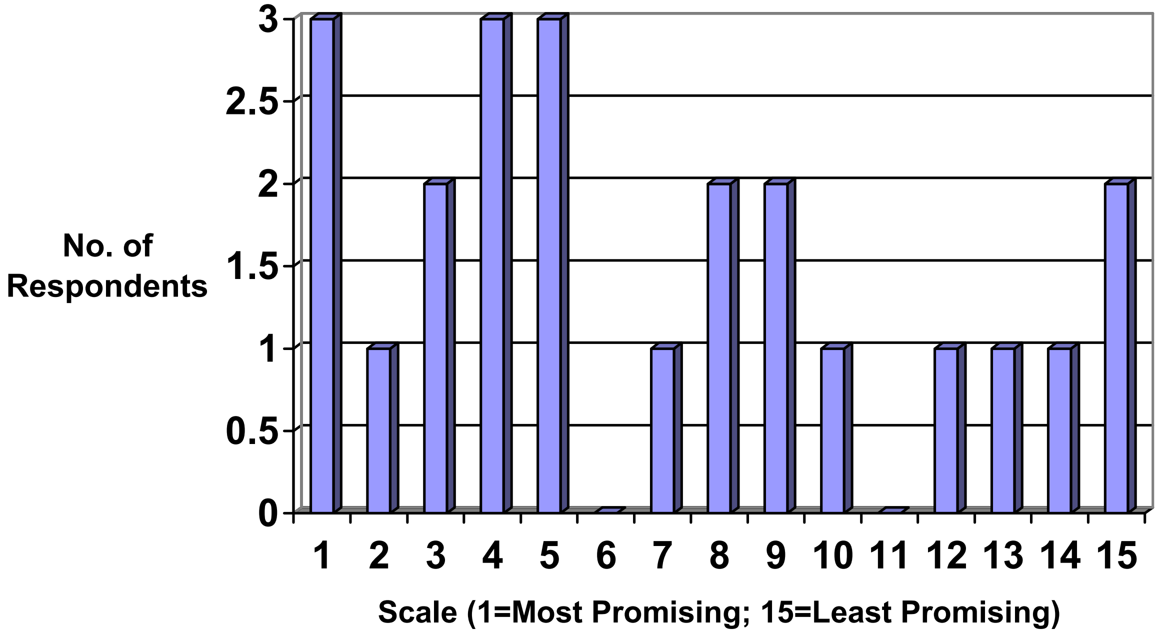
Evaluation Of Humanoid Robot Applications: RSTA



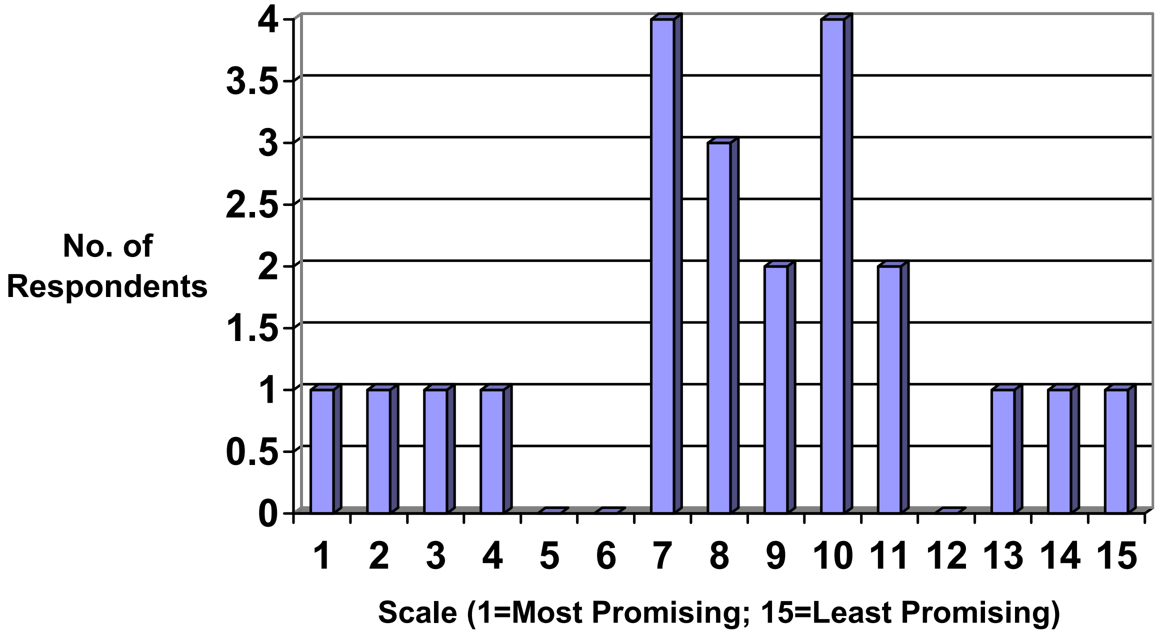
Evaluation Of Humanoid Robot Applications: Driving/Piloting



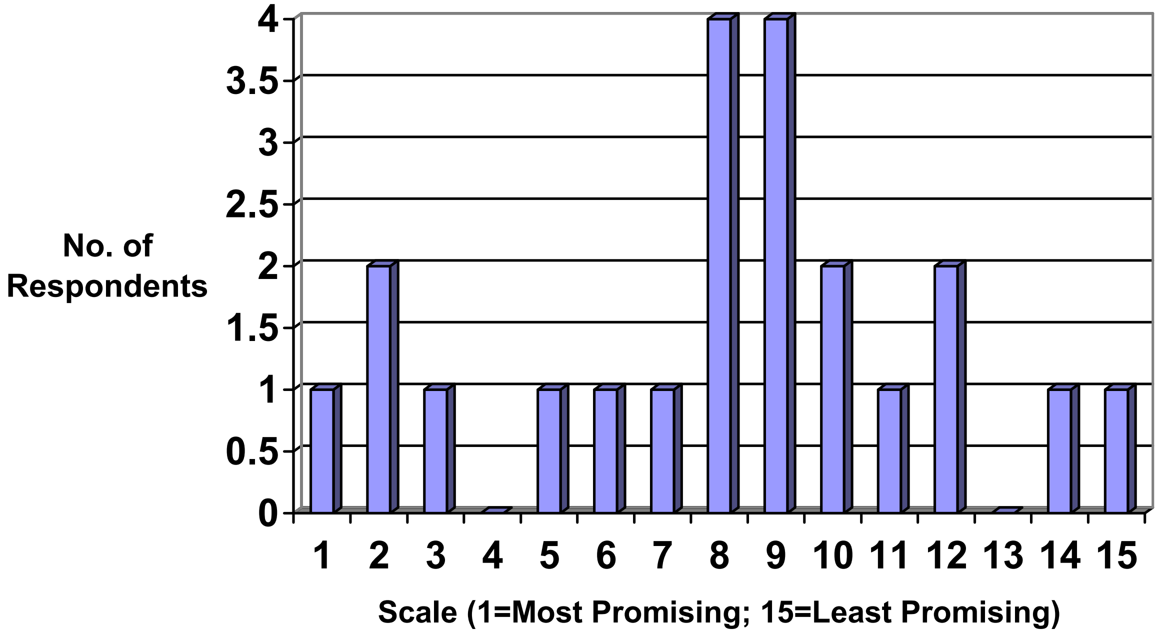
Evaluation Of Humanoid Robot Applications: Infantry



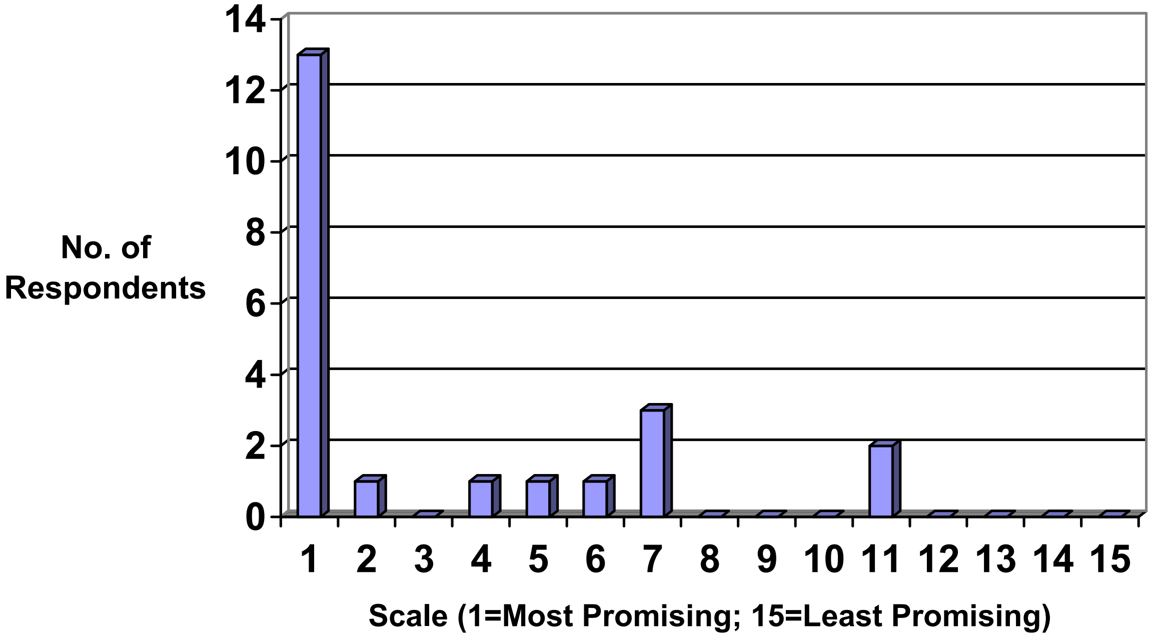
Evaluation Of Humanoid Robot Applications: Direct Fire



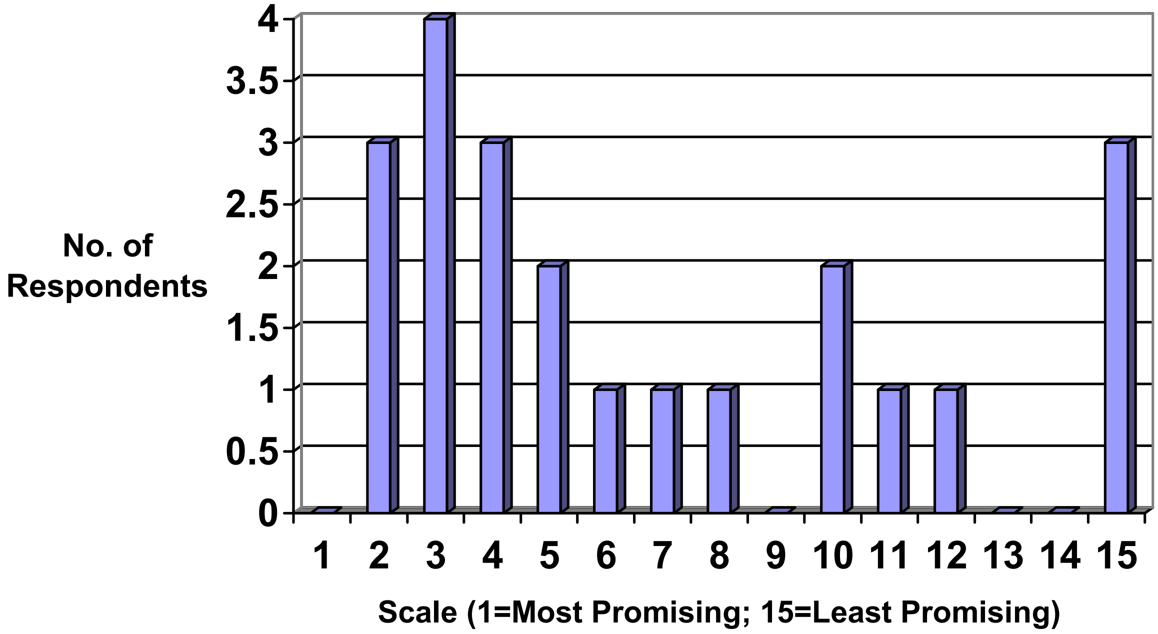
Evaluation Of Humanoid Robot Applications: Indirect Fire



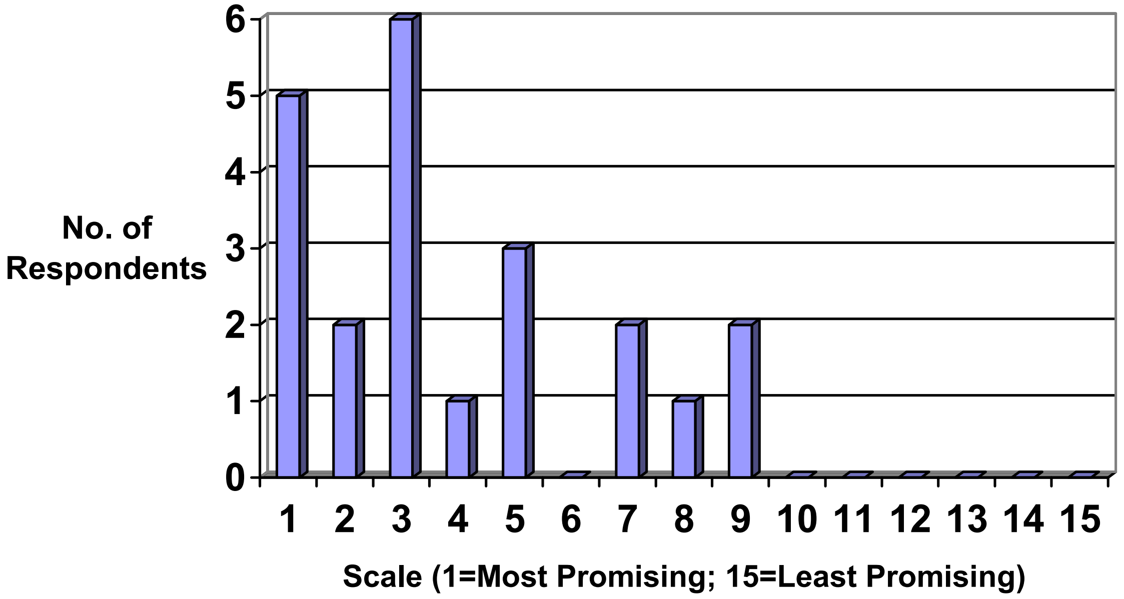
Evaluation Of Humanoid Robot Applications: MOUT



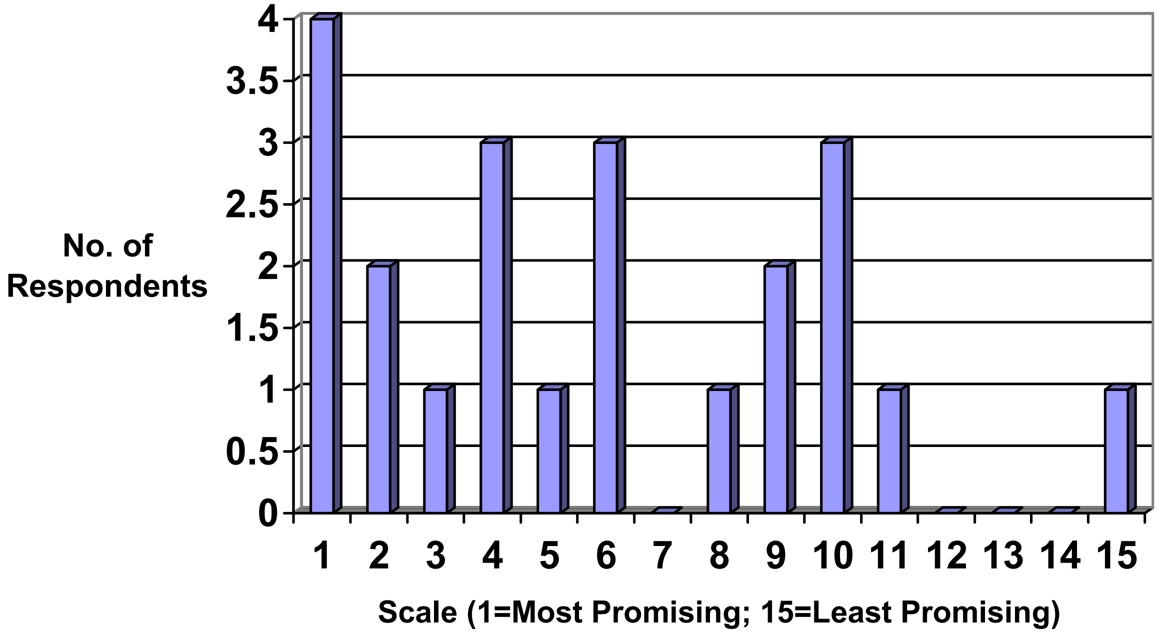
Evaluation Of Humanoid Robot Applications: Countermine



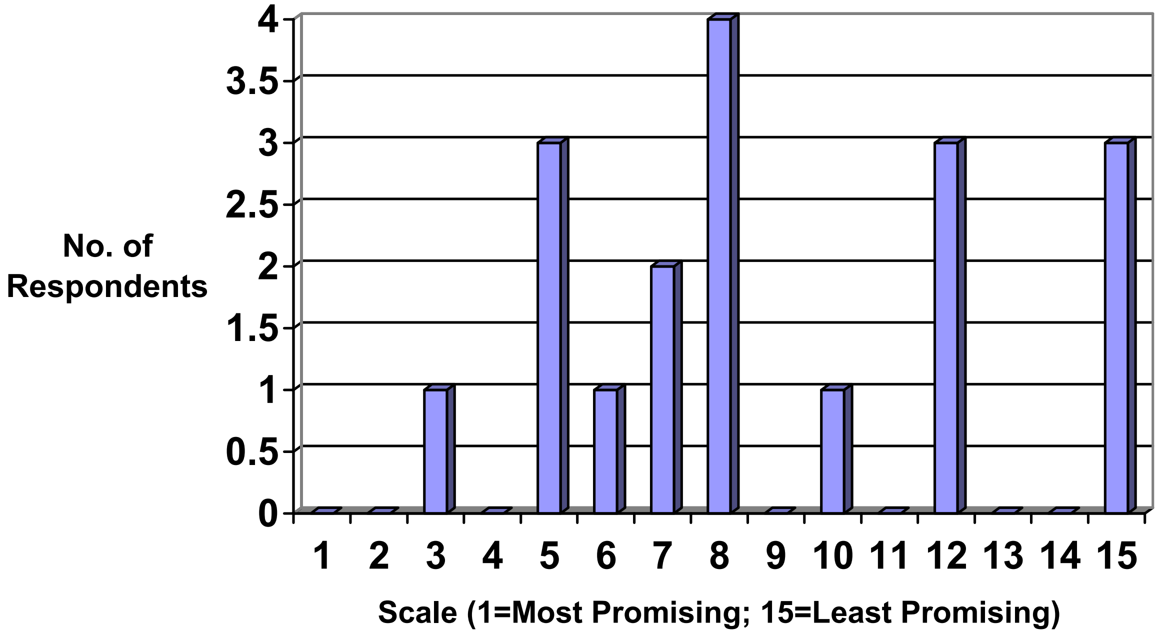
Evaluation Of Humanoid Robot Applications: Target Designation



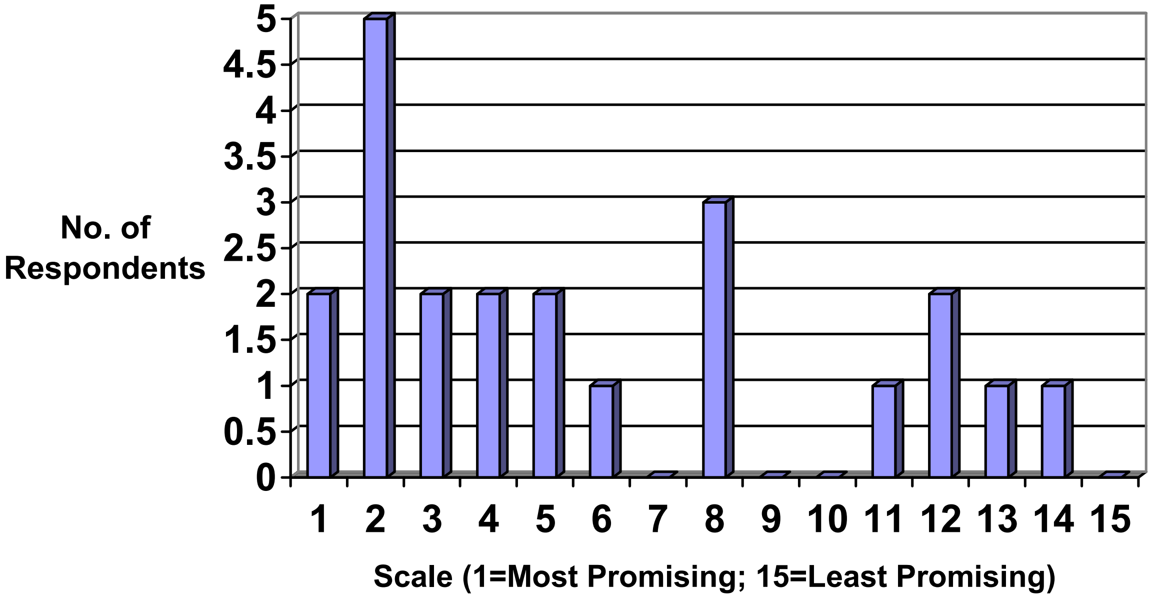
Evaluation Of Humanoid Robot Applications: Logistics



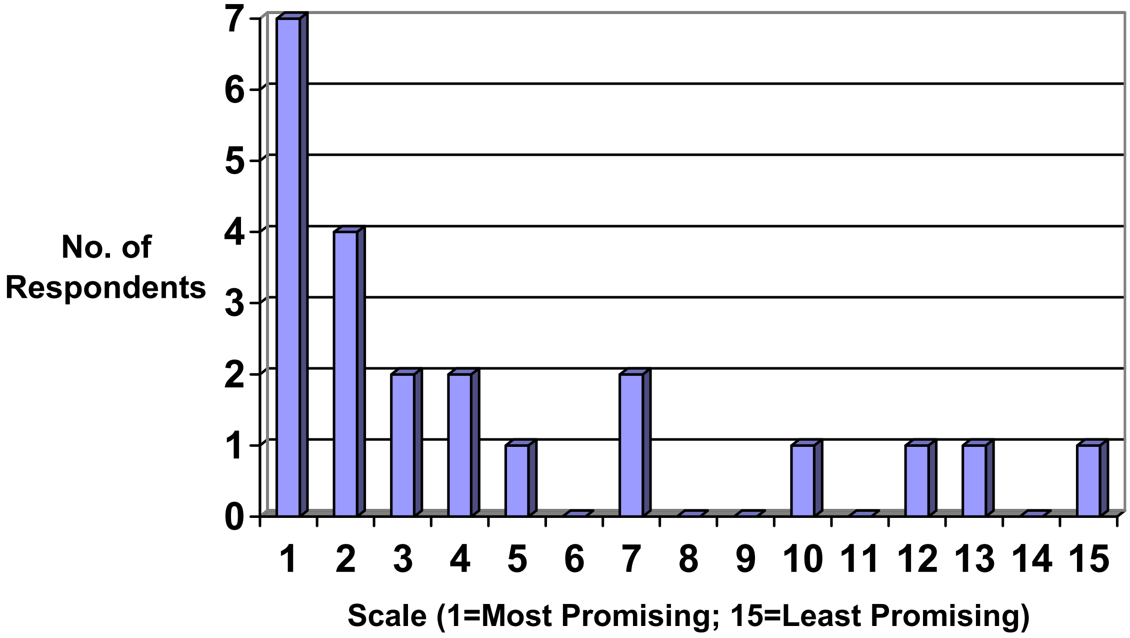
Evaluation Of Humanoid Robot Applications: Air Defense

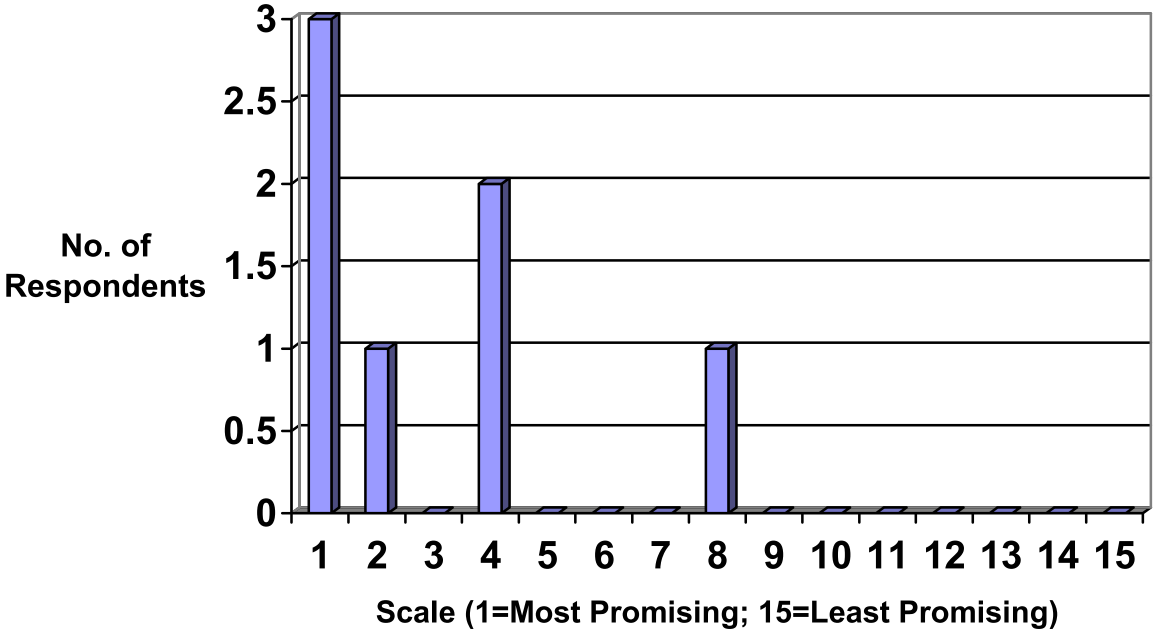


Evaluation Of Humanoid Robot Applications: Counter-Terrorism

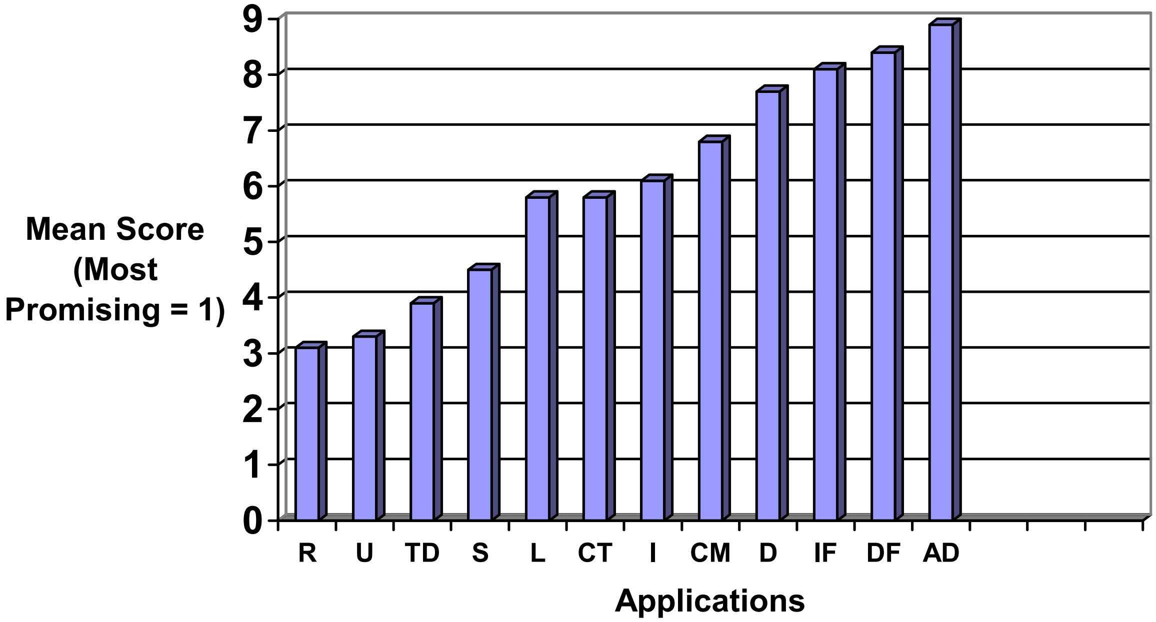


Evaluation Of Humanoid Robot Applications: Space





Evaluation Of Humanoid Robot Applications: Other



Evaluation Of Humanoid Robot Applications: Mission Means

Key to Applications (Missions) on Chart

R = Reconnaissance, Surveillance, Target Acquisition (RSTA)
U = Military Operations in Urban Terrain (MOUT)
TD = Target Designation
S = Satellite Operations/Space Exploration
L = Logistics/Material Handling
CT = Counter-Terrorism/Special Forces
I = Infantry (e.g., Operating Small Arms)
CM = Countermine Operations
D = Driving or Piloting Vehicles
IF = Indirect Fire Weapons (e.g., Operating Artillery)
DF = Direct Fire Weapons (e.g., Operating Tank/Antitank Weapons)
AD = Air Defense (e.g., Operating Air Defense Artillery/Missiles)

Comments (if any): [The following are verbatim or edited responses].

- ☐ *MOUT operations will be very costly in terms of American soldiers' lives. This can justify the cost of development, and will probably drive the funding priorities.*

- ☐ *Applications marked 1 are very promising; applications marked 3 are promising; applications marked 7 allow use of existing equipment; future vehicles/weapons will be self driving.*

- ☐ *Countermine operations can be tackled with much less expensive solutions. Air defense would not particularly benefit from humanoid robot technology.*

- ☐ *Many of these applications can be done by robots that are not humanoid. I think one has to be careful in making that distinction, but at the same time I think it is hard to know at this stage whether humanoid or non-humanoid forms are the best.*

- ☐ *Other: as a physical interface to a range of personal assistant agents for various tasks of information gathering, planning and organization.*

- ☐ *Other applications for humanoid robots include NBC ops, medics, cooking (someone has to do it), and equipment repair.*

- ☐ *Other: The humanoid robot could also serve as a suit (exoskeleton) that a soldier could use for sustained life from chemical, biological, or radiation environments. It could also provide additive capabilities to make soldier stronger, faster, or have extended performance.*

- ☐ *Specific leverage exists anywhere there is advantage to adopt equipment and facilities designed to meet a human's ergonomics, where humans and robots are expected to collaborate in the same physical environment, and where anthropomorphic form factor has advantages (applications requiring remote programming of humanoid devices).*

☐ *These estimates depend on the development time.*

☐ *Several of the applications listed above can already be handled, to various degrees of autonomy, with autonomous robots and embedded systems of non-humanoid form. It is critical to keep in perspective why humanoid form is used, since it adds a very significant overhead in control complexity. Therefore, it should be reserved for domains where the form offers significant advantages over other morphologies. Such domains typically involve direct interaction with humans or with environments and objects that were constructed to be handled by humans. I have marked above with NH the application areas where there is significant existing automation technology in non-humanoid robotics that could be effectively applied. I used H where humanoid form is most appropriate. In some cases, both are appropriate and their possible interaction may bring further performance improvements.*

☐ *Some of these applications, such as driving or piloting vehicles, are much better performed by something not in a humanoid form.*

☐ *Many of these tasks are better to suited to task-specific robots. A car can drive itself without a full humanoid robot. That would be a waste. A humanoid robot can be used to replace a human when the human form is helpful.*

☐ *Other: Medical*

☐ *Your listing has some apples and oranges. It should be focused on function. Counterterrorism could involve all the various functions and is too broad. I am not sure why a humanoid robot would be better than a non human shaped robot for infantry, anti-tank etc. There may be better configurations for these applications. Having a humanoid operate machinery designed for humans to operate in very hazardous conditions seems to be the right focus. There is no need for the expense of redesigning all new systems and vehicles to be totally unmanned. Just insert an android.*

☐ *Other: crew station work onboard military platforms, such as fire fighting aboard ship.*

☐ *I can't think of humanoid applications for air defense that isn't piloting vehicles.*

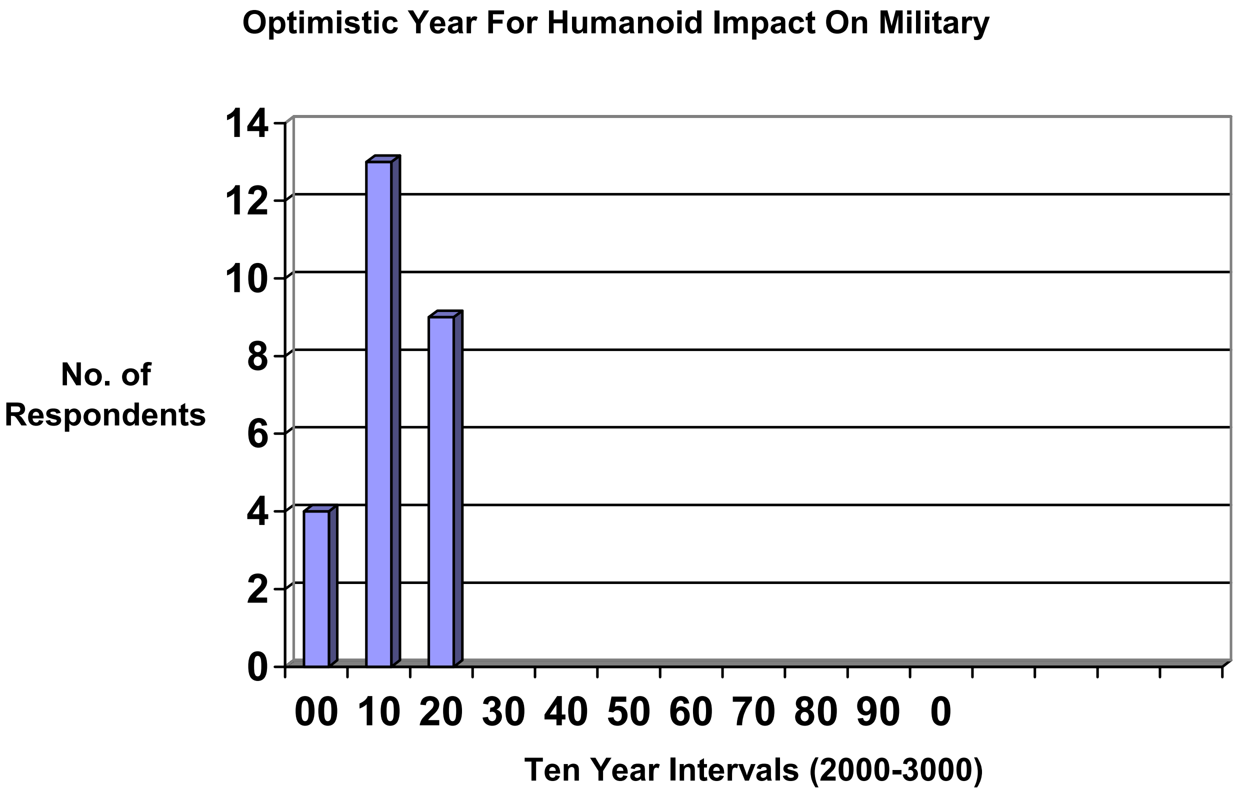
☐ *It is necessary to avoid operations requiring a high level of reasoning and uncertainty.*

(6) By what year will humanoid robots have a significant impact on the U.S. military (e.g., commonly performing functions and missions)? Please insert your estimate of the year for each case below:

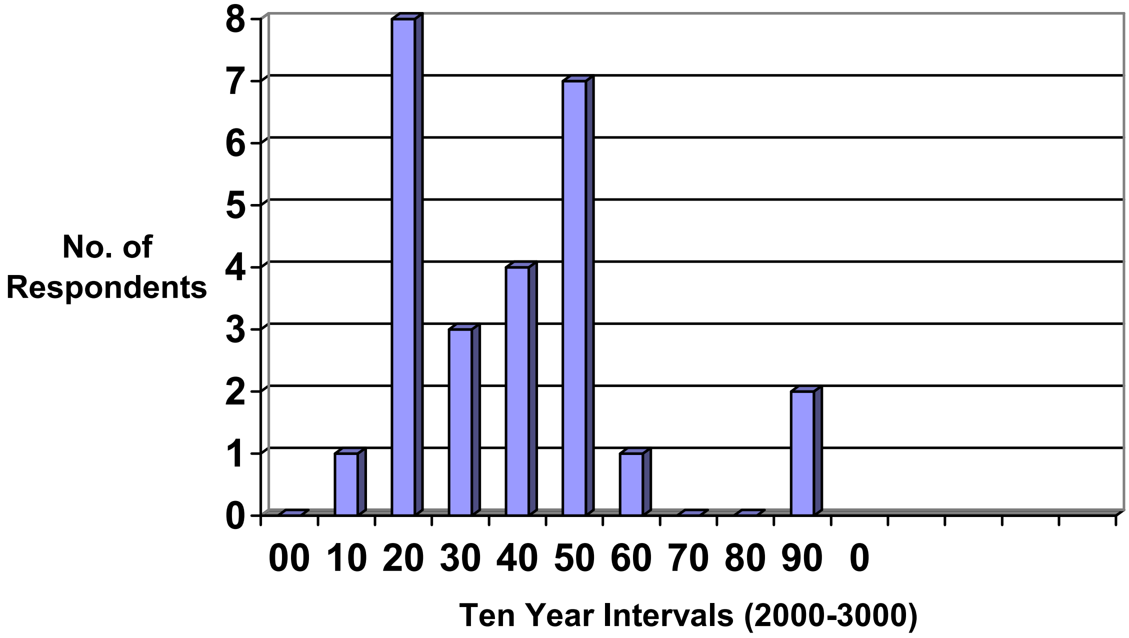
Optimistic Year ___________
Pessimistic Year __________
Most Likely Year _________

TYPE YEAR	MEAN	STA. DEV.	N
Optimistic	2015	5.2	26
Pessimistic	2041	21.4	26
Most Likely	2022	7.2	26

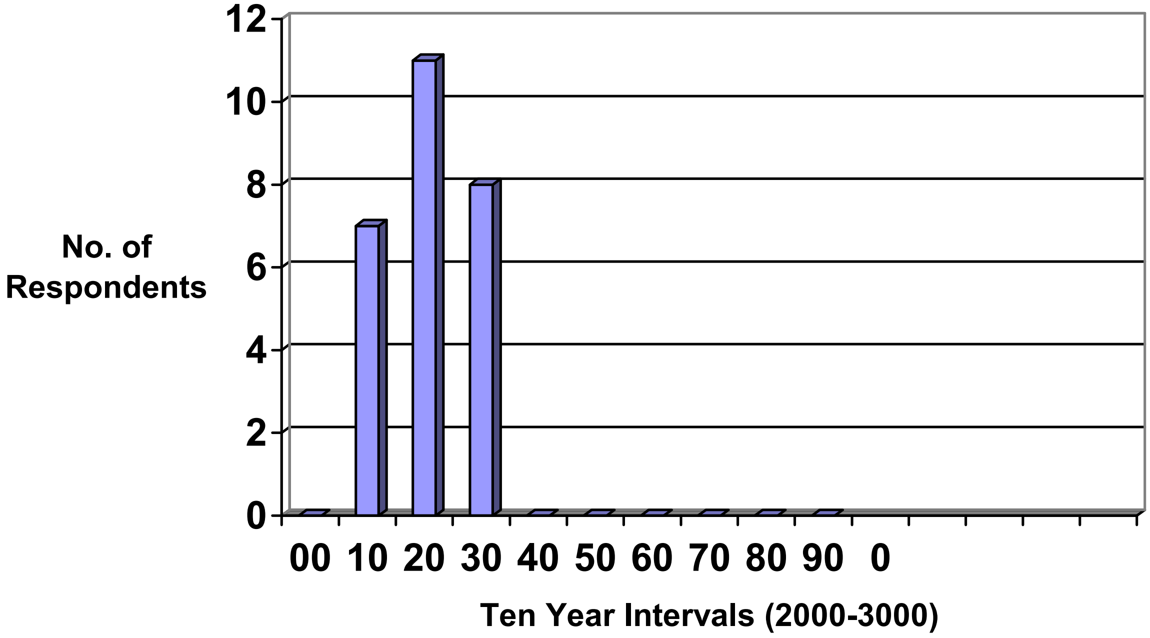
Using a Beta distribution assumption: **Expected (Mean) Year = 2024; Standard Deviation = 4.3 years.**



Pessimistic Year For Humanoid Impact On Military



Mosy Likely Year For Humanoid Impact On Military



Comments (if any): [The following are verbatim or edited responses].

- ☐ *By significant, I assume you mean a measurable effect on staffing of the U.S. military operations.*

- ☐ *I believe that humanoid robots can have an important role in selected military applications sooner than 2022, but not necessarily a significant impact.*

- ☐ *Humanoid robots will be a social issue. There is a need to work back/niche markets.*

- ☐ *Fuel cells and batteries are improving. Nuclear power is another option. Moore's Law supports human like intelligence sometime between 2030 and 2050 if you believe digital processing is comparable to neural /biological processing. MEMS technologies might help actuation efficiencies, but address thermal concerns.*

- ☐ *Assuming "stable" focus and funding.*

- ☐ *These estimates assume a significant level of development in this area.*

- ☐ *It all depends on the complexity of the missions. There are simplifications that could make these estimates change significantly. For example, 2-legged locomotion is very difficult but may not be necessary for various applications where dexterous two-arm manipulation and humanoid head/face form is more critical. Or vice versa. Again it is important to consider why humanoid form is being used in particular.*

- ☐ *We've already seen small urban robots getting action (in Afghanistan) and they are only a few years old. The time from research lab to field is getting shorter.*

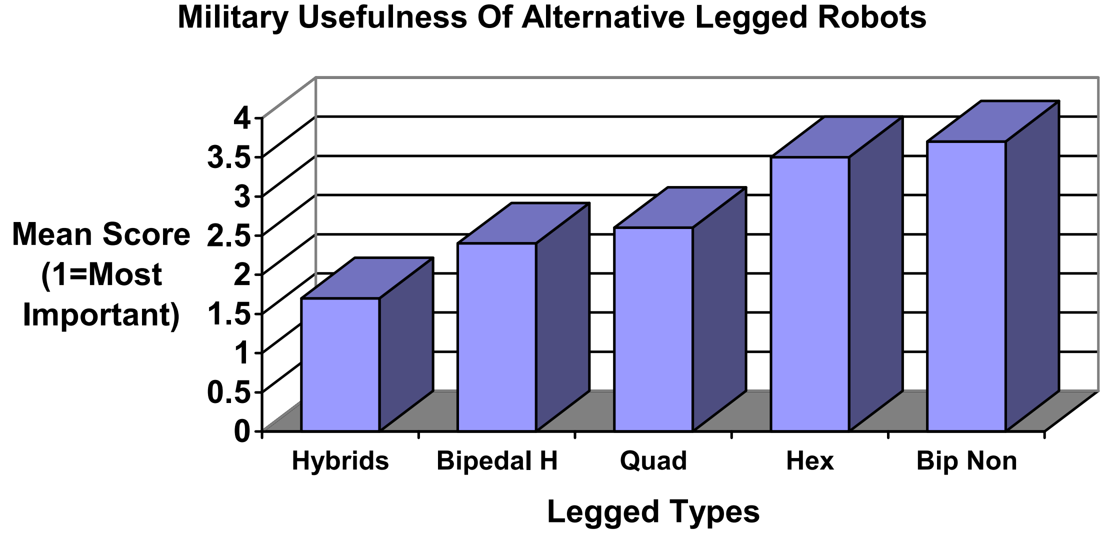
- ☐ *There might be a pessimistic year of "never," since it might be the case that other robots fit the requirements better. My estimate of 2020 assumes a 1-1 direct teleoperation.*

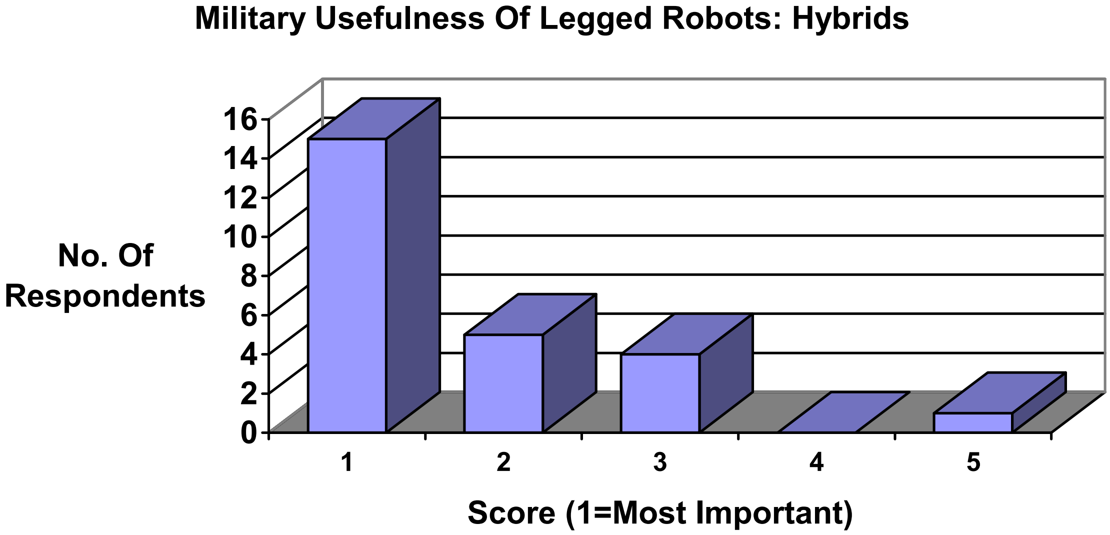
- ☐ *May not be used by the U.S. military first, just as U.S. Army was a late adopter of UAV technology.*

(7) Considering all types of *legged supervised autonomous robots*, which are potentially the *most useful* to the U.S. military. Please rank the alternatives from 1 (the most important) to 5 (the least important):

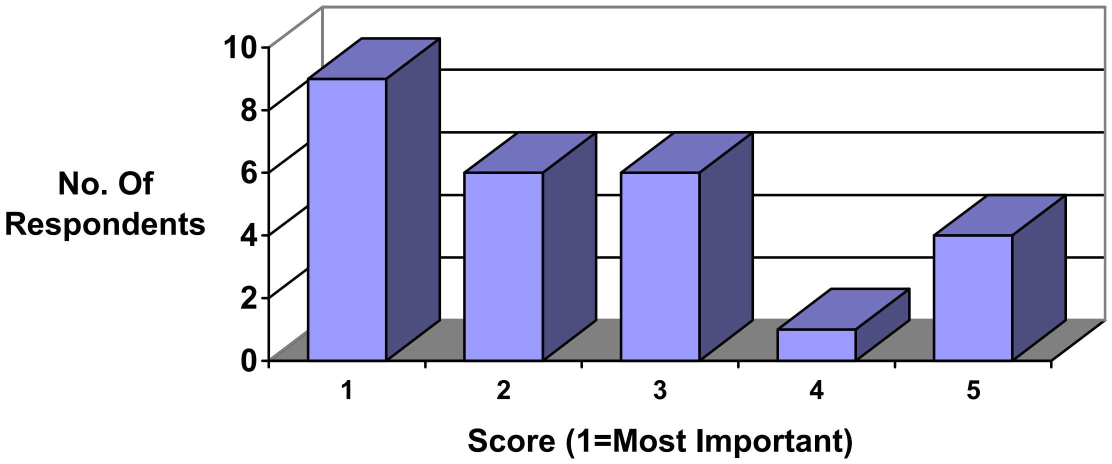
Bipedal humanoid __________
Bipedal non-humanoid __________
Quadruped __________
Hexapod __________
Hybrids (e.g., quadruped with arms, etc.) __________

Statistic	Bipedal Humanoid	Bipedal Non-Humanoid	Quadruped	Hexapod	Hybrids
N	26	25	26	26	25
Mean	2.4	3.7	2.6	3.5	1.7
Sta. Dev.	1.4	1.2	1.2	1.2	1.0
Median	2.0	4.0	2.5	3.5	1.5
Range	1-5	1-5	1-5	2-5	1-5

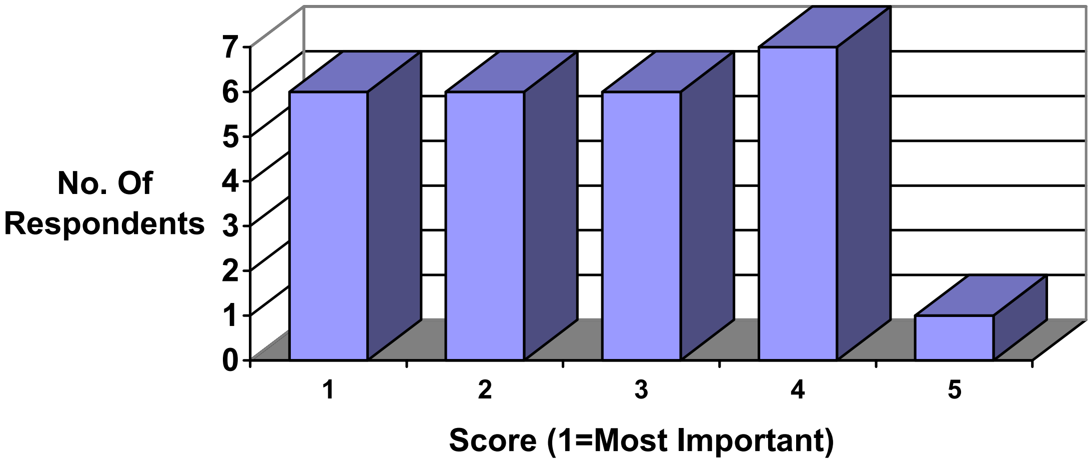




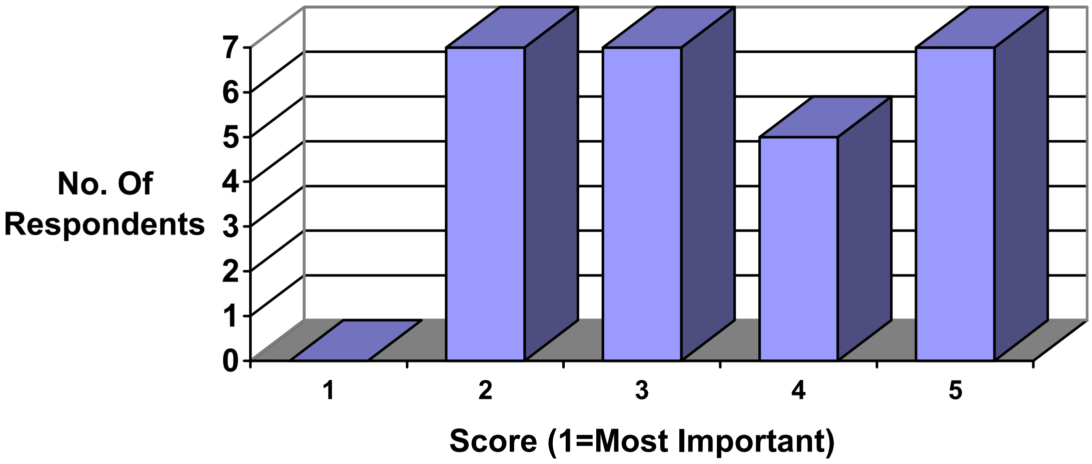
Military Usefulness Of Legged Robots: Bipedal Humanoid



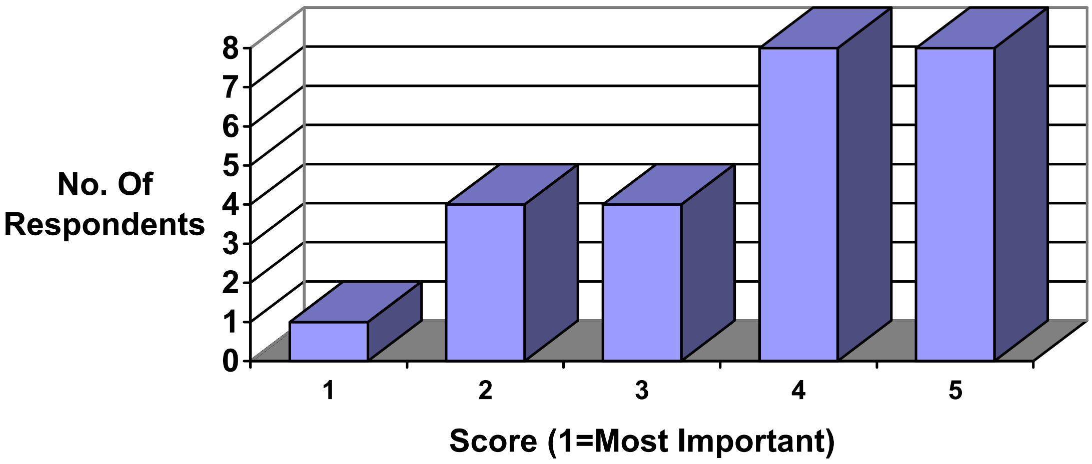
Military Usefulness Of Legged Robots: Quadruped



Military Usefulness Of Legged Robots: Hexapod



Military Usefulness Of Legged Robots: Biped Non-Humanoid



Comments (if any): [The following are verbatim or edited responses].

- ☐ *A robot mule that can carry heavy loads over rough terrain will be most useful. A mule that can open doors and cut fences will also be useful. A biped will be more difficult and expensive, but eventually useful as a buddy on the battlefield. The extra pair of legs on a hexapod has little advantage from a control and dynamics standpoint, and simply is extra weight to carry around. A fact of nature:* ***There are no large land creatures with six legs, and there never have been.***

- ☐ *Hexapods are useful for simple robots, but do not typically have the agility of other systems. Quadrupeds are good for speed, but are beaten by wheeled vehicles in that application.*

- ☐ *I think bipedal robots will ultimately be the most interesting, but there is a lot of basic technology that needs to be developed. Whether the bipeds should be humanoid or not is an open question.*

- ☐ *This is the long range use of autonomous robots. I can quite imagine that in the shorter term hexapods will be useful until our technology progresses to the point of using quadrupeds (as the latter are likely to be faster). With the exception of scouting tasks, I would imagine that most bipedal non-humanoids, quadrupeds, or hexapods, would have optional attachment manipulators (whether in place of a "head/mouth" or attached otherwise) to make them more capable at performing tasks due to the different requirements between manipulation and support/walking/running.*

- ☐ *It will be a matter of fitting through openings designed for humans.*

- ☐ *Applications drive the configuration, but they are limited by existing technologies.*
- ☐ *I am not sure how you're defining humanoid here. To me, humanoid refers most directly to two arms/two legs. The two arms part is critical to the successful application by the military. The mobility base should consist of modular options for an upper body.*

- ☐ *Integrated locomotion and manipulation are key technologies.*

- ☐ *If we attempt to best model the robots to the various task domains, then hybrids are most likely to be successful, even if entirely un-biological in form. The most frequently found insect forms, like hexapods, which have already been proven to be highly effective for rough-terrain navigation are likely to remain so. As stated earlier, purely humanoid form (two legs, two arms, etc.) is likely to be best for limited human-interaction-involved domains. It is difficult to imagine why bipedalism without human form would be of any use at all, given how difficult bipedal locomotion is on its own.*

- ☐ *Quadrupedal robots, I believe, have the potential to have significant impact soon. They are more likely to be more useful, since balance, gait robustness, and speed might be better. They have a lower to the ground profile and a hybrid has the potential to stand bipedally to get their sensing center higher. Bipedal humanoid is better than bipedal* *non-humanoid since one of the main advantages would be a better fit to the soldier operator. The more accurate the telepresence can be, the better the soldier-robot combo will perform. Hexapods are unnecessary since quadrupeds can do whatever hexapods can.*

☐ *Most applications can benefit from a robot or unmanned system which is not human shaped and may have multiple legs. Again, only for those applications involving replacing a human driven machinery or vehicle, or operating in a facility specifically designed for human mobility, is where a humanoid buys any benefits. These are important but, not dominant in military missions.*

☐ *So many application environments (crew stations) are designed around an anthropomorphic form factor, that it's hard to imagine anything else being more useful.*

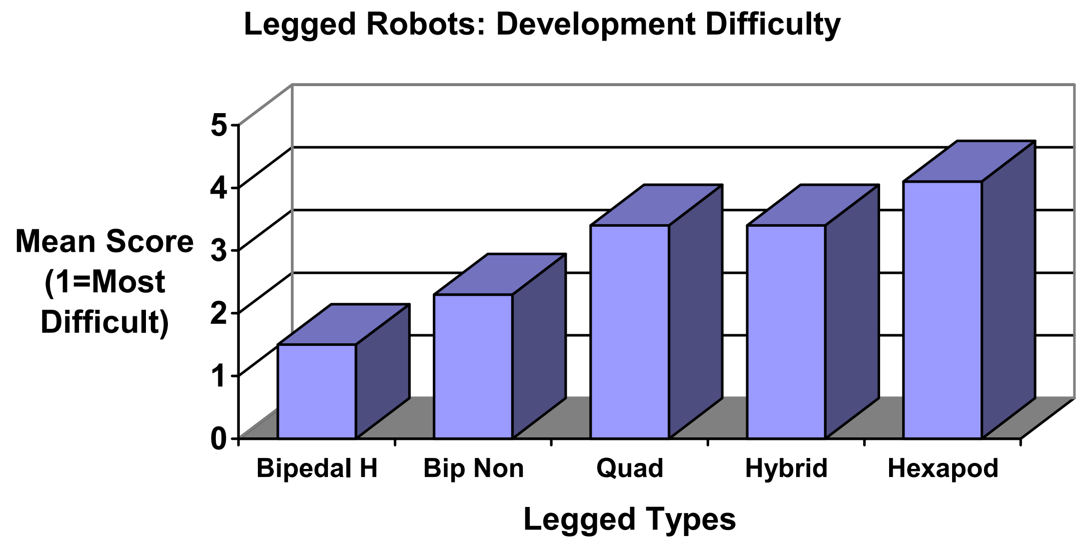
☐ *This is very application dependent. I think miniature hexapods could be most important for stealthy surveillance/recon with very small, simple robots. Bipeds are useful for adaptability. Quadrupeds are useful as "pack mules."*

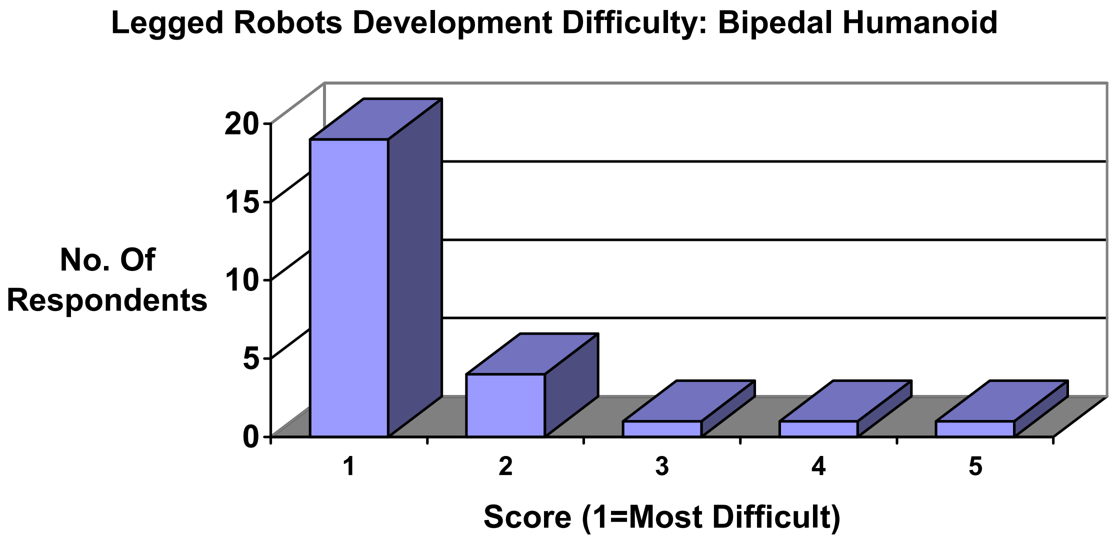
☐ *It is hard to determine - most useful for what? Bipedal may be most difficult technically, relative to balance in some situations. Why develop humanoid only to look like human? Where is the utility?*

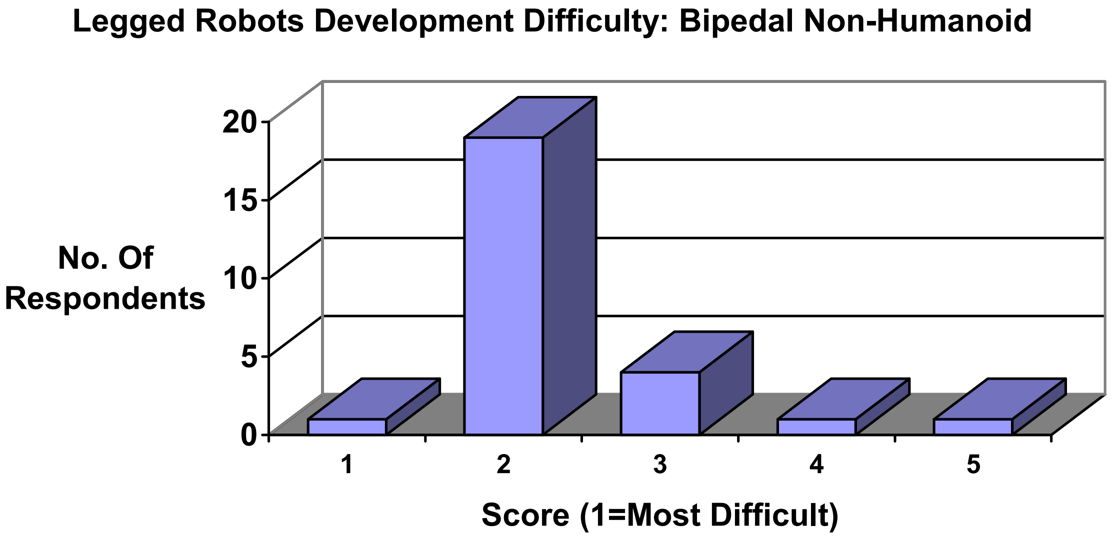
(8) Considering all types of supervised *legged autonomous robots*, which are potentially the *most difficult* to develop into useful systems for the U.S. military. Please rank the alternatives from 1 (the most difficult) to 5 (the least difficult):

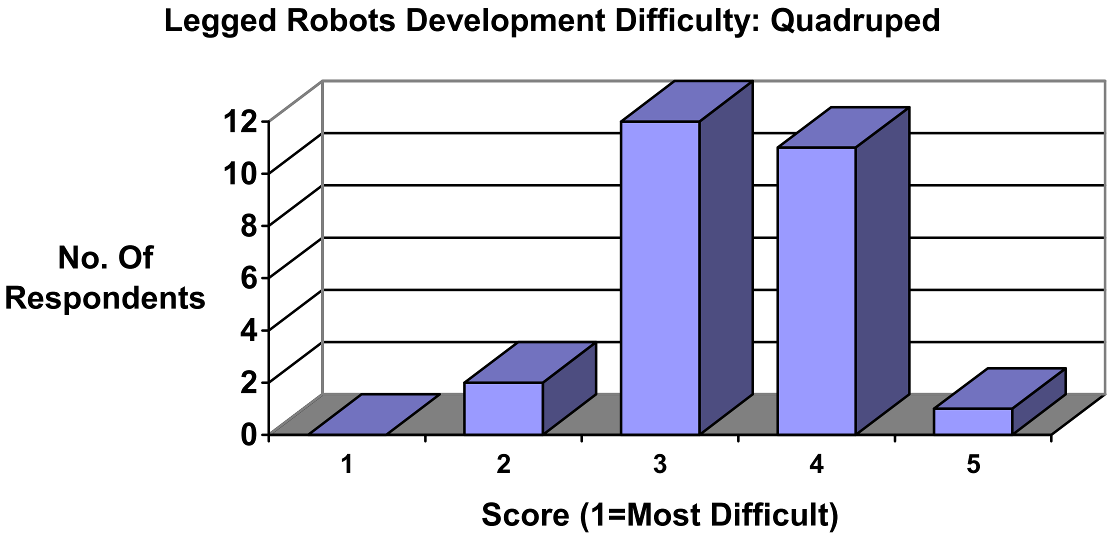
Bipedal humanoid __________
Bipedal non-humanoid __________
Quadruped __________
Hexapod __________
Hybrids (e.g., quadruped with arms) __________

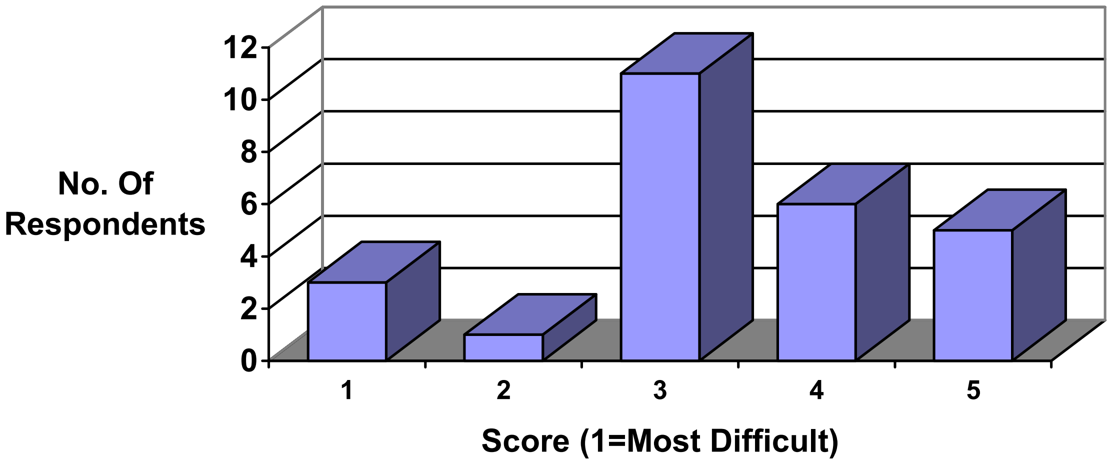
Statistic	Bipedal Humanoid	Bipedal Non-Humanoid	Quadruped	Hexapod	Hybrids
N	26	26	26	26	25
Mean	1.5	2.3	3.4	4.1	3.4
Sta. Dev.	1.0	0.79	0.70	1.1	1.2
Median	N/A	N/A	3.0	N/A	N/A
Range	1-5	1-5	2-5	2-5	1-5


Legged Robots: Development Difficulty
Mean Score (1=Most Difficult)
0
1
2
3
4
5
Bipedal H
Bip Non
Quad
Hybrid
Hexapod
Legged Types

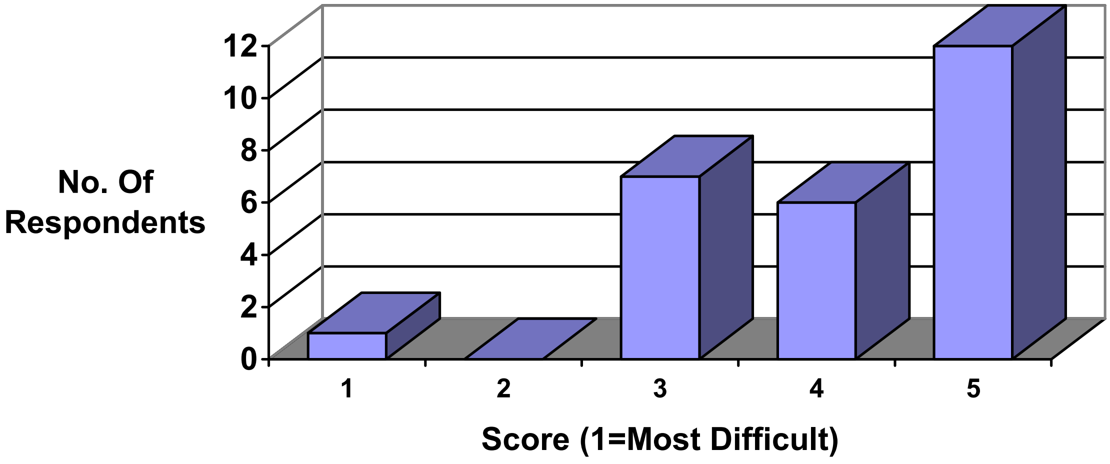

Legged Robots Development Difficulty: Bipedal Humanoid
No. Of Respondents
0
5
10
15
20
1
2
3
4
5
Score (1=Most Difficult)


Legged Robots Development Difficulty: Bipedal Non-Humanoid
No. Of Respondents
0
5
10
15
20
1
2
3
4
5
Score (1=Most Difficult)


Legged Robots Development Difficulty: Quadruped
No. Of Respondents
0
2
4
6
8
10
12
1
2
3
4
5
Score (1=Most Difficult)



Legged Robots Development Difficulty: Hybrid



Legged Robots Development Difficulty: Hexapod

Comments (if any): [The following are verbatim or edited responses].

☐ *A bipedal humanoid is hardest because of posture, foot placement, and the dynamics of running, jumping, falling and recovering. A hybrid is more difficult than quadruped because of arms and hands for manipulation tasks. A quadruped is harder than hexapod because of need to compute dynamics for trotting, galloping, and bounding. A Hexapod is easiest because there is no need to worry about dynamics.*

☐ *As above: hexapods might be a useful stepping stone to quadrupeds. Quadrupeds are a better alternative to hexapods as they are likely to be faster and more capable (if the robot is of any significant size) due to the decreased weight. While mechanics are a challenging problem, I feel that control and learning are the real challenges that will make legged robots capable – or not, as the case may be.*

☐ *The Hexapod is the easiest, and the true android is the most difficult, based on the form factor.*

☐ *Bipedal locomotion is more difficult than multi-legged approaches. While fully humanoid forms are very valuable for working within an existing infrastructure, I believe many engineering aspects of locomotion, balance, force application, etc. are easier to develop if you have a multi-legged base to work with.*

☐ *A hybrid robot can be of any convenient and useful form (and not constrained, a priori, to some predetermined configuration), and so it should be the easiest to develop into a useful military system. It would be most difficult to duplicate the manifold characteristics of the bipedal human form.*

☐ *As I stated above, hexapod navigation has already been demonstrated extensively and is well within the state of the art; similarly for quadruped locomotion, but with added complexity. For machines of small and medium size, it is hard to imagine why 6 legs are not the best option in almost all cases. As the number of legs decreases, locomotion challenge increases, and this has to be duly justified. By the time we are down to 2 legs, it really better be worth the complexity of balance and locomotion. Humans are bipedal due to the process of evolution, but why do our robots need to be?*

☐ *This is a difficult question that depends a lot on the size of the various robots.*

☐ *My response is based on current technology (especially Japanese work.)*

(9) What is your estimate of *the cost* (in today's dollars) of a militarily useful supervised autonomous *humanoid* robot by *2020*? Please insert your estimate of the unit cost (in dollars) for each case below:

Optimistic cost ______________
Pessimistic cost ______________
Most likely cost ______________

TYPE COST	**MEAN ($)**	**STA. DEV. ($)**	**N**	**MEDIAN ($)**	**Range ($)**
Optimistic	285,700	336,516	20	150,000	9,000-1,000,000
Pessimistic	482,500	3,141,080	20	1,500,000	100,000-10,000,000
Most Likely	813,750	973,783	20	650,000	50,000-4,000,000

Results: Using a Beta distribution assumption: **Expected (Mean) Unit Cost = $1,003,866; Standard Deviation = $366,133.**

Comments (if any): [The following are verbatim or edited responses].

- ☐ *My estimate is based on the assumption of a few hundred units. For quantities of thousands, software development and sensor development costs can be amortized, and costs may be discounted by 50% or more.*
- ☐ *Much of the costs of the device are in the sophistication of sensors and telemetry. Unsophisticated units may cost less. On the other hand, costs will increase with the "athletic" capability of the unit. Also, costs of supervision, support, and transport for the unit may far outstrip the stand-alone cost of the unit itself. This is too general a question.*
- ☐ *I have no idea so my estimate would not be useful.*
- ☐ *As with any technology, price will depend on volume. We think that humanoid robots will not involve fundamentally expensive technologies such as jet engines that require special materials, so there is no reason why, in sufficient quantities, they could not be produced for the cost of an automobile.*
- ☐ *Cost is relative. If the project could leverage existing work, and be sustained for a limited period of time, this could work wonders with the average American innovation. It would not seem like the rest of the world is passing us by because our only effort is an academic exercise.*
- ☐ *Cost will decrease with the market – the humanoid industry predicts a cost comparable to that of a car – yearly lease of the humanoid robot Asimo is about $20K.*
- ☐ *I have no good way to estimate these costs.*

☐ *If you meant R&D costs, not individual robot cost, the recent Japan humanoid project cost about $500 million, I believe. The results are far away from a militarily useful humanoid. There's a lot of work to be done in a large number of related fields. I'd say twice that effort. If the focus were on military, a project could potentially result in a militarily useful supervised humanoid. If you go with 100% teleoperation, then I think a $50 million effort might get you close. A pessimistic R&D cost of $10 billion is based on the fact that this might be a harder feat than putting a man on Mars.*

☐ *Production quantity matters tremendously and it could bring down the cost to less than $20k.*

☐ *It should be the cost of a smart weapon (JSOW, AMRAAM, etc.).*

☐ *Cost is very dependent on size and ability. Man-portable, mini-bipeds could be very cheap. Human-size robots will be very expensive. All these estimates are in high volume and targeted for simpler, utility/defensive applications. (An infantry robot would be very expensive due to liability, etc.).*

☐ *Is this a production unit? How many are there? Is the total life cycle cost?*

(10) What is your estimate of *the cost* (in today's dollars) of a militarily useful supervised autonomous *quadruped or hexapod* robot by *2020*? Please insert your estimate of the unit cost (in dollars) for each case below:

Optimistic cost ______________
Pessimistic cost ______________
Most likely cost ______________

TYPE COST	MEAN ($)	STA. DEV. ($)	N	MEDIAN ($)	Range ($)
Optimistic	173,750	184,632	20	150,000	5,000-500,000
Pessimistic	1,870,000	3,171,020	20	550,000	100,000-10,000,000
Most Likely	633,750	1,131,146	20	200,000	50,000-5,000,000

Using a Beta distribution assumption: **Expected (Mean) Unit Cost = $763,125; Standard Deviation = $282,708.**

Comments (if any): [The following are verbatim or edited responses].

☐ *The costs are the same as the humanoid, with the same assumptions of numbers. Control and sensing are simpler, but there are more and heavier actuators and mechanical structures.*

☐ *Same cost as the humanoid, except perhaps for the cost of the added "legs."*

☐ *I base this on the current cost of Packbots, the first militarily deployed robots in Afghanistan. They are currently $45K per unit, although lifetime maintenance adds to that significantly, but the replacement cost on the day of delivery is $45K per unit. Legged robots would be much more expensive today, but I expect Packbots to be down to the sub $5K level by 2020.*

☐ *I have no idea so my estimate would not be useful.*

☐ *The above numbers assume a large enough platform to carry weapons or materiel. There will also be a market for small insect-like hexapods for surveillance applications.*

☐ *We do not have to worry about balancing, but we have the other problem of coordination.*

☐ *Assuming some support from product volume in associated areas.*

☐ *Smaller legged robots will be much less expensive.*

☐ *Again, I have no way of estimating this other than to say that this is likely to be less costly than bipedal locomotion if we are basing the cost on the difficulty of the problem. But both are well worth pursuing.*

☐ *The number of units is of course a large factor here.*

☐ *Again, if you meant R&D costs and not individual robot costs: A hexapod like RHex is probably fieldable today in many limited situations. Developing a quadruped could cost (R&D) as little as $1.8 million, if off the shelf power components are feasible. My company will soon be performing an Army SBIR study to see if such a robot is feasible. If not, then more research in power sources and actuation technology will be required.*

☐ *If the robot has multi-segmented legs, e.g., 3 joints per leg, the costs for quadrupeds and hexapods quickly becomes as high as for the humanoid robot.*

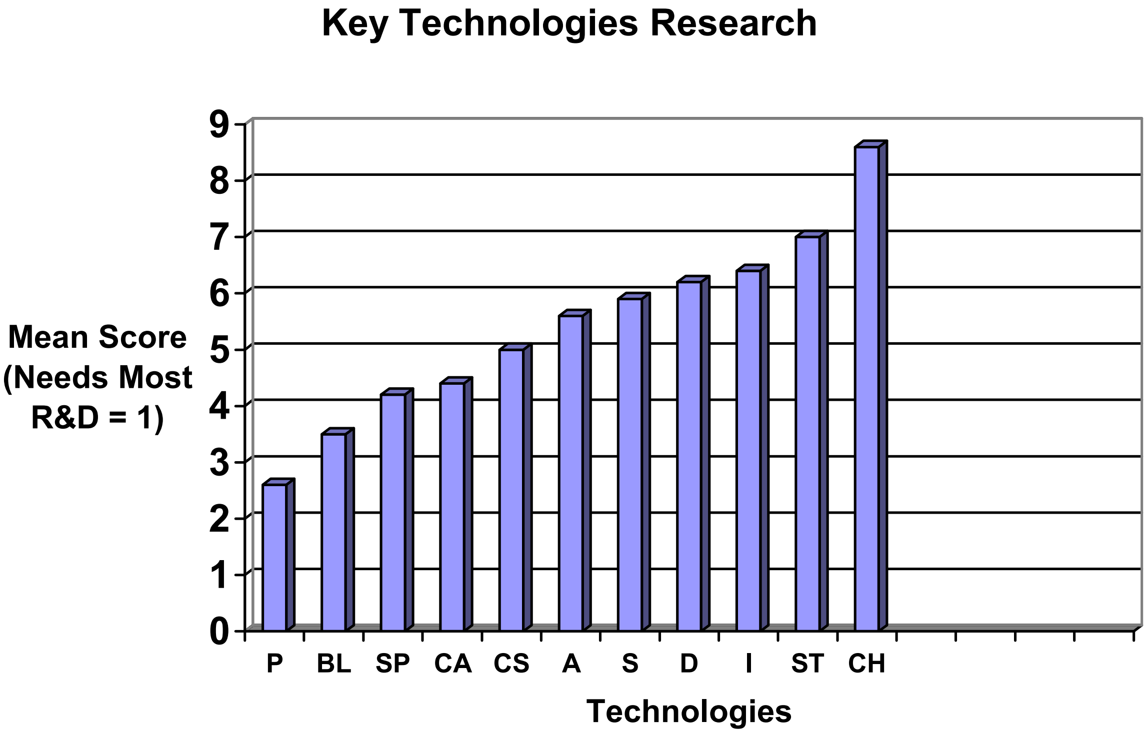
☐ *My estimate assumes no manipulator.*

☐ *A miniature hexapod for recon with little autonomy could be quite cheap. Most quadrupeds will be material handling types with minimal intelligence (i.e. platooning), but with significant payload capability.*

(11) Which *key technologies* need the most research and development in order to achieve significant improvements in supervised autonomous humanoid robotics? Please score each of the choices from 1 (needs the *most* R&D) to 11 (needs the *least* R&D):

Sensors ______________
Sensor processing ______________
Computer software ______________
Software tools ______________
Control system architectures ______________
Databases and world modeling ______________
Bipedal leg control/balance/mobility ______________
Arms and end effectors ______________
Computer hardware and hardware architecture ______________
Propulsion and energy systems ______________
Human/Robot interfaces ______________
Other (please describe) ______________

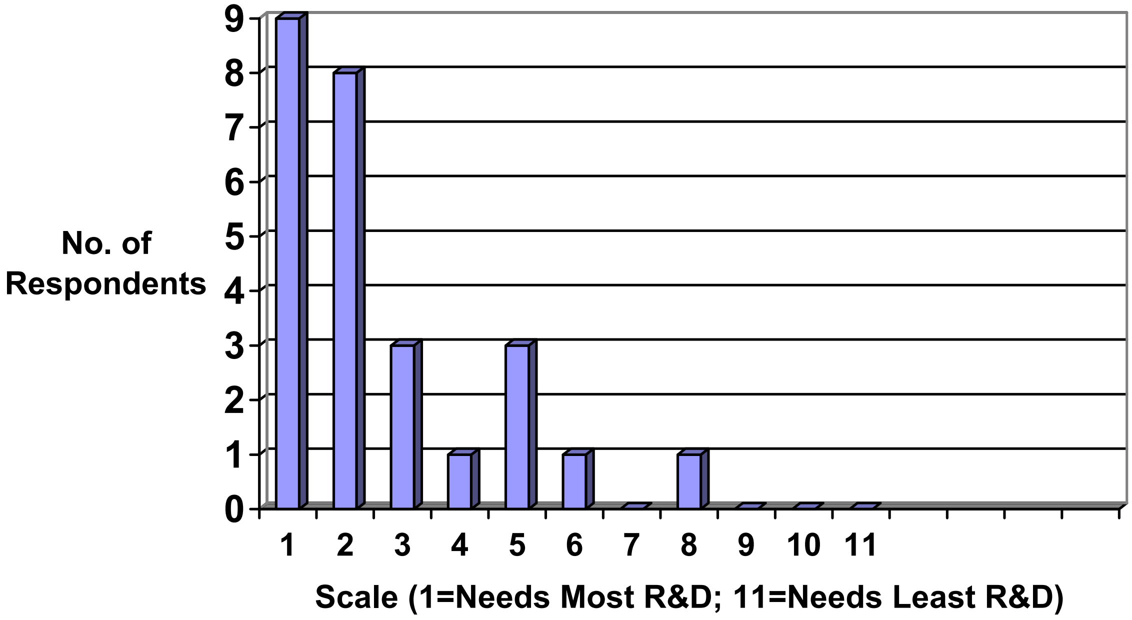
Technology/Statistic	**Mean**	**Sta. Dev.**	**N**	**Median**	**Range**
Sensors	5.9	2.4	26	5.5	3-10
Sensor Processing	4.2	2.5	26	4.0	1-9
Computer Software	5.0	3.3	26	4.5	1-11
Software Tools	7.0	3.0	26	6.5	1-11
Control Sys Arch	4.4	2.6	26	4.0	1-9
Databases, Modeling	6.2	2.8	26	6.0	1-10
Bipedal Leg Control	3.5	2.9	26	2.5	1-11
Arms, End Effectors	5.6	2.8	26	6.0	1-10
Computer Hardware	8.6	2.6	25	8.5	1-11
Propulsion, Energy	2.6	1.9	26	2.0	1-8
Interfaces	6.4	3.1	26	6.5	1-12
Other	2.0	1.7	3	2.0	1-4



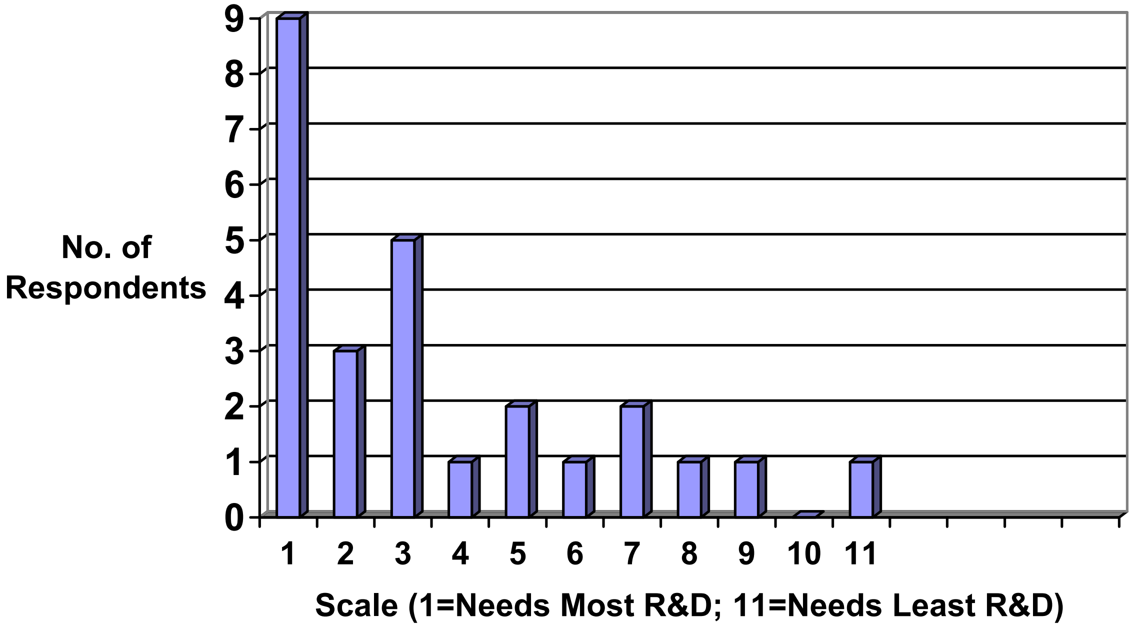
Key to Technologies on Chart

P = Propulsion, Energy
BL = Bipedal Leg Control
SP = Sensor processing
CA = Control System Architecture
CS = Computer Software
A = Arms, End Effectors
S = Sensors
D = Databases, World Modeling
I = Interfaces For Humans/Robots
ST = Software Tools
CH = Computer Hardware

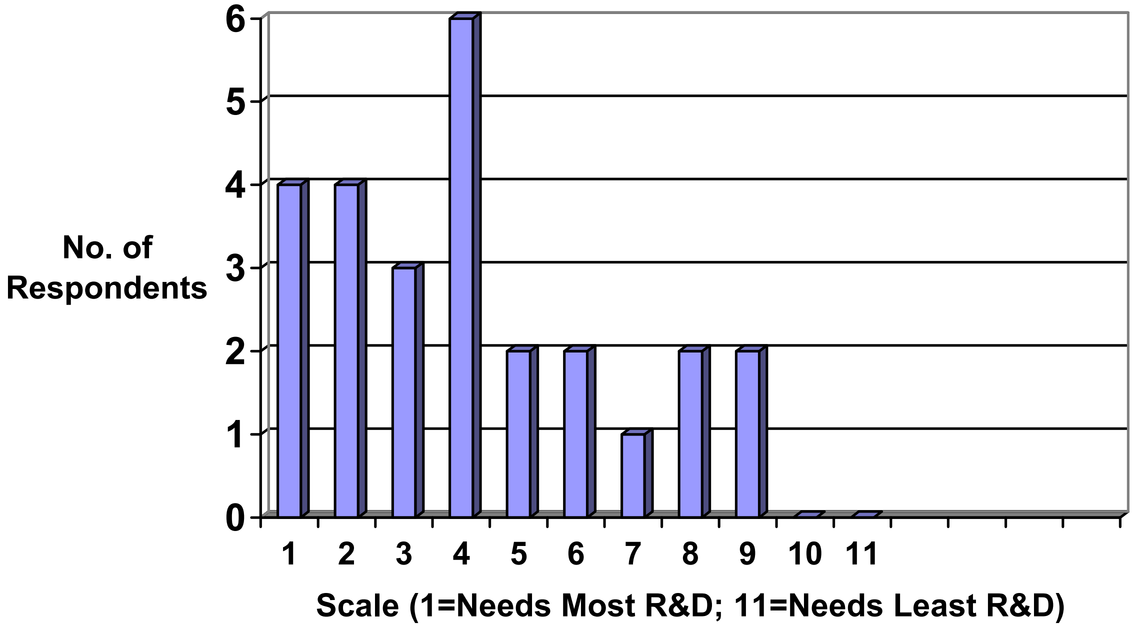
Evaluation Of Key Technologies: Propulsion



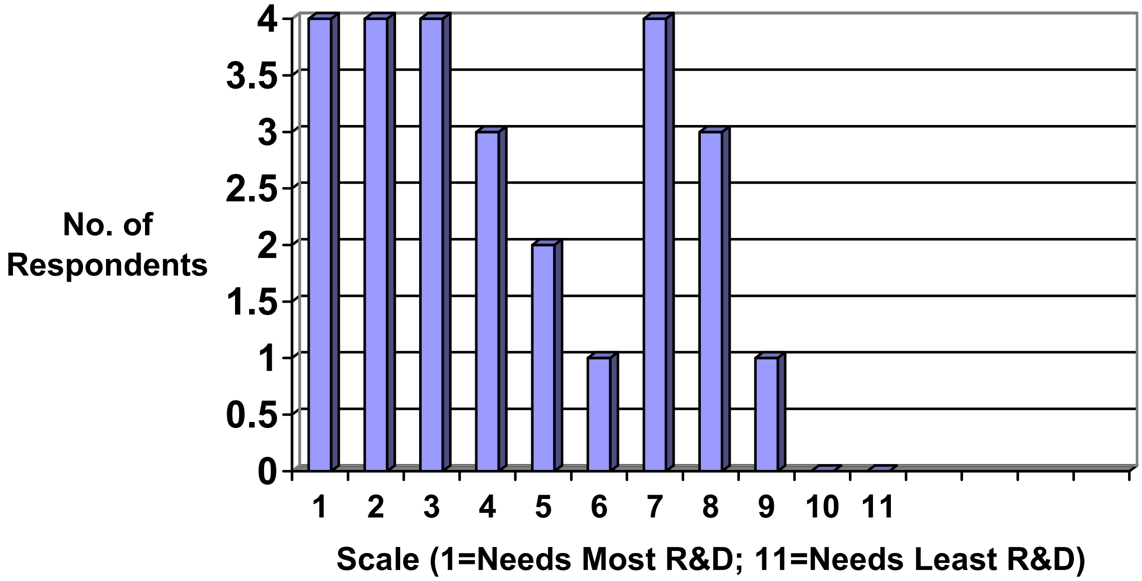
Evaluation Of Key Technologies: Bipedal Leg Control



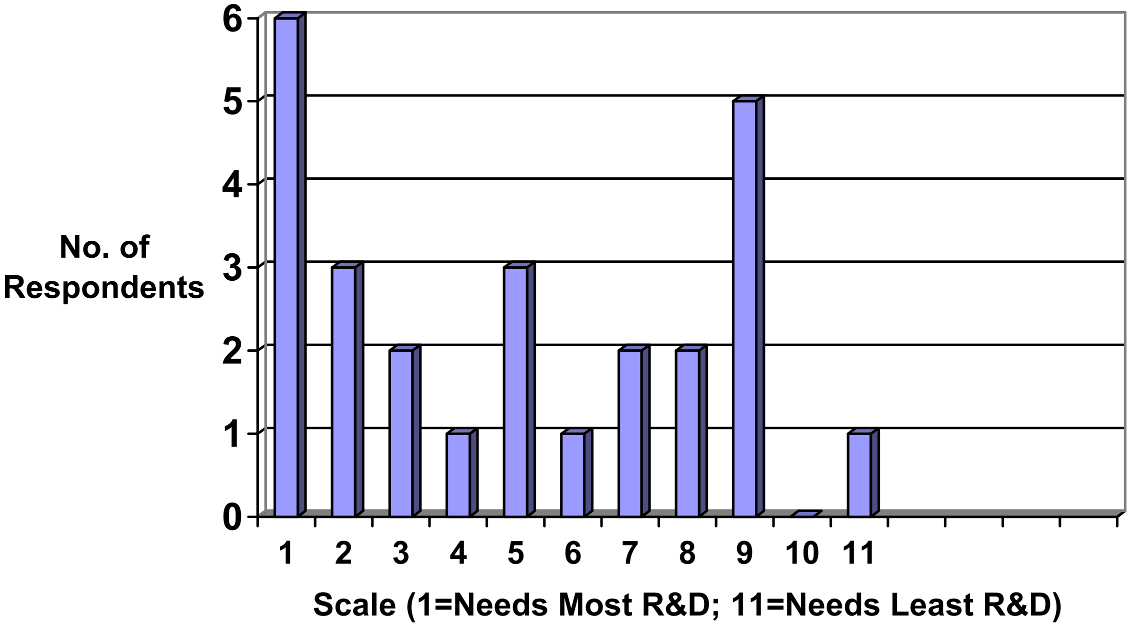
Evaluation Of Key Technologies: Sensor Processing



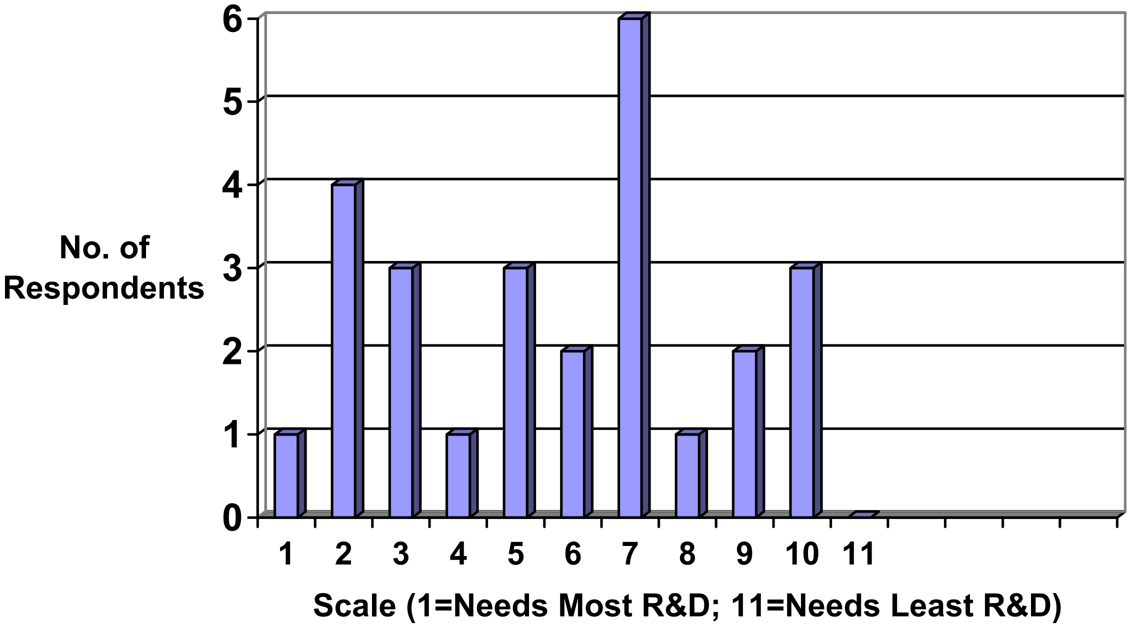
Evaluation Of Key Technologies: Control System Architecture

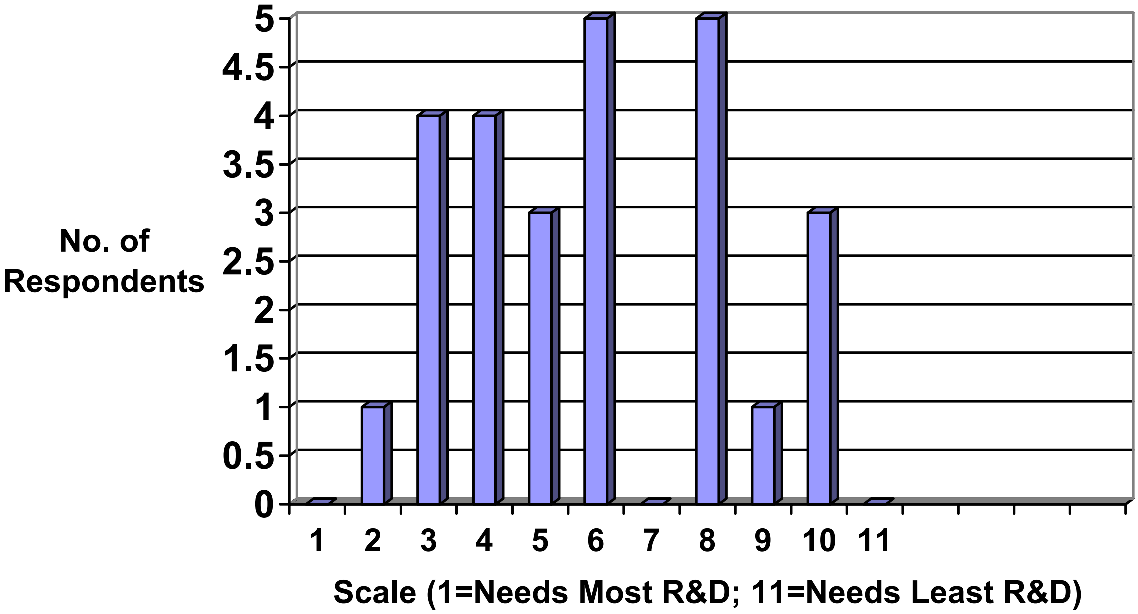


Evaluation Of Key Technologies: Computer Software

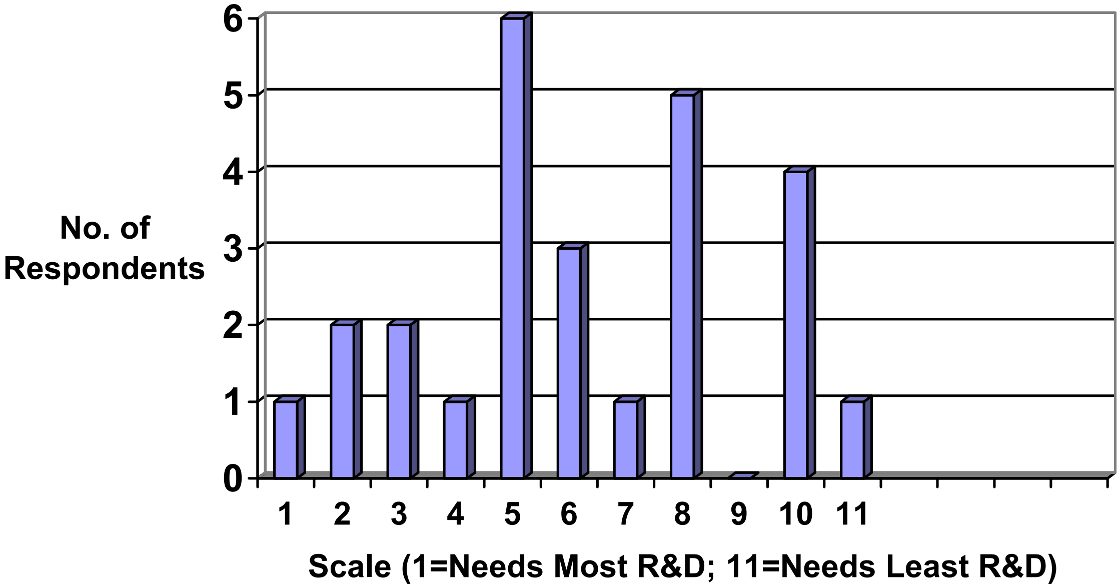


Evaluation Of Key Technologies: Arms & End Effectors



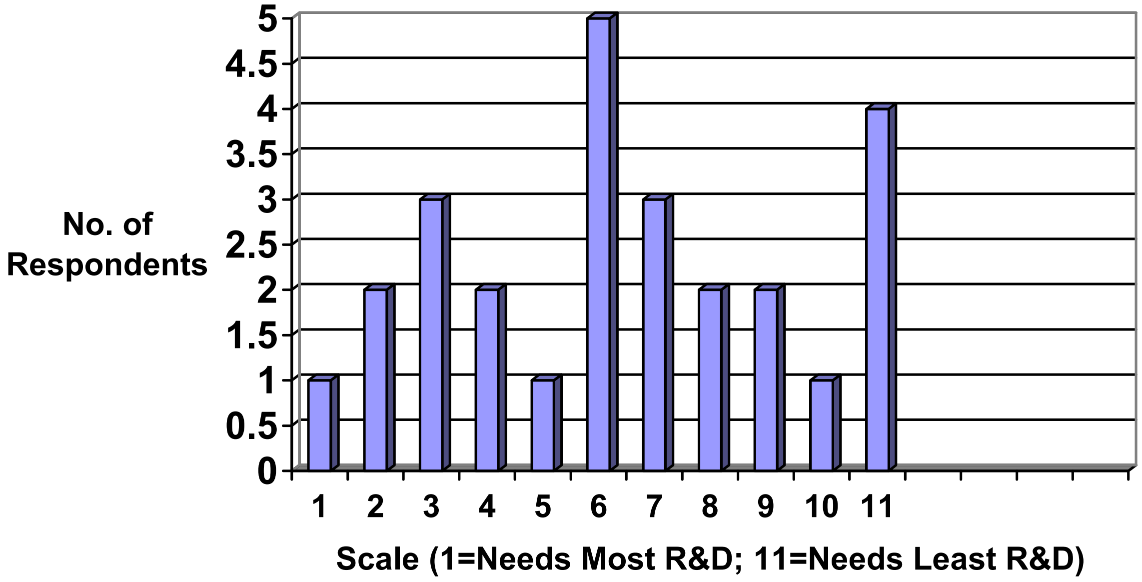


Evaluation Of Key Technologies: Sensors

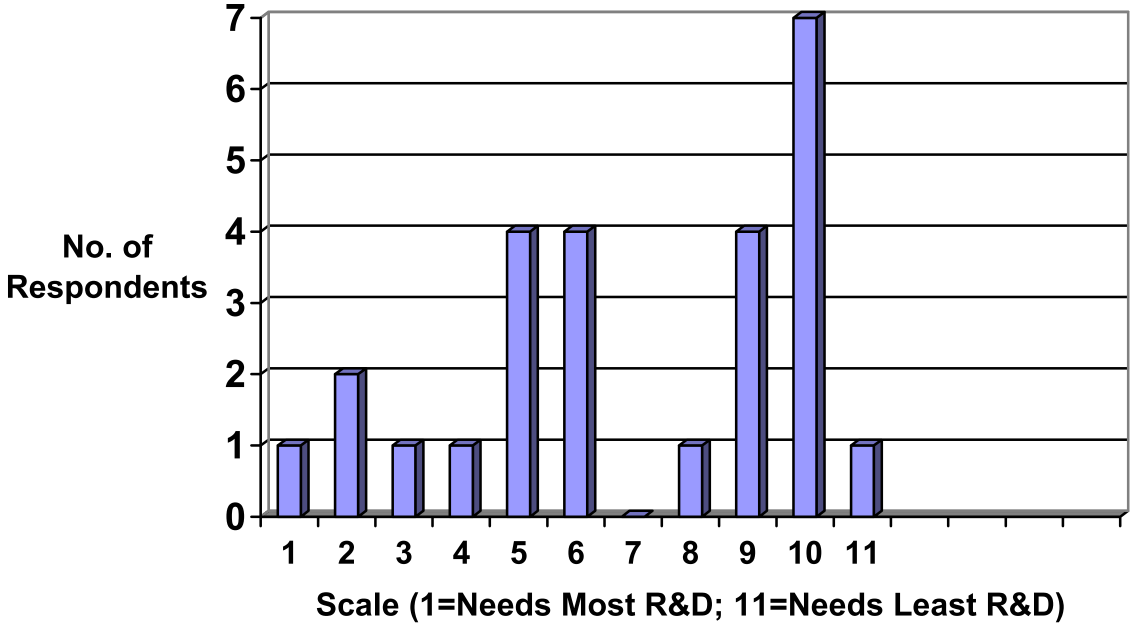


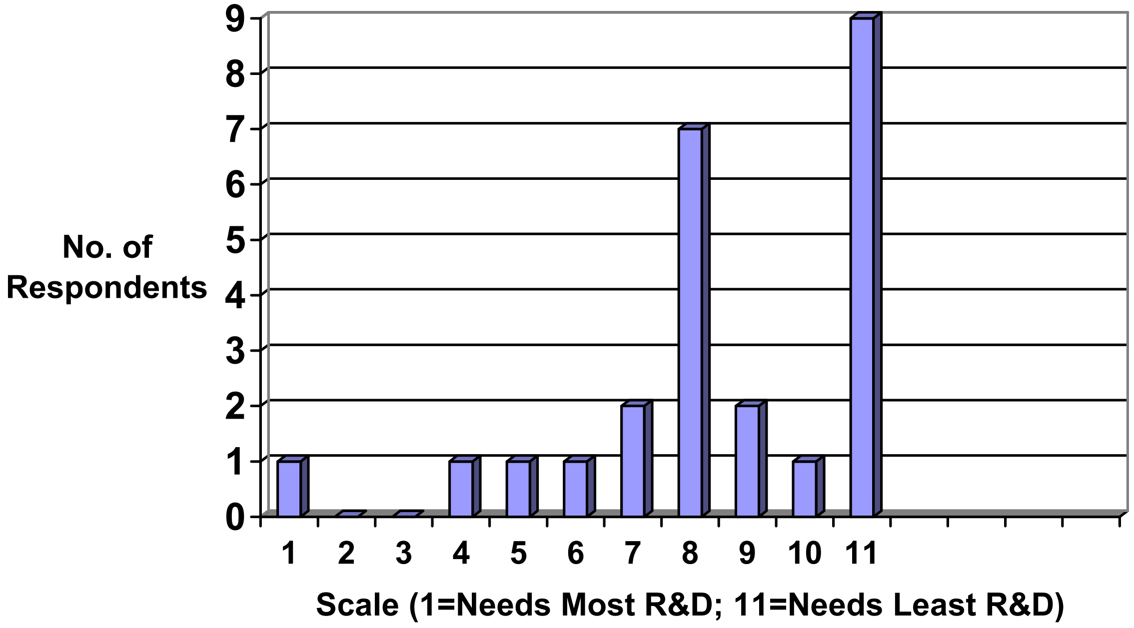
Evaluation Of Key Technologies: Databases & World Modeling

Evaluation Of Key Technologies: Interfaces For Humans/Robots



Evaluation Of Key Technologies: Software Tools





Evaluation Of Key Technologies: Computer Hardware

Comments (if any): [The following are verbatim or edited responses].

- *The artificial equivalent of leg muscles is biggest challenge, followed closely by a power source that can produce enough power from diesel fuel with good efficiency and impedance match. Sensors and perception are next, followed at considerable distance by the others.*

- *The key to humanoids will be control, learning and adaptation. Clearly, to walk/run/climb etc requires good control techniques. More importantly, we need the ability to quickly reconfigure humanoids and teach them new tasks. This implies robust learning techniques which will inherently require good human/robot interface mechanisms. It will be virtually impossible to code by hand a many DOF humanoids with any reliability. We will clearly require the hardware mechanisms to allow the robots to be capable of a diverse range of activities. However, I feel that this challenge can easily be met, provided we have the industry interest and support to investigate the necessary approaches. World modeling, debugging techniques will be required pervasively to make it really work.*

- *I think the stepping stone will be through direct control of the end effectors at short distances for latency. Humanoid robots will sell for social issues. Telepresence is a potential application, along with replicating human operator movements.*

- *Software is the key.*

☐ *They are all important, and we require multiple areas to progress simultaneously to reach our goal.*

☐ *Other: Adaptivity and the ability to learn in order to cope with uncertainty and changing environments and tasks; also the development of springy, compliant materials for the bodies of such machines and control techniques for managing them.*

☐ *There are various open research issues above and it is hard to rank them. However, some are clear to be major issues: energy, human-robot interaction, control of walking and complex arms, two-arm interaction, modularizing complexity of trajectory planning, etc. to allow real-time movement and response.*

☐ *Certain topics will be covered by the private sector regardless of government funding. Computer processors and architectures will continue to advance at great speeds without government funding. Other topics, such as original humanoid robotic hardware, need specifically DARPA money because the private sector has no motivation for funding or research.*

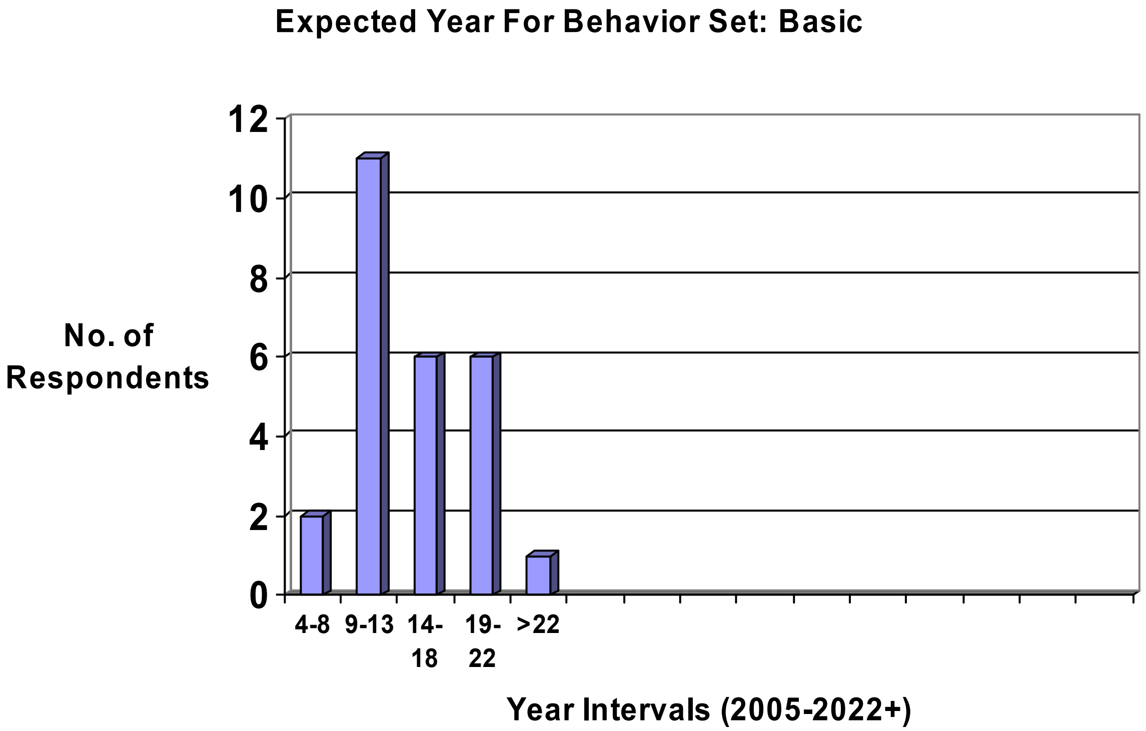
☐ *In ordering these, I took the view of a mostly-teleoperated robot. That's why I scored human/robot interfaces as important and world modeling as not important.*

☐ *Other: systems integration, a systems approach, to make this work; and intelligent behavior algorithms.*

(12) By which *year* will supervised autonomous humanoid robots be able to demonstrate *all* of the following example behaviors: *(1) manipulation*: load, aim, and shoot a rifle; unlock a door with a key; collect environmental samples; disable explosives; cut the pant leg of a wounded soldier and apply appropriate pressure to a wound; *(2) perception and cognition*: locate and map suitable foot placement; *(3) dynamics*: compute posture and balance; *(4) legs*: carry loads of practical size and weight over uneven terrain. (Please place an "X" on the appropriate position along the scale)?

Results: n = 26; **M = 2015** Sta. Dev. = 6.0; **Median ~ 2014**; Mode = 2009-2013; Range = 2005-2022+

/---------/---------/---------/---------/---------/----X----/---------/---------/---------/--------/
2004 06 08 10 12 14 16 18 20 22 >22
Year



Comments (if any): [The following are verbatim or edited responses].

☐ *Much depends on funding levels. This estimate is based on my best guess of a funding profile.*

☐ *The abilities to disable explosive and cut pant legs are much harder than other tasks listed.*

☐ *When these particular supervised functions can be demonstrated depends on the urgency of the project. I believe they could be demonstrated in just a few years. Otherwise, the question is one of prediction.*

☐ *Manipulation (1) is the hardest of these. The rest will be much earlier and easier.*

☐ *This assumes a major, broad industry (for hardware) and research (to use the hardware) initiative to achieve these goals. There are key research challenges that are perhaps more difficult than any currently addressed in robotics. It is not going to be easy, but I believe is very doable.*

☐ *We believe that 1 is far more difficult than 2, 3 and 4.*

☐ *By 2012 there might be crude operations, with refined and more sophisticated operations a few years later. The second time around is always better.*

☐ *Obviously depends upon the level of investment.*

☐ *Assuming development starts now.*

☐ *Assuming just the specifications listed and the simplest solution to that problem.*

☐ *Fielding and demonstrating are two very different levels of maturity. Many of these items are almost ready now, but far from being fielded.*

☐ *I think (1) is the limiting factor here.*

☐ *This is asking for way too much. Some of these tasks, such as disable explosives, will need to be completely teleoperated well beyond our lifetimes. Therefore, I again will assume that the robot is operated one to one with a talented soldier in a telepresence situation. In that case, perhaps 2020 at the earliest, but I'd say more like 2030.*

☐ *Being able to aim and shoot a rifle, particularly one which is not adapted to work with the android, but one which the android adapts to, would be the most challenging of these tasks. It is an area which has not been worked on, as have the other areas for unmanned and robotic vehicles.*

☐ *Most of these tasks are doable now (or soon) as scripted behaviors. The trick is having the robot know "when" to execute said behaviors, and in what order (behavior aggregation).*

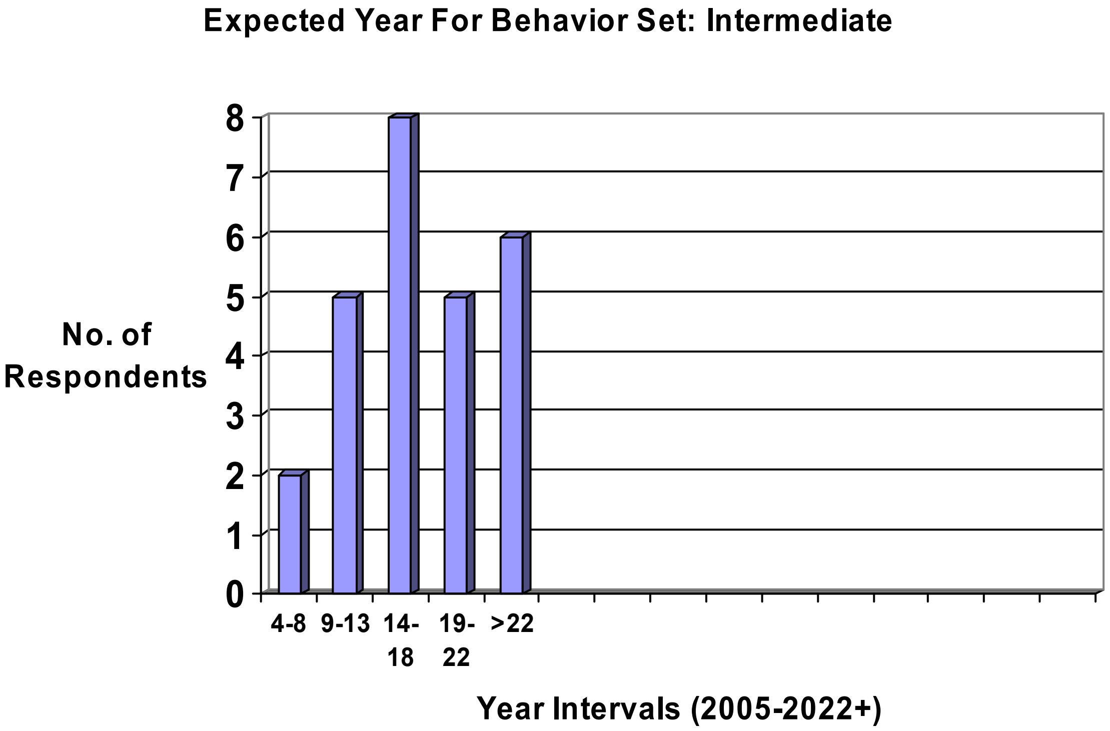
☐ *These tasks could be done sooner in a research environment.*

☐ *Treating a wound is an area that requires high levels of understanding and decision making – not practical for a robot.*

(13) By which *year* will supervised autonomous humanoid robots be able to demonstrate *all* of the following example behaviors: *(1) manipulation*: pick up and carry a wounded soldier to safety; give injections and IVs to the wounded; apply telemedicine intervention; change a tire; *(2) perception and cognition*: detect, classify, and track moving objects, including humans and vehicles; interact safely with humans; *(3) dynamics*: run, jump, and crawl; fall safely and get up; *(4) legs*: operate in an outdoor urban environment with tactical posture and gait. (Please place an "X" on the appropriate position along the scale)?

Results: n = 26; **M = 2019** Sta. Dev. = 7.7; **Median ~ 2017**; Mode = 2014-2018; Range = 2005-2022+

/---------/---------/---------/---------/---------/---------/---------/---------/--------X/---------/--------/
2004 06 08 10 12 14 16 18 20 22 >22
Year



Comments (if any): [The following are verbatim or edited responses].

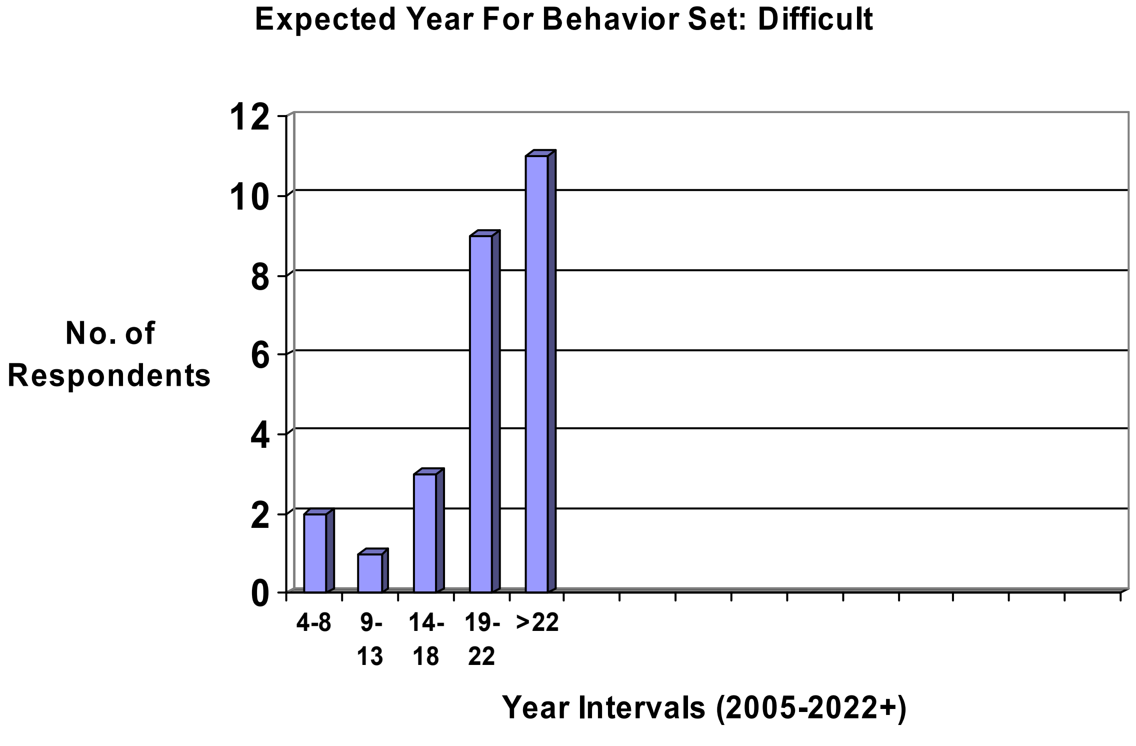
- ☐ *It could happen much sooner, if sufficient funds are thrown at it.*
- ☐ *Again, this list is wildly varying in difficulty, with applying IVs difficult for even humans to do.*
- ☐ *Four years more than for the previous question.*
- ☐ *Again, (1) is the hardest. The others will happen earlier.*
- ☐ *This forecast is based on a continuous effort, starting now. Advancement will come over a period of time.*
- ☐ *Assuming development starts now.*
- ☐ *These tasks demand a higher sensor processing fidelity/bandwidth than is currently practical.*
- ☐ *These tasks could be done sooner in a research environment.*

☐ *I think more than 22 years plus – I do not think you would want a machine administering IVs and injections.*

(14) By which *year* will supervised autonomous humanoid robots be able to demonstrate *all* of the following example behaviors: *(1) manipulation*: rescue victims from rubble and wreckage; suture wounds; *(2) perception and cognition*: analyze many tactical and other situations, solve problems, and devise solutions; *(3) dynamics*: climb, rappel, and parachute; *(4) legs*: operate in an outdoor urban environment with tactical posture and gait. (Please place an "X" on the appropriate position along the scale)?

Results: n = 26; **M = 2023** Sta. Dev. = 7.2; **Median ~ 2021**; Mode = >22; Range = 2006-2022+

/---------/---------/---------/---------/---------/---------/---------/---------/---------/---------/-------X/
2004 06 08 10 12 14 16 18 20 22 >22
Year



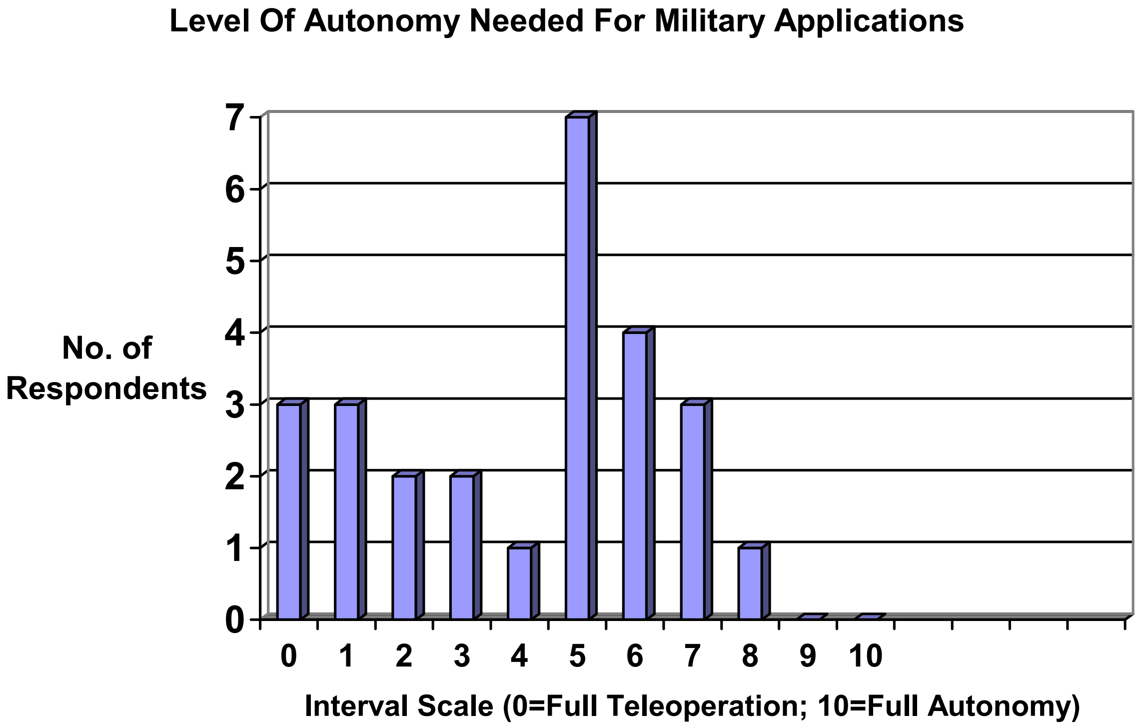
Comments (if any): [The following are verbatim or edited responses].

- ☐ *Four years more than the previous question. However, this question, if not the others, implies some level of "perceptive and cognitive" autonomy. In my answers I have keyed on the notion of "supervised" devices. Partial or full perceptive and cognitive autonomy is a whole different issue.*
- ☐ *When we can do all the things in the previous question, we'll be able to do the behaviors in this question.*
- ☐ *Sometime beyond my last answer. The first industrial prototype will be able to do only 85% of its intended operations. It cannot do everything for everybody. However, it will be repeatable and adaptable to multiple applications.*
- ☐ *Presuming that (1) is significantly supervised and that (2), (3), and (4) are largely autonomous.*
- ☐ *Some of these problems are very difficult, like rappelling in real situations. Devising solutions is also a pretty big category.*
- ☐ *These are all feasible, again, in a teleoperated sense, but "perception and cognition**:** analyze many tactical and other situations, solve problems, and devise solutions"! Many of today's soldiers aren't even required to be able to do that. I would put a year of about 3000 on cognition. Easier problems which will be solved before then: living forever, near speed of light travel, world peace.*
- ☐ *I would have placed the timeline much earlier – perhaps 2012 – if it weren't for number (2) involving analyzing tactical situations. That to me is more complex in the nature of abstractions than the other tasks.*
- ☐ *These tasks could be done sooner in a research environment.*
- ☐ *This is probably not a sound operational concept. You should investigate alternative approaches.*

(15) What minimum level of autonomy is needed for most practical militarily applications of humanoid or other legged robots? Please place an "X" on the appropriate position along the scale:

Results: n = 26; **M = 4.4** Sta. Dev. = 2.5; **Median ~ 5**; Mode = 5; Range = 0-8.5

```
    /---------/---------/---------/---------/----X-----/---------/---------/---------/---------/--------/
    0         1         2         3         4         5         6         7         8         9        10
Full Teleoperation                    Semi-Autonomy                              Full Autonomy
```



Comments (if any): [The following are verbatim or edited responses].

- *Full teleoperation is impossible [as a useful mode of operation], while full autonomy is unnecessary for most applications.*

- *I believe that fully supervised (teleoperated) devices can be of significant use in military applications with only enough autonomy as required by the device to move in a sure-footed way, sometimes undetected and sometimes not.*

- *I think we will need quite a bit of autonomy with only supervisory control to make them practical. In particular, it will be important to have mobility (walking, running, picking foot placements) be completely autonomous. For grasping one might have a supervisory command for "grasp that," but the details need to happen autonomously.*

- *This is a misleading question. A behavior approach with arbitration will not deliver the deliberate and repeatable response desired. However, complete knowledge in a deterministic world is not necessary for the robot to accomplish its job.*

- *Practical deployment will require increasing autonomy in lower level behavior.*

- *In practice, many applications may only require some level of augmented teleoperation.*

- ☐ *I think it is a bad idea to mix humanoid and other legged robots, as they are very different. Hexapods, for example, can already function fully autonomously, while we are yet to make balanced bipedal robots, humanoid or not. So the assessment on this is rather arbitrary.*

- ☐ *If these systems worked well in full teleoperation mode, they would be very useful. Autonomy is nice, but not at all necessary if the other problems such as energy density have already been solved.*

- ☐ *I think full autonomy is important if there are to be large numbers of robots. This is definitely the case in insect style robots, but I'm not sure it's completely relevant for larger humanoid style robots. I think these robots would do fine to be semi-autonomous. They could explore, survey, and perform simple tasks and then give up control to a human operator for more complex tasks. For example, one human remote operator may be able to watch ten or more semi-autonomous humanoids and only intervene in complex situations.*

- ☐ *In my mind, full teleoperation is a perfectly valid solution, and perhaps best way to go in many cases. If we could achieve a realistic feeling of telepresence in a robotic soldier, then we could keep human soldiers out of harms way. Of course, it is important that the robots can perform nearly as well as the humans. A typical urban combat scenario for example could have teleoperated robots up front being operated from afar and scoping out the areas, detecting snipers and what not. Backing up the robots could be foot soldiers using the information from the robots to determine where the enemy combatants are. If a robotic soldier goes down, it could be replaced by a new one that is waiting to be activated, or just acting as a sensor location. Also, I believe we should think in terms of the human plus a robot as a system, not just the robot itself. A lot of the technologies that will be required will be on the human end – better displays, better sensor suits, better studies on how a real soldier performs his job.*

- ☐ *I believe you can use a humanoid robot to drive a vehicle or run certain machinery which is teleoperated. NASA was looking at its space station maintenance robotic concepts, which were humanoid in design and also fully teleoperated as envisioned, back in the late 1980s.*

- ☐ *A fairly high degree of autonomy is reasonable much sooner if the task and environment are bounded.*

- ☐ *Most applications need a high degree of semi-autonomy, but not the easiest or earliest or most common.*

- ☐ *You need a definition of terms – too amorphous.*

(16) In your opinion, what is needed for the successful development of tactically useful, military humanoid robots? Please respond below: [The following are verbatim or edited responses].

☐ *The most important requirement is for moderate but sustained and slowly growing funding over a 20 year period. I would suggest, start in FY2004 at $1M per year, and increase to $10M per year by the year 2024. The second most important requirement is to fund the right people. There are very few persons in this country with the knowledge and ability to address this problem effectively. They should be funded at a rate that will enable slow steady technological progress, and slow steady growth in the community of people working on the problem.*

☐ *System integration and design – and good mechatronics like the Japanese have demonstrated.*

☐ *We need an aggressive humanoid robotics research program, which simply does not exist in the US at this time.*

☐ *We need to identify plausible tactical needs, and match them with acceptable projected costs.*

☐ *There is very little mobility for current humanoid robots. There could be legged or wheeled solutions. Object recognition and arbitrary object manipulation are the big current challenges.*

☐ *As mentioned above, I see two key parts: (a) getting industry involved with producing humanoid hardware of all varieties; (b) getting research institutions involved in using the hardware from (a) to address the key research issues of control, learning, human/robot interaction. Achieving these two parts is critical to success. If we don't achieve this, then there is a great danger that other countries will investigate humanoids successfully (e.g., Japan is already far ahead).*

☐ *Develop humanoid robots in a spiral development process. Develop end effectors. Develop telepresence applications first to get past social issues.*

☐ *A humanoid robot will be useful as soon as teleoperation works well. This means that the lowest level functions of walking and obstacle avoidance must be handled by the robot. If it works robustly and is relatively simple to operate it will be highly effective. Additional autonomy will allow for a higher ratio of robots to operators and thus cost savings. Additionally, if the robot must enter areas where communication with a teleoperator is difficult, additional autonomy will be necessary.*

☐ *If it accomplishes a job better than the man, and takes man out of harm's way, it will be successful. The robot is a tool, but it must become economically viable. It must also be proven in the field as something useful, with very minimal limitations.*

☐ *The technical risk areas for a humanoid type robot are in the areas of: (1) mobility (balance), (2) dexterity and manipulation, and (3) "cognitive" processing, i.e. interpretation of and interaction with its environment. Research in these areas must progress if this type of project were to succeed. These are not simple tasks.*

☐ *Most importantly, investment in humanoid robot technologies is needed. While arms and hands have been significantly advanced in this country, lower body work, particularly bipedal, needs further development. The integration between functional lower body systems and complex, versatile upper bodies with human size and human strength is likely to be quite complex. Finally, making autonomous robots with these characteristics is likely to be more difficult than we would like. It seems quite likely to me that initial implementations will focus on the robotics hardware and rely upon teleoperation and semi-autonomous behavior until the hardware issues have all been resolved.*

☐ *A suitably funded, coherent, 20-year project is needed. The project should be coordinated with other robotic development projects, including FCS, and funded at an average of about $25 million per year for 20 years.*

☐ *We need a pointed program to integrate sub-disciplines (hardware, programming, and interface) that succeeds in coordinating geographically distributed scientists and engineers, and makes a long enough term commitment to encourage technology developers to address this problem.*

☐ *What is needed is a comprehensive program that addresses the development of the missing technologies and deals with the integration of these technologies into a robust working system.*

☐ *There are some key lacking abilities and technologies: (1) the ability to move arms in real time to reach for and manipulate objects and people, as well as respond to urgent situations; standard trajectory planning methods from classical robotics do not scale to complex humanoids, and alternatives are only being explored; (2) bipedal balance and locomotion; (3) construction and control of human-like bodies, involving springy, compliant properties instead of rigid (and thus less robust) constructions; (4) the ability to provide on-board energy that is not so heavy as to require major changes in the humanoid design and can enable it to function for some useful time-period; (5) the ability to interact with humans in a natural fashion; (6) the ability to learn from humans from task demonstration and imitation and to adapt to complex environments and tasks.*

☐ *We need coordinated funding efforts, with a focus on achieving realistic short-term milestones in a series that work toward the ultimate goals.*

☐ *One of the major functions to be developed is that of mobility over natural terrain. This heavily depends on control and sensing. Propulsion and energy systems also continue to be a major problem in remote operations.*

- ☐ *Money is needed for direct research and, I believe, some continuity with research aimed at more private sector enterprises and health enterprises. There is an overlap between humanoid robots, exoskeletons, rehabilitative robots, and prosthetic and orthotic devices. By tapping into the research and corporate funds for other non-military applications, the military state of the art can be achieved faster and for less money. For example, funding to develop orthoses for paralyzed patients (high profile because of Christopher Reeve) will lead to technologies that will enable bipedal robots.*

- ☐ *We need more research and development on: (1) Gait algorithms. There is a lot of progress to be made here and a lot of low hanging fruit. A lot can be done with little sensing and no cognition. A lot of human walking is spinal or lower-brained. These capabilities still need to be successfully demonstrated on a robot. (2) Dexterous anthropomorphic arms and hands. The NASA Robonaut is a good example along these lines. To make a case for having a humanoid, it's important to have the manipulation capabilities of a human. (3) Human-machine interfaces. Again, I believe teleoperation is crucial and therefore, better morphing of man and machine is necessary. (4) High power density actuators and power supplies. These are being investigated through the DSO Exoskeleton program and other programs. I believe there should be a whole separate program for these technologies, rather than masking funding for them through a robotics program. Some of the best universities and companies for developing these technologies might not be part of a program that they think is for robotics and not purely for power and actuator sources.*

- ☐ *Major advances in cognitive systems and power are needed, as well as significant advances in most other humanoid systems.*

- ☐ *A multidisciplinary research program is needed to build appropriate hardware, develop appropriate actuators and appropriate sensing and control tools. Collaboration with biologists and behavioral psychologists would be useful. A team of experts (about 20-30 total) at universities and professional lab/companies should be assembled to direct a well-coordinated research program with clear milestones. A common hardware platform should be developed that can be given to other labs such that they can conduct additional research. Realistic performance metrics need to be suggested and integrated into a research plan. Initial research can focus on control and sensing issues in tethered hardware and off-board computing. At a later stage, on-board power and computing will have to be developed, possibly by dedicated VLSI design. Adaptive control and autonomous learning might be among the most important issues to accomplish flexible and robust sensory-motor control in complex and dynamically changing environments. Incorporation of principles from primate neuroscience could help to speed up development cycles, and also have a positive spin-off towards clinical applications.*

- ☐ *I would start out by selecting a very small repetitive task which requires a robot to be in a human form to perform effectively. That means it would either involve the operation of a vehicle or work in a facility in which mobility or operation of equipment requires human type mobility and manipulation, as well as space considerations. For example having a humanoid robot enter and drive an obstacle breaching vehicle, in which there is* *a high degree of risk. Perhaps the driving is relatively simple, involving moving forward in a fairly straight path. I would then expand it so the robot could operate or drive more complex vehicles, perhaps a truck or a tank. I would look at replicating jobs which robots have already shown an ability to perform, such as security or washing toxic agents off vehicles. But I would look at doing these jobs in environments in which a humanoid is better capable than a wheeled or tracked robot, such as performing security in a building with lots of stairs, or in external environment requiring lots of climbing.*

☐ *On board naval, airborne, and space platforms (where mobility is constrained and power available), we should begin development of humanoid robots within the next few years. For walking systems (ala Honda P3), portable, compact power will be the pacing item for the foreseeable future.*

☐ *More study of embodied intelligence is needed. Mechanisms of this complexity cannot be programmed by hand. They must learn to interact with the environment.*

☐ *I believe the need for humanoid robotics comes mainly in the ability for robots to use tools designed for humans. Otherwise it is not clear that the human shape is best for most situations. If we instead focus on building robots to use human tools/machinery, then a human shaped robot is perhaps useful, but even then not necessarily optimal. In many cases robots may be made specifically for specific machinery which would drastically increase their usefulness and timeliness. In this case, the natural progression will be to develop military tools and machinery (not the robot part) that is suited for use by both humans and robots (easy to use by both) as there may be both cases when one is be better than the other. This approach would lead to significantly different estimates of the previous 14 questions in terms of time estimates, costs, and usefulness.*

☐ *We need a concrete vision and need such that the humanoid approach is the best alternative.*

(17) Additional comments (if any): [The following are verbatim or edited responses].

☐ *The US is far behind in this area compared to the Japanese; a lot of catching up needs to be done. I hate giving time estimates, so don't take them too seriously – no one can predict scientific progress accurately, as it often depends on breakthroughs.*

☐ *I have educated hunches on what it would take to support autonomous perceptive and cognitive capabilities, but am not prepared to make projections in this area without further research and experience on my part.*

☐ *There are numerous parallel benefits, especially with respect to medical advances and rehabilitation.*

☐ *This is very interesting and exciting work. Please keep me posted.*

☐ *I would be happy to be interviewed and can be reached anytime at the phone number listed above. I would be happy to come to the D.C area as well.*

☐ *I tend to be pessimistic on my technology extrapolation projections. Most engineers seem to be optimistic for some reason. Or perhaps those are the ones that make it into books, magazines, and TV. I have faith in our capabilities to build things that do not require cognitive abilities. That's why I am gung-ho about teleoperated robots. Put as much as possible in the robot, but use the tremendous cognitive and dexterous capabilities of a real human. Humanoid robots are a hard sell since they are so difficult. I believe that there should be lots of funding in this area. It's just hard to justify it through short timeline (20 year) military payoff. The potential long term payoff (100+ years) is tremendous. And like exploring outer space, making humanoid robots is one of man's grand challenges and should be heavily funded. One of the best application selling points for humanoid robots is that there is as little need for interpretation between the human operator and the robot. In fact there is the possibility that the human operator could feel as though he/she IS the robot. Therefore I believe humanoid robots and telepresence go hand in hand. If there is no operator, then other styles of robots are better suited for just about any situation. One of the best science selling points for humanoid robots is to better understand ourselves. I'd be happy and willing to do a follow on interview or provide any other help or information.*

☐ *The Japanese are investing in this area, even with the dismal state of their economy. It would be a shame if DARPA failed in its assigned mission to "prevent technological surprise."*

APPENDIX D: USER SURVEY PARTICIPANTS

Adams, William
U.S. Army Maneuver Support (ATZT-CD)
Directorate of Combat Developments
573-563-6165
adamswh@wood.army.mil

Allen, Larry
U.S. Army Directorate of Combat Developments (ATZT-CDE)
573-596-0131 X37264
allenl@wood.army.mil

Bizzell, Tom
U.S. Army Engineers (DCD)
573-596-0131 X37218
bizzellt@wood.army.mil

Clough, Bruce
U.S. Air Force (AFRL/VACC)
937-255-2831
bruce.clough@wpafb.af.mil

Cruz, Wilfred
U.S. Army Combat Engineers
973-724-6220
wcruz@us.army.mil

DeBolt, Christopher
U.S. Navy Explosive Ordnance Disposal (PEO-LMW, PMS-EOD)
301-744-6837
debolt@eodpoe2.navsea.navy.mil

Delashaw, James
U.S. Army Experimentation Branch (DCD)
334-255-3652
delashawj@rucker.army.mil

Platt, David
U.S. Army TACOM ARDEC EOD
973-724-3868
dplatt@pica.army.mil

Rodriguez, Irving
U.S. Army Infantry Center (ATZB-WC-DFD)
706-545-5109
rodriguezi@benning.army.mil

Simino, Robin
U.S. Army Chemical Division (DCD)
573-329-8520
siminor@wood.army.mil

Soto, Eric
U.S. Army ARDEC EOD
972-742-4888
esoto@pica.army.mil

Smith, Robert
U.S. Air Force (AFRL/VACC)
937-255-8429
robert.smith2@wpafb.af.mil

Standley, Patric
U.S. Army Explosive Ordnance Disposal (USARPAC, APLG-MU-EODCT)
808-438-8095
standleyp@shafter.army.mil

Sterling, Robert
EOD Training Department
HQ/A Co 832d Ord Bn
256-313-2682
Robert.m.sterling@us.army.mil

Strano, Sal
U.S. Special Operations Command (USSOCOM)
813-839-3794

Tordillos, Santiago
U.S. Army TACOM ARDEC EOD
973-724-6237
tordillo@pica.army.mil

APPENDIX E:

SURVEY FORM
FOR SURVEY OF ROBOT USERS

SURVEY ON HUMANOID ROBOTS
FOR POTENTIAL MILITARY USERS

BACKGROUND

Robotic Technology Inc. (RTI) is performing a study for the Defense Advanced Research Projects Agency (DARPA) concerning a technology assessment of **bipedal humanoid robots** and **other legged robots**. DARPA (Dr. Alan Rudolph, DSO Program Manager) is interested in determining whether humanoid (and other legged robots) are technologically and economically feasible and can serve as tactically useful military systems. The results of this study may lead to DARPA support for the development of humanoid robots for military applications.

There are a number of ongoing programs in the Department of Defense (DOD) for the development of combat robotics, but they emphasize the development vehicle platforms, such as wheeled or tracked vehicles, not humanoid robots. But the world of **artifacts** is designed by humans for humans – such as tools, buildings, and vehicles. A humanoid robot, with biped legs, dexterous arms and hands, and sufficient intelligence, could function smoothly in that world. In the **natural environment**, military wheeled and tracked vehicles can operate on about 30% to 50% of the earth's land surface. Legged organisms and machines, including bipedal humanoids, can travel over nearly the entire land surface. Current developmental humanoid robots do not yet have cognition and situational awareness, so they are limited in their autonomous interaction with the environment (as well as lacking human-like proficiency in their basic motions). This **technology assessment** will examine their prospective military worth and the feasibility of achieving militarily useful behavior in the near to far term (e.g., years 2003 - 2030), and, if humanoid robots are worthwhile, to provide a technology roadmap for reducing developmental risk and eliminating technology gaps.

This survey is part of the overall study. We will also request **interviews** with some of the recipients of this survey in order to explore key issues in greater depth. You were selected to receive this survey because we understand that your position or experience is relevant to this topic; if it is not, we apologize for any inconvenience. We and DARPA appreciate your participation in this survey, and **you will receive a summary of the results** as an incentive for sharing your experiences and opinions.

Please rely on your own **knowledge, experience, and opinions** to answer the survey questions. **Please complete the survey and email (preferable), snail-mail, or fax it to:**

Dr. Robert Finkelstein
Robotic Technology Inc.
11424 Palatine Drive
Potomac, Maryland 20854-1451 USA
(301)-983-4194 Voice
(301)-983-3921 Fax
RobertFinkelstein@compuserve.com

Thank you very much for your help.

SURVEY ON HUMANOID ROBOTS FOR POTENTIAL MILITARY USERS

Last Name____ First____________________

Organization_______________________________________Position__________________

Address ____

____

Phone________________________ Email _______________________________________

(1) Please summarize your knowledge (if any) of military robotics.

(2) In what capacity or mission might you be a potential user of humanoid military robots?

(3) In your opinion, characterize the *potential* military worth of humanoid robots. Please place an "X" on the appropriate position along the scale:

/---------/---------/---------/---------/---------/---------/---------/---------/---------/--------/
0 1 2 3 4 5 6 7 8 9 10
Not Useful Somewhat Useful Very useful

Comments (if any):

(4) Assuming (supervised) autonomous humanoid robots become technically and economically feasible, to what extent do you think they will be fielded by the U.S. military in the 21st century? Please place an "X" on the appropriate position along the scale:

/---------/---------/---------/---------/---------/---------/---------/---------/---------/--------/
0 1 2 3 4 5 6 7 8 9 10
Not in Use Used in Several Applications Ubiquitous in the Military

Comments (if any):

(5) Which humanoid robot **applications**, **missions,** or **combat functions** (not all mutually exclusive) are **most promising** for the U.S. military? Please score each of the choices, from 1 (most promising) to 15 (least promising):

Reconnaissance, Surveillance, Target Acquisition (RSTA) ______
Driving or Piloting Vehicles ______
Infantry (e.g., Operating Small Arms) ______
Operating Direct Fire Weapons (e.g., Tank/Antitank) ______
Operating Indirect Fire Weapons (e.g., Artillery) ______
Military Operations in Urban Areas ______
Countermine Operations ______
Target Designation (e.g., with laser designators) ______
Logistics/Material Handling ______
Air Defense ______
Special Forces/Counter-Terrorism ______
Satellite Operations/Space Exploration ______
Medical ______
Food Service ______
Other (Explain) ______

Comments (if any):

(6) There are several prospective types of legged robots for military application. **Bipedal humanoid** robots resemble humans in general appearance, including having two arms and legs. **Bipedal non-humanoid robots** have two legs but have body forms not resembling that of a human. **Quadruped robots** have four legs and **hexapod robots** have six legs, with various body forms. **Hybrid robots** may have some body parts resembling that of a human, along with other forms of body parts (such as a Centaur-type robot with four legs and an upper human body). Considering these various types of **legged supervised autonomous robots**, which do you think are potentially the **most useful** to the U.S. military. Please rank the alternatives from 1 (the most important) to 5 (the least important):

Bipedal humanoid _________
Bipedal non-humanoid _________
Quadruped _________
Hexapod _________
Hybrids _________

Comments (if any):

(7) Given that a tank can cost several million dollars each and a HMMWV can cost a hundred thousand dollars: What is your estimate of the acceptable unit **cost** (in today's dollars) of a militarily useful, supervised autonomous **humanoid** robot? Please insert your estimate of the unit cost (in dollars) for each case (your estimate of the optimistic, pessimistic, and most likely acceptable costs) below:

Optimistic cost _____________
Pessimistic cost _____________
Most likely cost _____________

Comments (if any):

(8) Which **key user issues** need the most **attention** in order for (supervised) autonomous humanoid robots to be useful in the U.S. military? Please score each of the choices from 1 (needs the **most** attention) to 11 (needs the **least** attention):

Technology concerns (e.g., effectiveness) _______________
Safety concerns _______________
Political/public relations issues _______________
Educating/training users on the systems _______________
Reliability/maintenance concerns _______________
Logistics concerns _______________
Integration with existing systems _______________
Need for new tactics _______________
Need for new strategy and doctrine _______________
Intra/inter service rivalry _______________
Issues with U.S. allied forces _______________
Other (please describe) _______________

Comments (if any):

(9) Depending on the capability of the technology, humanoid robots may be completely controlled (at a distance) at all times by a dedicated operator (full teleoperation), or be fully autonomous (so that one human supervisor may supervise multiple robots), or be semi-autonomous, with various degrees of human intervention. In your opinion, what *minimum* level of autonomy is needed for most practical militarily applications of humanoid (or other legged) robots? Please place an "X" on the appropriate position along the scale:

/---------/---------/---------/---------/---------/---------/---------/---------/---------/--------/
0 1 2 3 4 5 6 7 8 9 10
Full Teleoperation Semi-Autonomy Full Autonomy

Comments (if any):

(10) Given that a humanoid robot is a new military system (perhaps serving as a weapons system): In your opinion, what should be done, by robot developers, in order to earn full acceptance, by military users, of humanoid (or other legged) robots? Please respond below:

(11) Additional comments (if any):

APPENDIX F:

AGGREGATED USER SURVEY RESULTS

USER SURVEY ON HUMANOID ROBOTS: RESULTS

Number of survey recipients: 70
Number of respondents (survey population): 16
Percentage of completed surveys: 23%

Respondent Distribution:

SERVICE	Army	Navy	Air Force	SOCOM
# RESPONDENTS	12	1	2	1

(1) Please summarize your knowledge (if any) of military robotics. [The following are verbatim or edited responses].

- ☐ *I perform strategic and operational planning and "marketing/resource collection" for robotic technology development activities in support of the Army's unmanned system efforts.*

- ☐ *I am the Science and Technology Advisor for the Engineer Division. I have some knowledge of robotics, but I would consider it limited.*

- ☐ *I have worked on combat developments for the Army Engineers since 1995 as a soldier, DA civilian, and support contractor. I have worked on several requirements documents concerning unmanned ground vehicles.*

- ☐ *I have in-depth knowledge of UAVs and UAV technology.*

- ☐ *I have seen robots being used by EOD personnel, and used for intelligence purposes.*

- ☐ *I have managed projects for Explosive Ordnance Disposal (EOD) robotics technology. I am currently the Program Manager for the Joint Service EOD Program, responsible for, among other systems, the MK2 Remote Controlled Transport, the MK3 Remote Ordnance Neutralization System, and the Man Transportable Robotic System. I am a Trustee of the Association for Unmanned Vehicle Systems International.*

- ☐ *I have been involved in studying the synergy that can be attained by teaming manned and unmanned aerial vehicles.*

- ☐ *I have 15 years experience with bomb disposal robots, 2 years experience with a search and rescue robot, and 5 years experience with the Tactical Mobile Robot (TMR) project.*

- ☐ *I have worked for the Unmanned Ground Vehicle Joint Project Office for more than 5 years, and the U.S. Army Infantry Center (USAIC), Directorate of Combat Developments, for 2 years. I developed requirements documentation for unmanned systems to support* *dismounted infantry operations, and I am currently working in the USAIC Dismounted Battlespace Lab (DBBL) conducting experiments with unmanned systems.*

- ☐ *I have worked in Chemical Corps payload and VT vehicle operations for over 2 years. I have briefed the Joint Robotics Program Working Group on 2 occasions about ongoing Chemical Corps initiatives. I am a member of AUVSI and active in Objective Force requirements determination.*

- ☐ *Other than occasional stories in public news sources, my primary knowledge of military robotics is of the air vehicle variety. My research exposes me to past, present, and future robotic aircraft, as well as many philosophical discussions surrounding their development and application.*

- ☐ *I have experience with EOD robotics and limited experience with search and rescue robotics.*

- ☐ *U.S. Army Explosive Ordinance Disposal (EOD) units use robots in the conduct of everyday operations. Specifically, I am familiar with a multitude of robots, including the Remotec Andros series, the Remotec MK8 Wheelbarrow, and the Foster-Miller Talon. These robots are designed primarily for defeating improvised explosive devices, but are also used to mitigate any hazard that presents a danger to the technician.*

- ☐ *Input came from individuals who have managed Special Operations Robotics programs.*

- ☐ *I have been using robots for the past 8 years for EOD and search and rescue.*

- ☐ *I am an EOD training instructor and I have worked with EOD robots for 10 years to include the SEOD, Andros MkV, Andros RONS, Andros MkVI, Talon, Wolverine, UK Wheelbarrow Systems and Sandia Labs advanced concept arm unit. I have used most of these systems in a real world as well as in training environments.*

(2) In what capacity or mission might you be a potential user of humanoid military robots? [The following are verbatim or edited responses].

- ☐ *Probably none: artificial intelligence, augmented cognition, and appropriate software should be able to have unmanned systems accomplish their military mission [without users per se].*

- ☐ *In ground attack: they will have a psychological impact on anyone they are attacking.*

- ☐ *I might be a user for countermine, RSTA, demolitions, breaching, construction, MOUT operations, and bridging.*

- ☐ *Combat Engineer applications, such as mine clearing and obstacle breaching.*

- ☐ *Fairly limited – maintenance applications.*

☐ *Humanoid military robots could provide greater mobility for EOD robots, such as climbing ladders and emplacing EOD tools.*

☐ *I might control/manage a robot for performing re-fueling and/or re-arming tasks at a Forward Area Refueling and Reaming site, and performing aircraft decontamination after it has been subjected to NBC contaminants.*

☐ *Bomb disposal, weapons, search and rescue applications.*

☐ *I would like to examine the possibilities of employing humanoid platforms in support of dismounted infantry operations. As part of the dismounted unit, humanoid platforms will be required to conduct operations in all terrain and weather conditions. I believe that only through the employment of humanoid platforms will we be able to meet all the mobility requirements of dismounted operations.*

☐ *To perform CBRN (Chemical, Biological, Radiological, Nuclear) reconnaissance missions in confined space and MOUT environments.*

☐ *I don't thin I would personally would use humanoid military robots. I could, however, see the Air Force using these robots for our standard "dull, dirty, or dangerous" missions, such as perhaps force protection.*

☐ *Reconnaissance and disablement.*

☐ *EOD units respond to a multitude of hazardous environments. These hazards include explosive, chemical (both industrial and weaponized), biological, and nuclear. EOD technicians use robots to limit our exposure to these environments. Currently our robotic systems are quite mobile, able to climb stairs, open doors, and maneuver over rough terrain; however, as our robots are "tracked" they are somewhat limited in sand and mud. It is my opinion the largest potential gain from humanoid robots would be in mobility.*

☐ *Environmental or tactical settings in which a wheeled platform or tracked platform just does not have the mobility.*

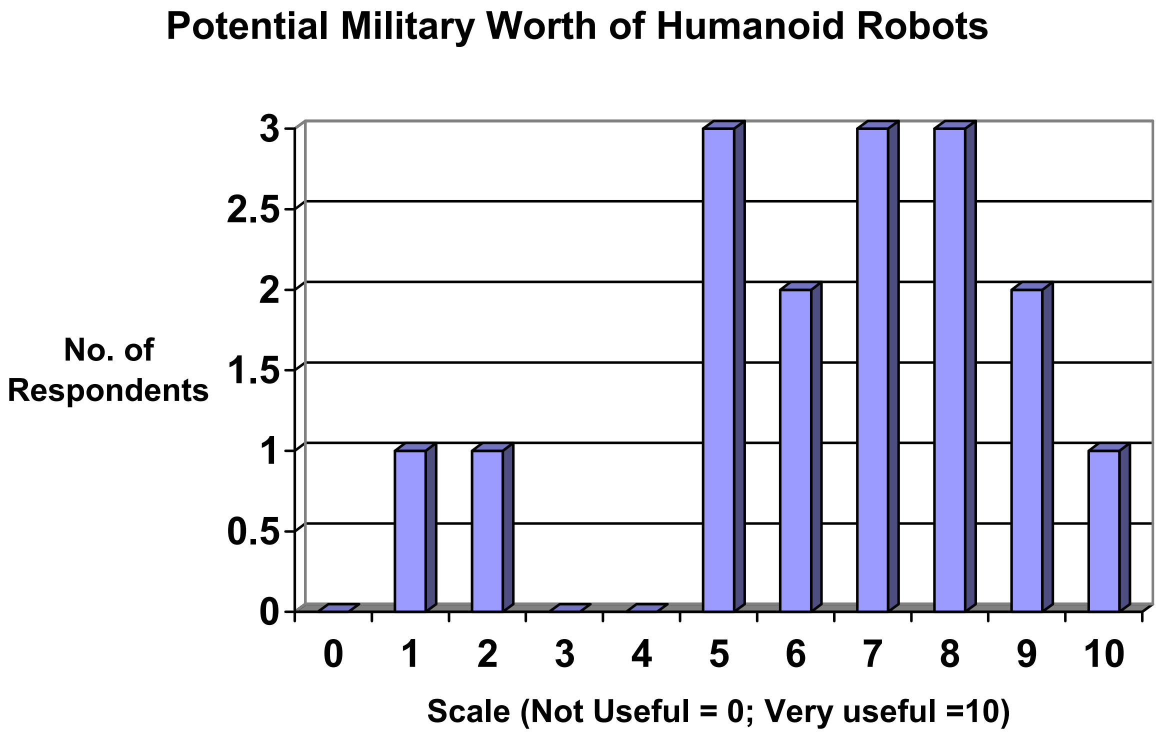
☐ *EOD and search and rescue incidents.*

☐ *As an EOD Specialist during the render safe and disposal of hazardous improvised explosive devices, unexploded ordnance, and standard as well as improvised CBRN weapons.*

(3) In your opinion, characterize the *potential* military worth of humanoid robots. Please place an "X" on the appropriate position along the scale:

Results: Number of Respondents (n) = 16; **Mean (M) = 6.9**; Standard Deviation (Sta. Dev.) = 2.3; **Median ~ 7.0**; Range = 1.9 – 10.

/---------/---------/---------/---------/---------/---------/-------**X**/---------/---------/--------/
0 1 2 3 4 5 6 7 8 9 10
Not Useful Somewhat Useful Very useful



Comments (if any): [The following are verbatim or edited responses].

- ☐ *If a robot can replicate the physical motions of a human EOD technician, it would assist our efforts to reduce the risk to life and limb.*
- ☐ *There is great potential for performing the Dull, Dirty, and Dangerous tasks.*
- ☐ *I believe that it will take a family of robotic platforms (humanoid, wheeled, air, and static) to provide the highest level of usefulness for dismounted operations.*
- ☐ *The potential is boundless. The applications will need to be tempered with common sense. Missions in the "not hard to do" lane should be attempted first to gain acceptance of this technology.*
- ☐ *One has to consider the advantages and disadvantages of robots in general and humanoid ones in particular. While bipedal locomotion allows navigation of a wider variety of terrain, it sacrifices speed to do so. Quadrupedal locomotion is much faster. The point is that specific missions may recommend themselves to humanoid robots, where it is critical for them to use the same tools and/or facilities that we humans use. If this is*

not a critical feature of the mission, then a special-purpose robot may perform the mission much better than a general-purpose humanoid robot.

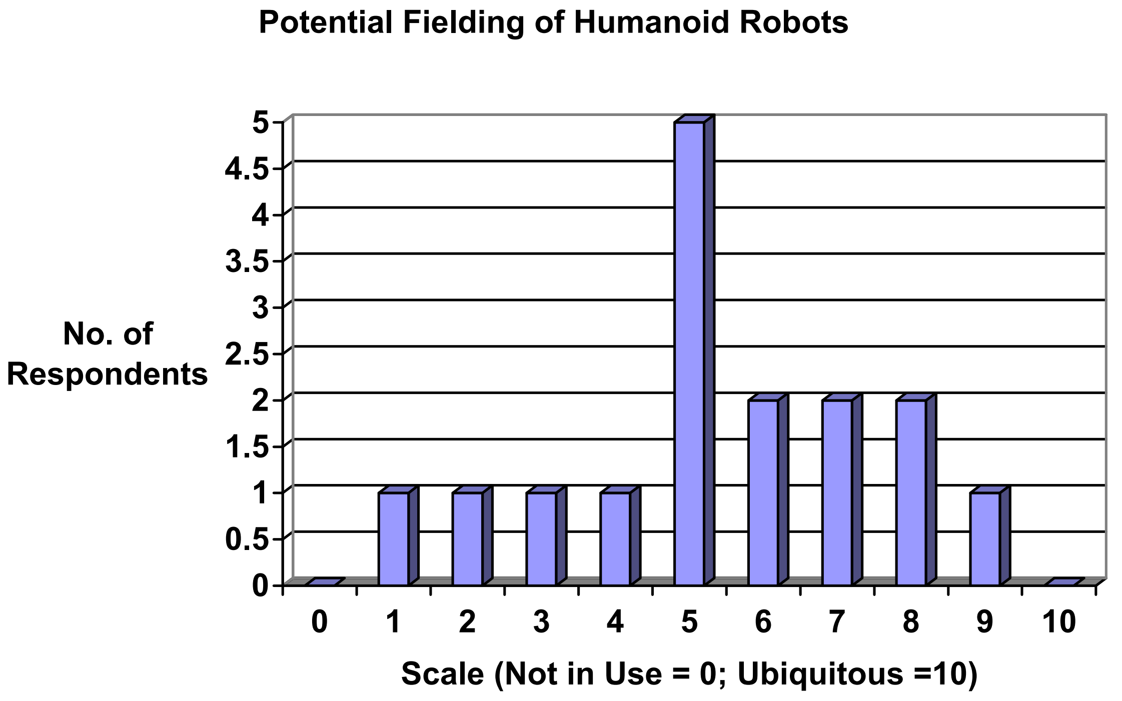
- *Currently, adding mechanical complexity, especially in the form of manipulation or articulation typically increases the required power and final system weight, while reducing reliability and maintainability of the overall system. I am basing the potential military worth evaluation on the aforementioned being resolved. If that is not the case than the utility is diminished.*

- *In my experience a robot is an effective tool, and just that, a tool. Tools must be appropriate for the situation and no one tool can perform every job. Sure, you could use a crescent wrench to hammer a nail, but would you want to?*

(4) Assuming (supervised) autonomous humanoid robots become technically and economically feasible, to what extent do you think they will be fielded by the U.S. military in the 21st century? Please place an "X" on the appropriate position along the scale:

Results: Number of Respondents (n) = 16; **Mean (M) = 5.8**; Standard Deviation (Sta. Dev.) = 2.1; **Median ~ 5.8**; Range = 1.9 – 9.9.

/---------/---------/---------/---------/---------/------**X**-/---------/---------/---------/--------/
0 1 2 3 4 5 6 7 8 9 10
Not in Use Used in Several Applications Ubiquitous in the Military



Comments (if any): [The following are verbatim or edited responses].

- ☐ *Need to be sensitive to the issue of a machine replacing a man. I assume that we are talking mechanics/mobility, not intelligence and reasoning.*

- ☐ *Having autonomous humanoid platforms available in the military is one thing. However, properly training, understanding, and trusting these platforms in support of life-threatening missions may take more time.*

- ☐ *Applications of robotics would be best served by missions that represent scenarios of high risk to humans and that do not require quick decisions by the robots, e.g., CBRN reconnaissance of confined space. One life saved would go a long way to gain acceptance of robotics for military applications. Weapons-firing robots would take time to gain acceptance.*

- ☐ *If the performance of a general-purpose humanoid robot does not "buy" its way into the field, then perhaps the very real political concerns may drive their use as it is currently doing with unmanned air vehicles. It comes back to the "dull, dirty, and dangerous" missions that are being considered for air vehicles. Robots don't get tired or distracted. There are no letters to be sent to families when a robot gets blown up.*

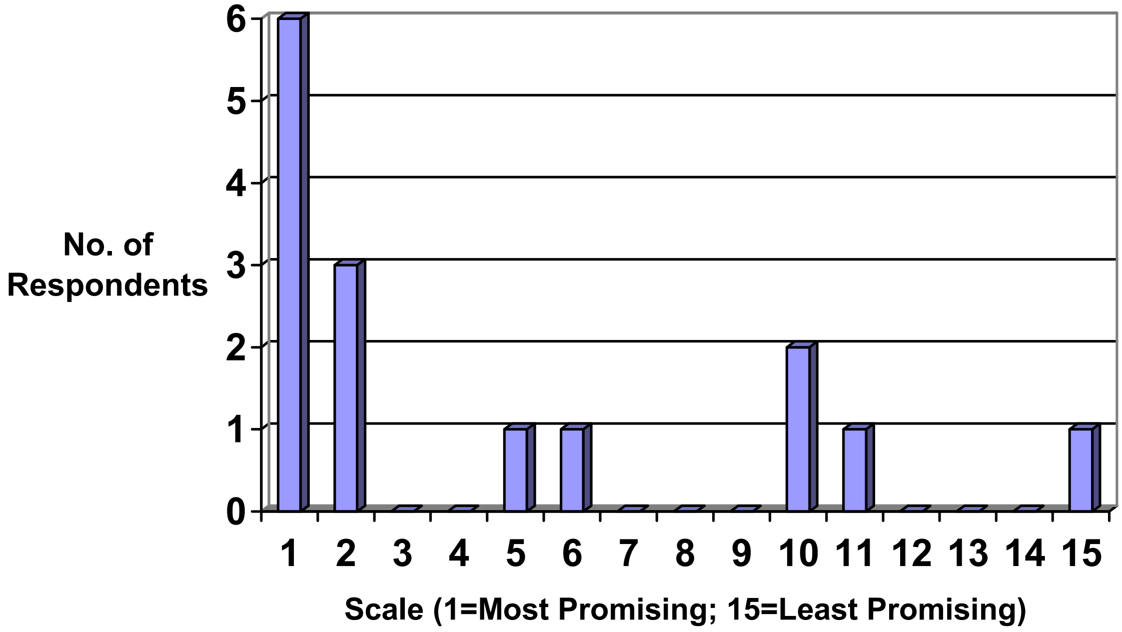
- ☐ *We are talking about an infinite amount of humanoid robotic configurations to satisfy mission requirements. No one platform will be capability of satisfying all requirements.*

- ☐ *Must prove worth to troops and commanders.*

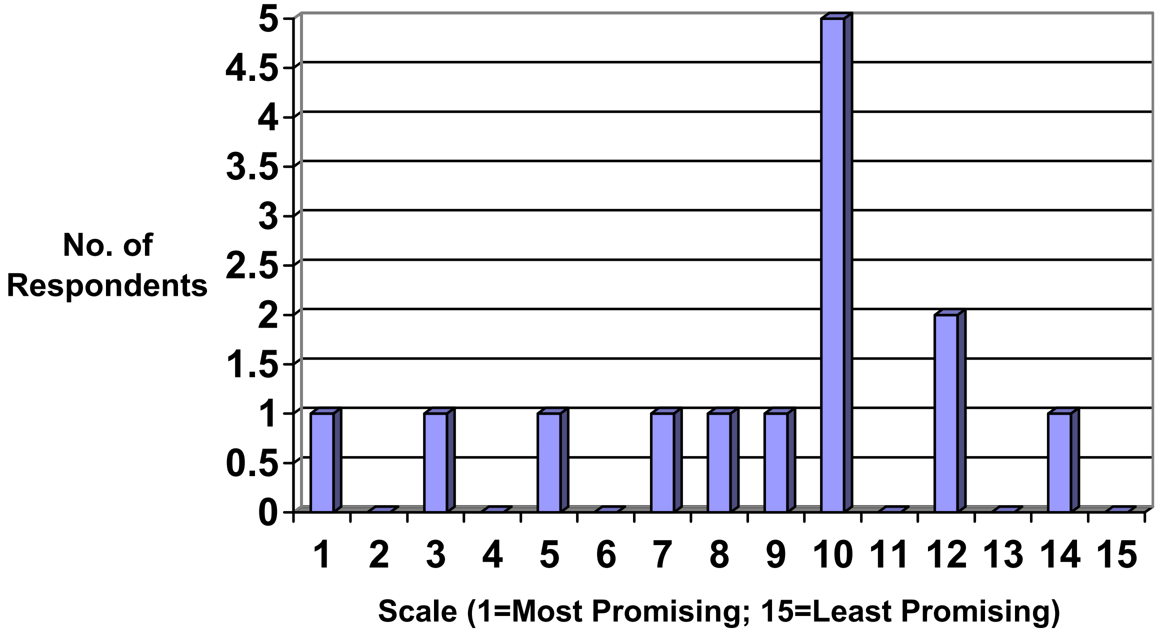
(5) Which humanoid robot *applications, missions*, or *combat functions* (not all mutually exclusive) are *most promising* for the U.S. military? Please score each of the choices, from 1 (most promising) to 15 (least promising):

		N	Mean	Sta.Dev.	Rng.
Reconnaissance, Surveillance, Target Acquisition (RSTA)	____	15	4.6	4.7	1-15
Driving or Piloting Vehicles	____	14	8.6	3.6	1-12
Infantry (e.g., Operating Small Arms)	____	15	7.6	3.9	2-15
Operating Direct Fire Weapons (e.g., Tank/Antitank)	____	15	8.2	4.1	1-14
Operating Indirect Fire Weapons (e.g., Artillery)	____	15	8.5	4.1	1-15
Military Operations in Urban Areas	____	15	5.0	3.9	1-15
Countermine Operations	____	15	4.0	4.1	1-10
Target Designation (e.g., with laser designators)	____	15	4.9	3.4	1-10
Logistics/Material Handling	____	15	6.9	4.1	1-12
Air Defense	____	15	8.7	4.6	1-15
Special Forces/Counter-Terrorism	____	15	9.1	4.8	1-15
Satellite Operations/Space Exploration	____	14	6.5	5.2	1-15
Medical	____	15	8.7	3.4	1-13
Food Service	____	15	8.9	4.8	1-15
Other (Explain)	____	11	6.6	5.8	1-15

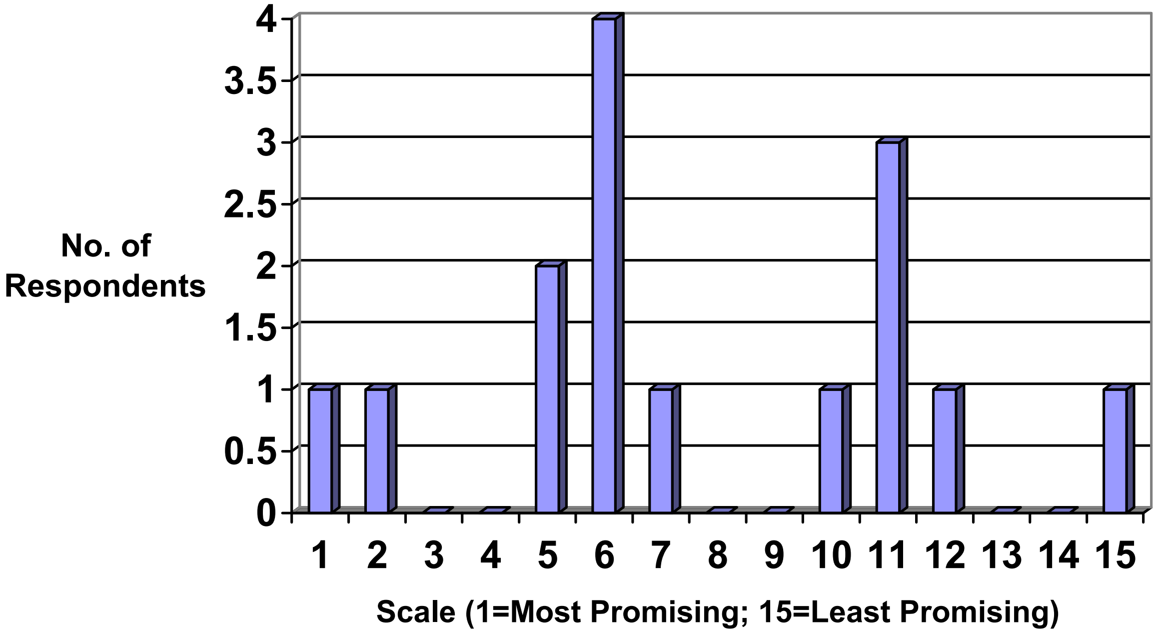
Evaluation Of Humanoid Robot Applications: RSTA



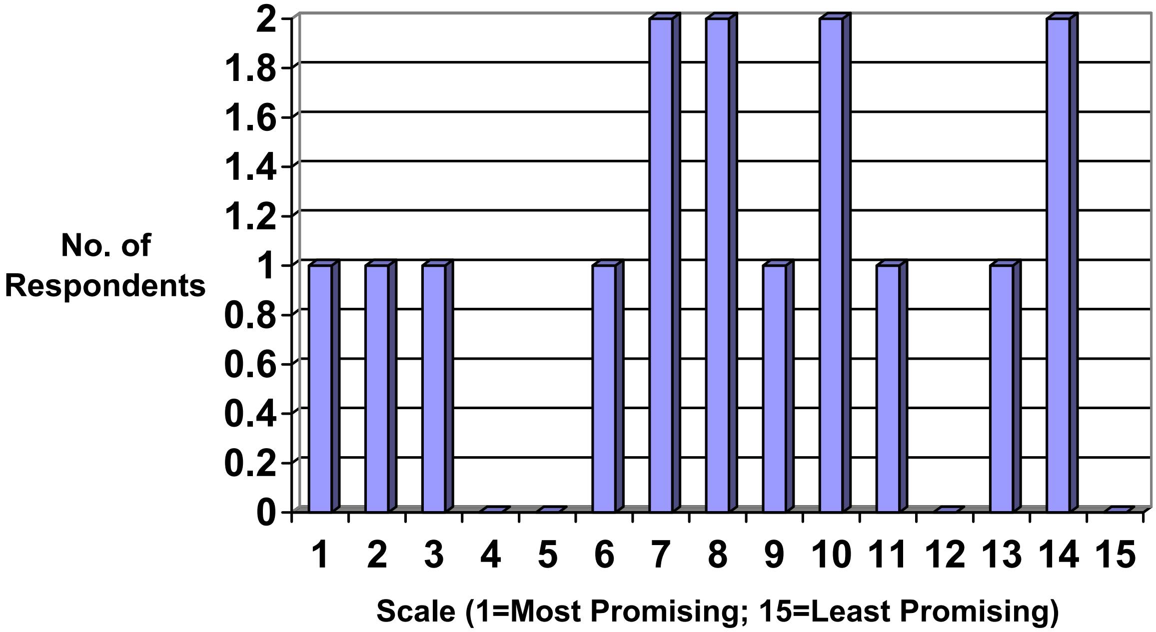
Evaluation Of Humanoid Robot Applications: Driving/Piloting



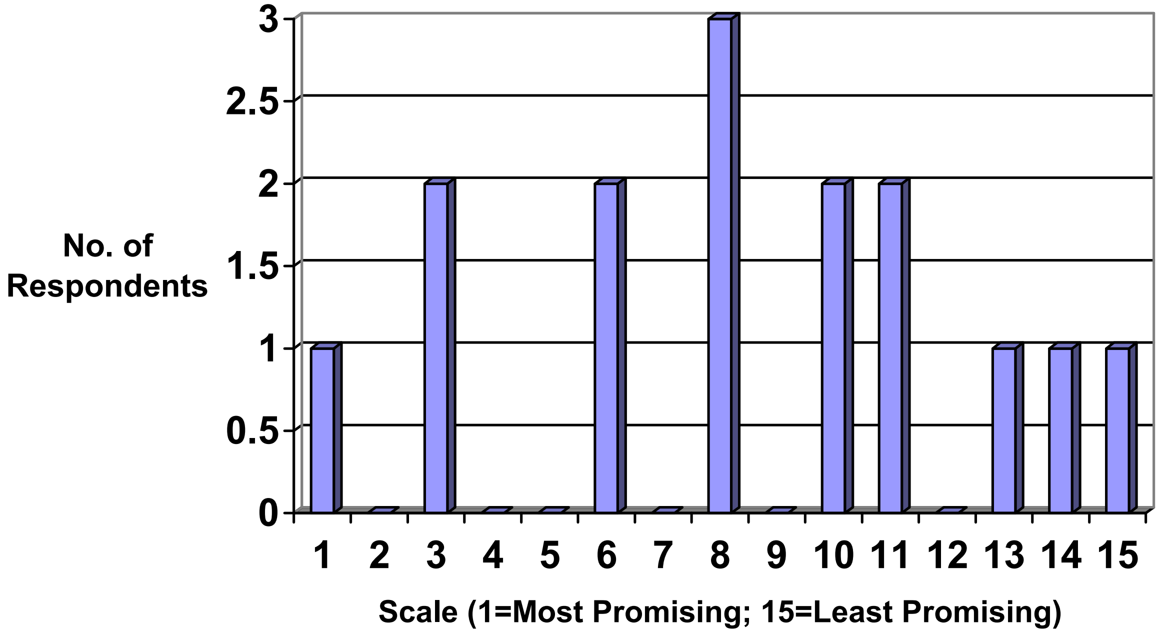
Evaluation Of Humanoid Robot Applications: Infantry



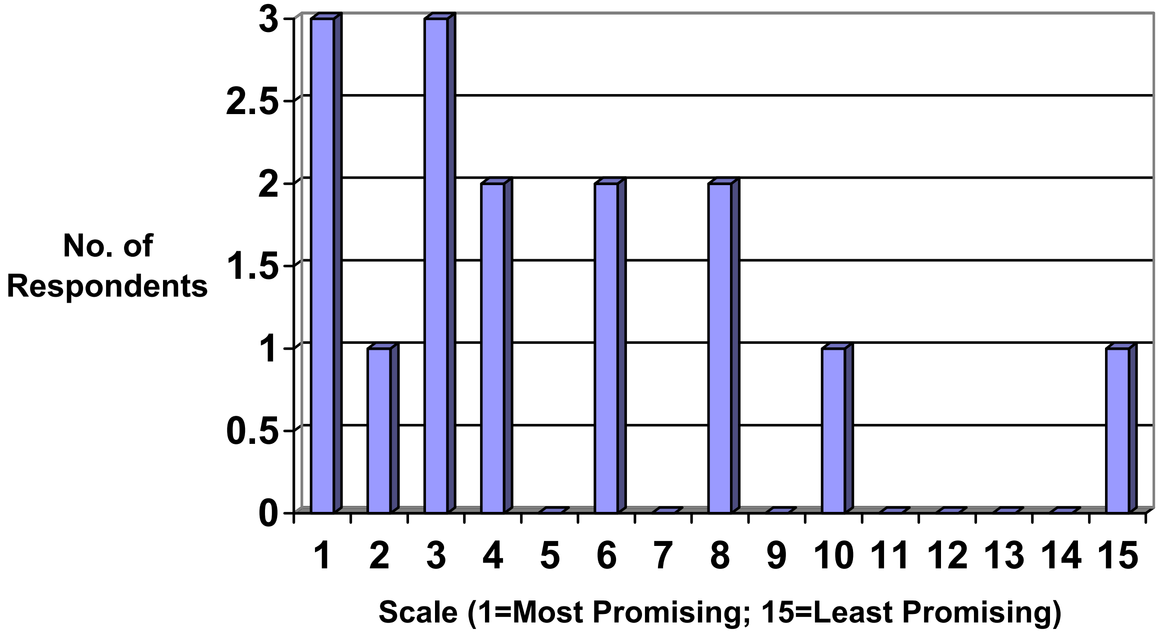
Evaluation Of Humanoid Robot Applications: Direct Fire

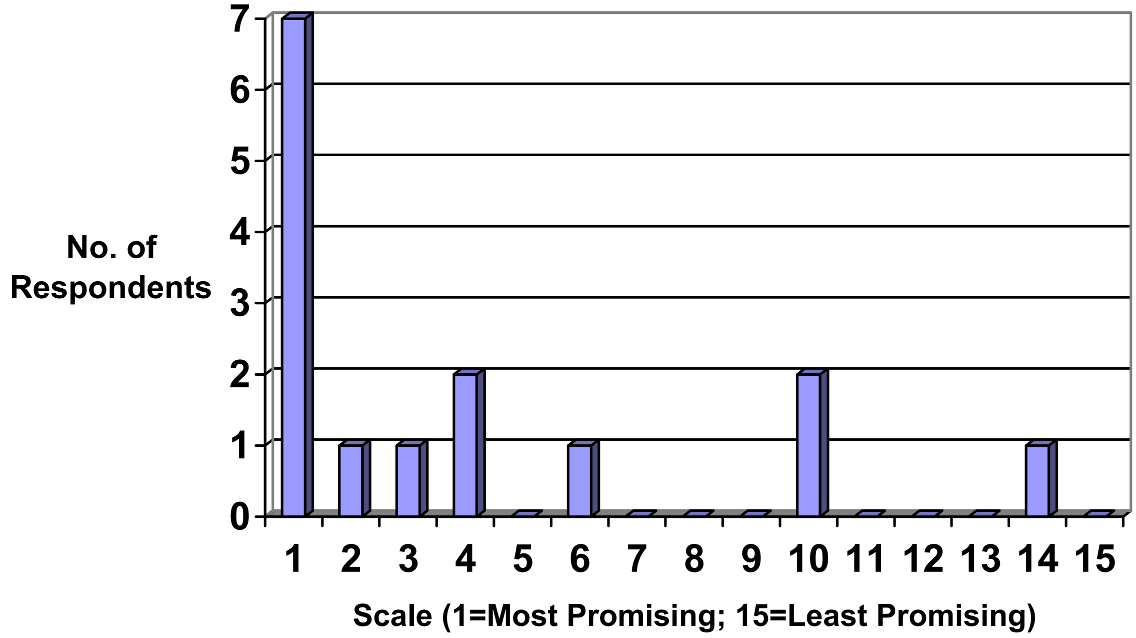


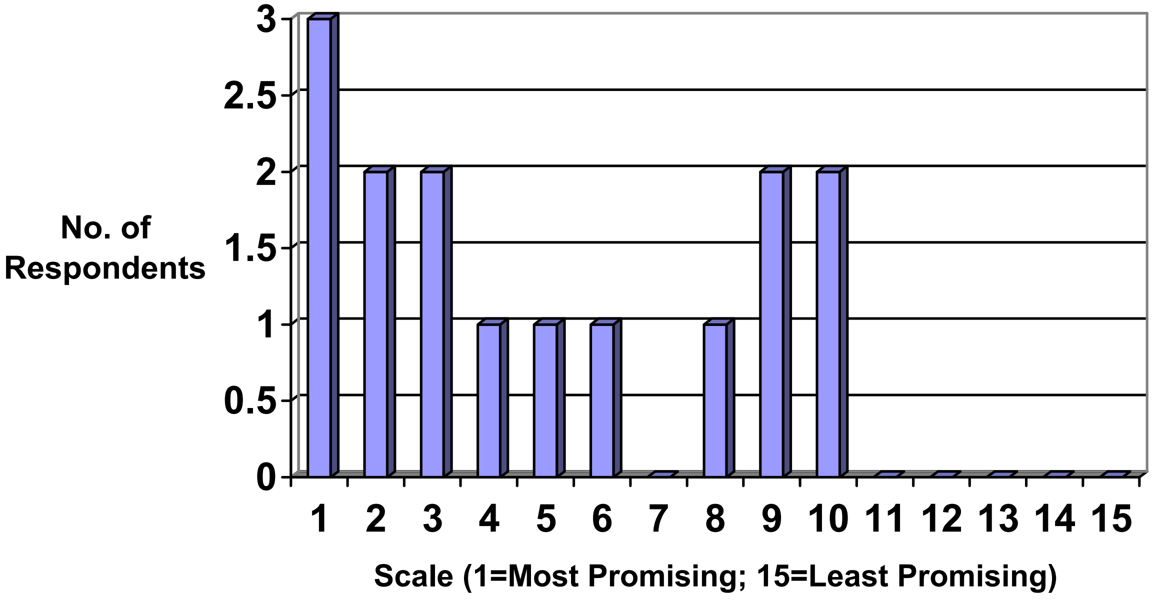
Evaluation Of Humanoid Robot Applications: Indirect Fire



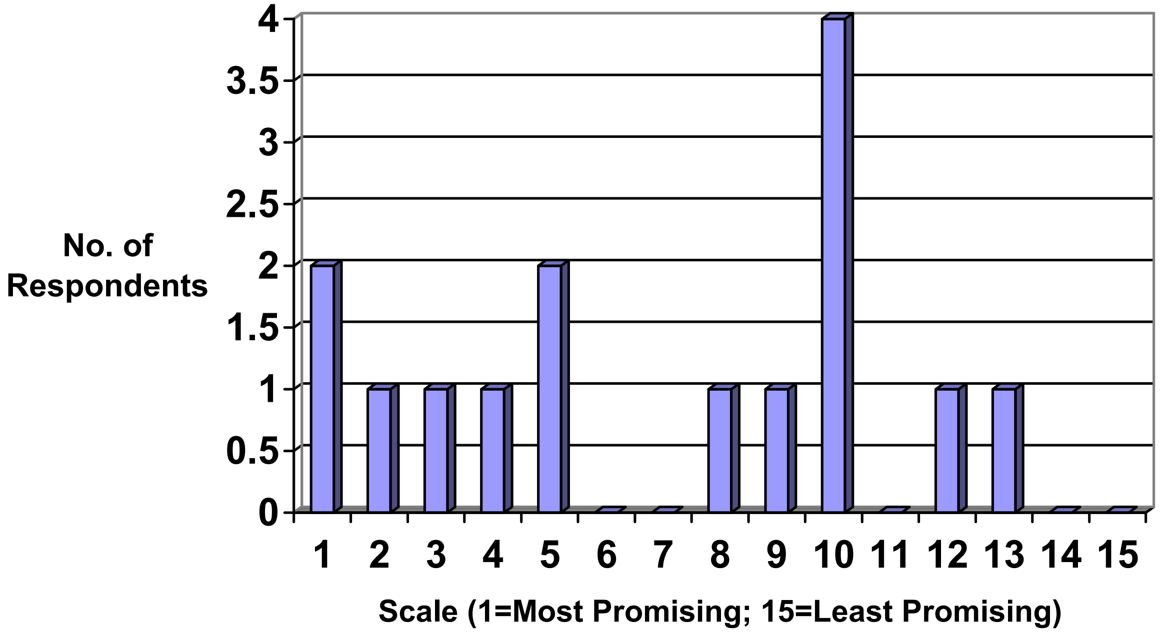
Evaluation Of Humanoid Robot Applications: MOUT



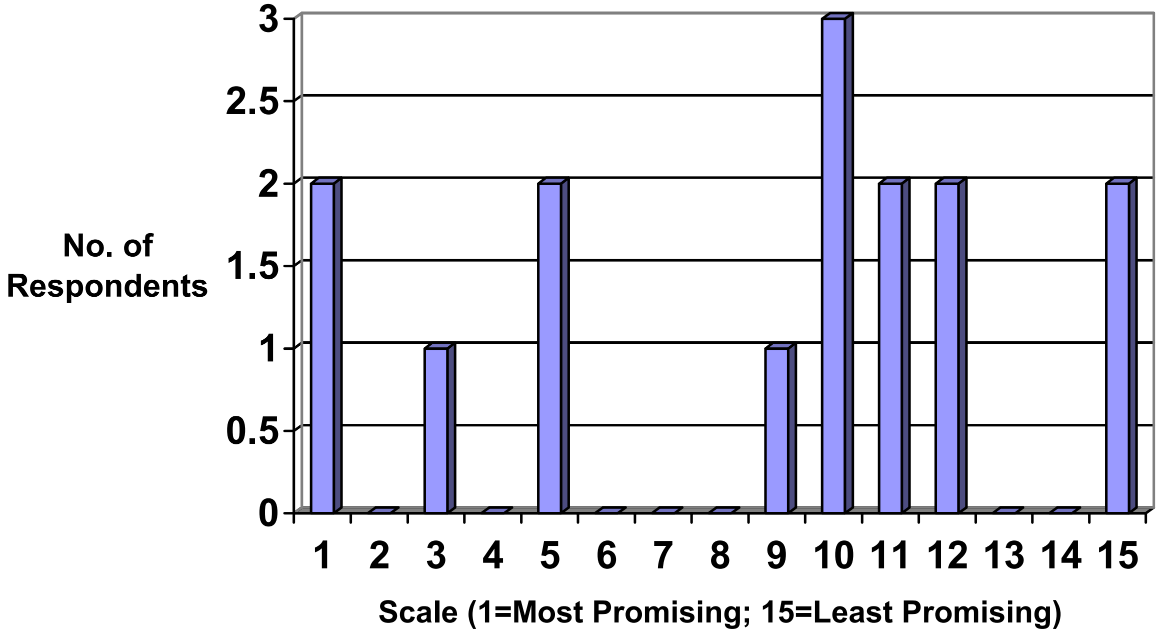

Evaluation Of Humanoid Robot Applications: Countermine


Evaluation Of Humanoid Robot Applications: Target Designation

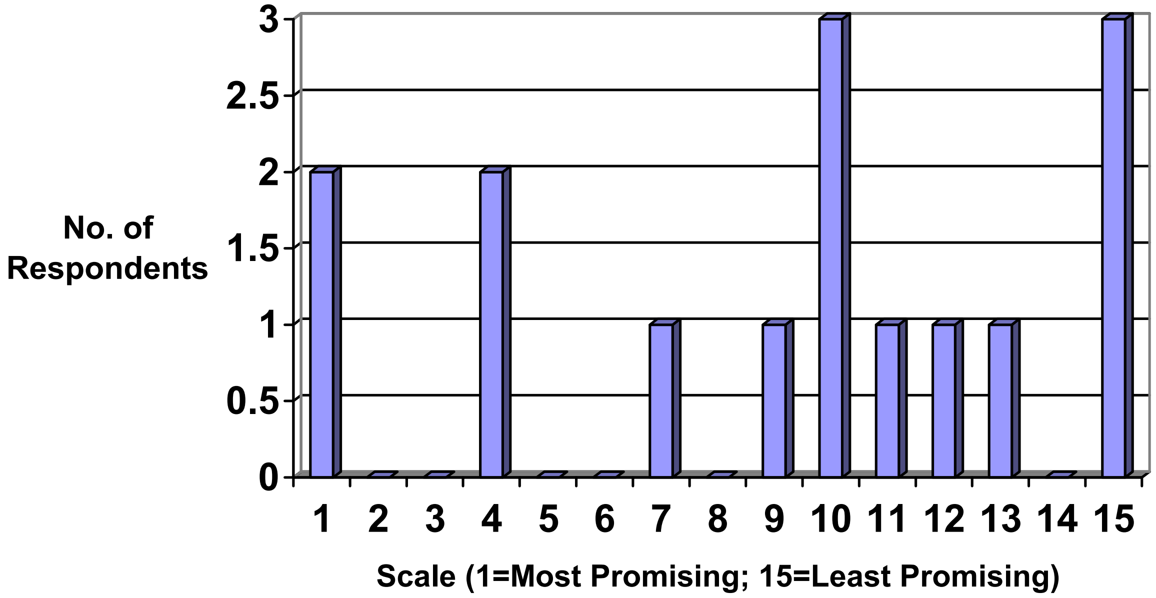
Evaluation Of Humanoid Robot Applications: Logistics



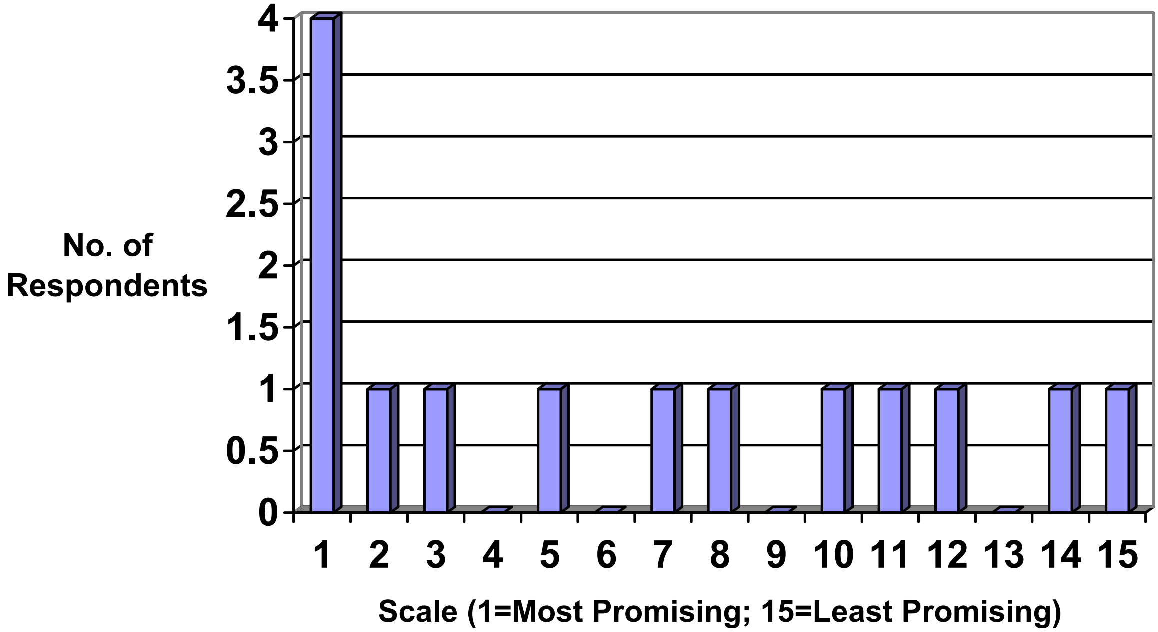
Evaluation Of Humanoid Robot Applications: Air Defense



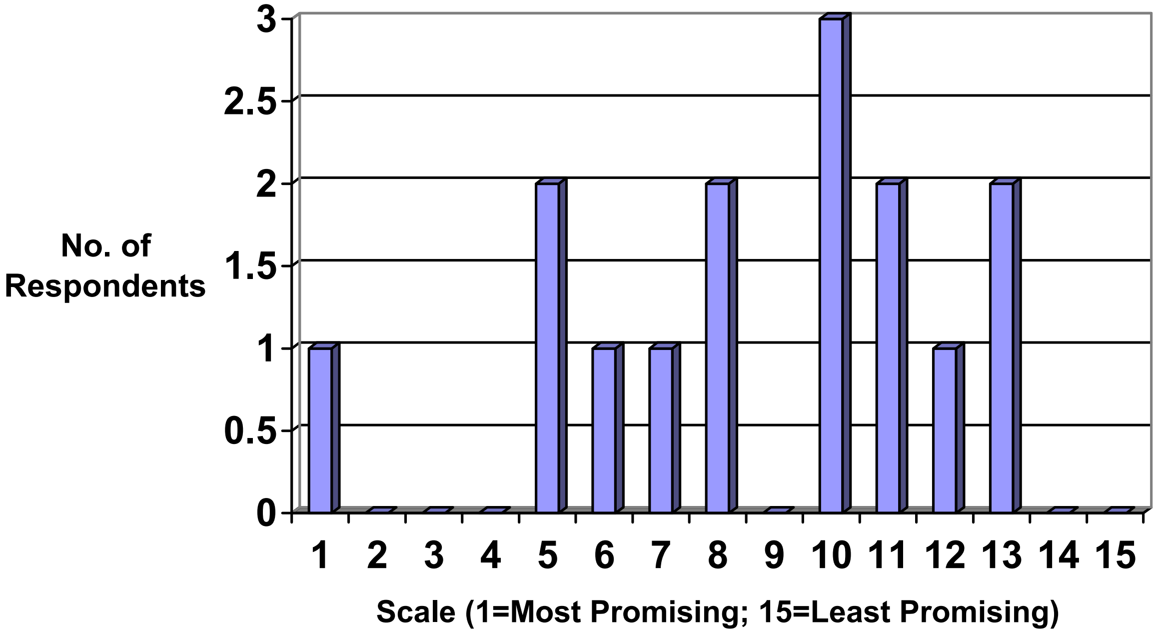
Evaluation Of Humanoid Robot Applications: Counter-Terrorism



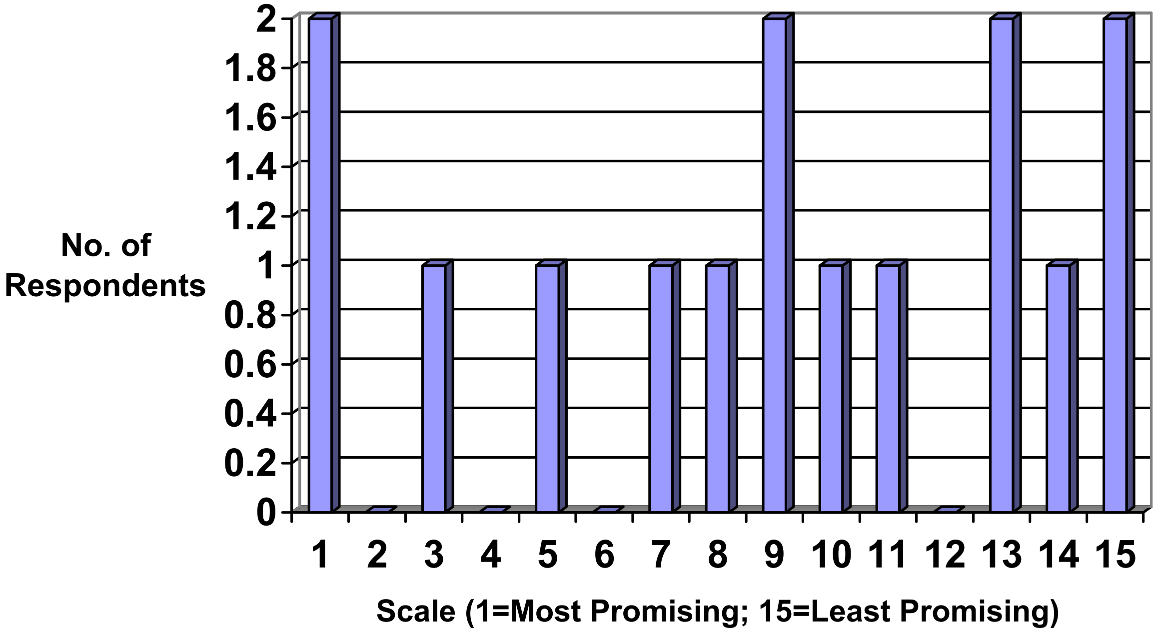
Evaluation Of Humanoid Robot Applications: Space



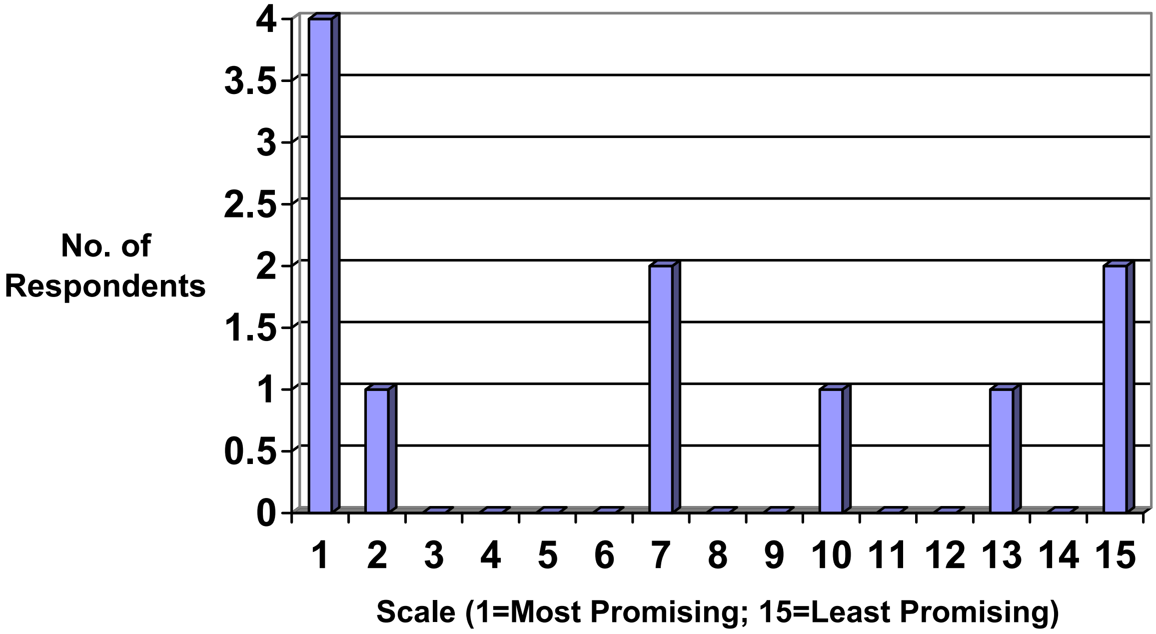
Evaluation Of Humanoid Robot Applications: Medical



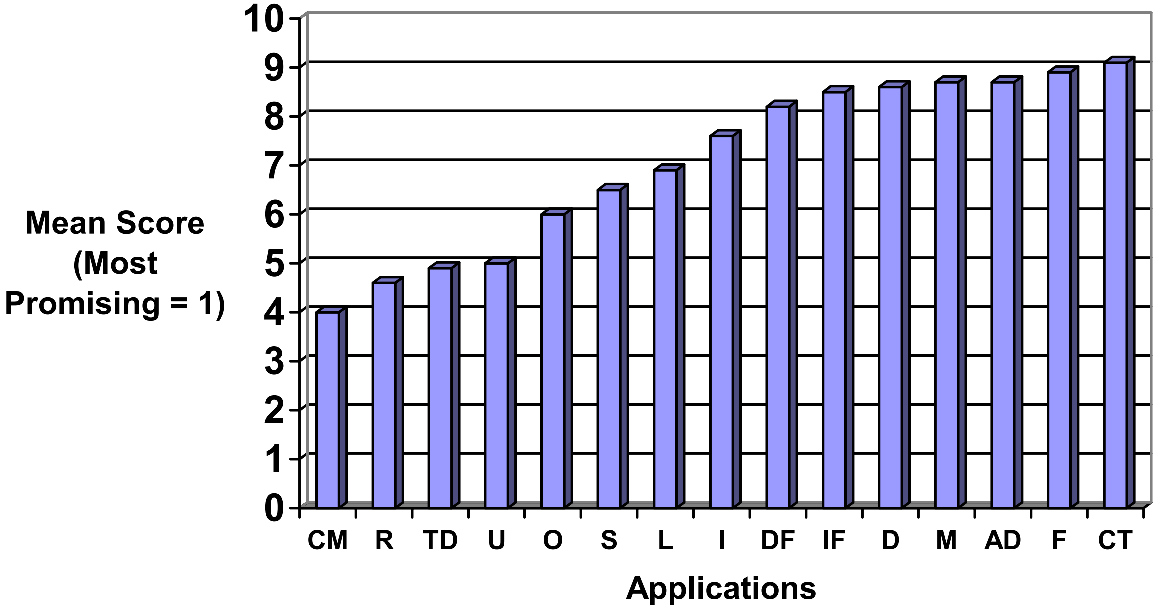
Evaluation Of Humanoid Robot Applications: Food Service



Evaluation Of Humanoid Robot Applications: Other



Evaluation Of Humanoid Robot Applications: Mission Means



<u>Key to Applications (Missions) on Chart</u>

CM = Countermine Operations
R = Reconnaissance, Surveillance, Target Acquisition (RSTA)
TD = Target Designation
U = Military Operations in Urban Terrain (MOUT)
O = Other
S = Satellite Operations/Space Exploration
L = Logistics/Material Handling
I = Infantry (e.g., Operating Small Arms)
M = Medical
DF = Direct Fire Weapons (e.g., Operating Tank/Antitank Weapons)
D = Driving or Piloting Vehicles
IF = Indirect Fire Weapons (e.g., Operating Artillery)
AD = Air Defense (e.g., Operating Air Defense Artillery/Missiles)
F = Food Service
CT = Counter-Terrorism/Special Forces

Comments (if any): [The following are verbatim or edited responses].

- ☐ *Robots should be designed to best fulfill the mission for which they are intended. Soldiers perform the RSTA mission, but the human body is not optimized for that mission. Something which could move faster, closer to the ground, and perhaps telescope higher, would be better suited to the RSTA mission. But people are people and perform the mission despite our limitations. Robots should not be constrained by our limitations.*

- ☐ *Other application: military police*

- ☐ *We should also mechanize "animal" type robots for tasks where more than two legs are needed.*

- ☐ *Other application: search and rescue*

- ☐ *TACOM ARDEC Warren and TACOM ARDEC Picatinny are currently working on three different weapon (armed) robots.*

- ☐ *Driving or piloting vehicles should be built-in robotic operations. Satellite operations/space exploration is currently being done without humanoids. All weapons systems applications will require man-in-the loop operation/supervision. Special operations applications will be based on the stealth capabilities of the robot.*

- ☐ *Other application: force protection, securing an area or other such duty that is reasonably well-defined but requires some level of persistence that may cause humans to lose effectiveness.*

☐ *RSTA will very likely be automated, but not necessarily by humanoid robots. Robotic vehicles will be common, but won't give up a seat for a humanoid robot. Infantry will likely remain human for superior sensory and reasoning capabilities. Larger (tank, etc.) weapons can be automated, but not necessarily with a humanoid robot. MOUT is a highly dangerous, but somewhat structured, mission through terrain built for humans, thus making a humanoid robot highly appropriate. Countermine, like NBC detection, is a very dangerous mission that should be automated, but, again, not necessarily by humanoid robots. Target designation could probably be done better by equipping a humanoid robot with a laser designator. Logistics is another area where existing human equipment can be used by robots to do a labor-intensive job. It is important to use the existing human equipment because this material will be handled on one or both ends by the end user, who is human, and who can use the same equipment. Food service is an interesting area where I definitely think humanoid robots can play a role. Again, using human equipment is important and it would be likely that humans and robots may work closely together.*

☐ *Other application: infantry ambush*

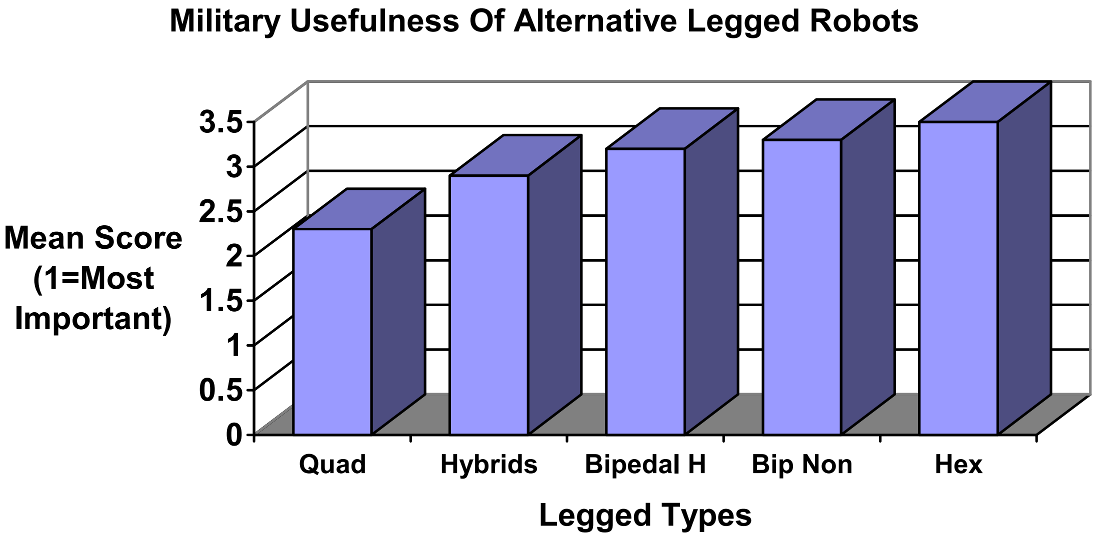
☐ *Other application: bomb disposal*

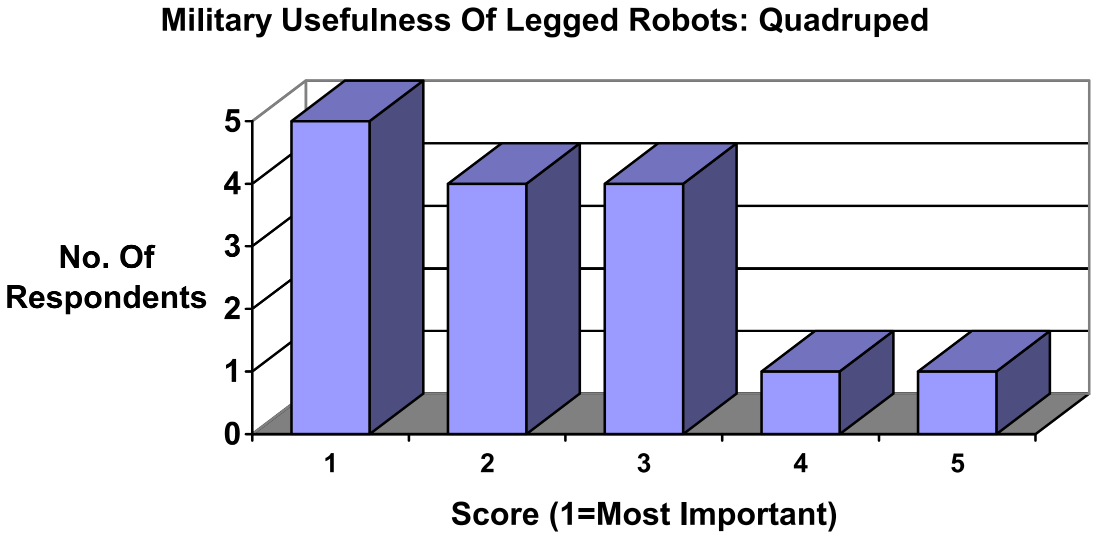
☐ *I am making many assumptions here on technology growth.*

☐ *Other application: UXO/EOD*

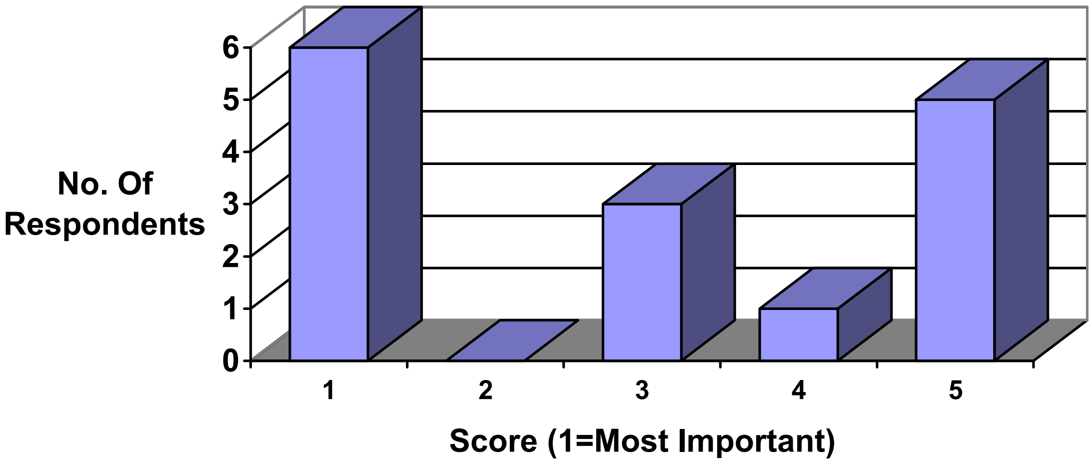
(6) There are several prospective types of legged robots for military application. *Bipedal humanoid* robots resemble humans in general appearance, including having two arms and legs. ***Bipedal non-humanoid robots*** **have two legs but have body forms not resembling that of a human. *Quadruped robots* have four legs and *hexapod robots* have six legs, with various body forms. *Hybrid robots* may have some body parts resembling that of a human, along with other forms of body parts (such as a Centaur-type robot with four legs and an upper human body). Considering these various types of *legged supervised autonomous robots*, which do you think are potentially the *most useful* to the U.S. military. Please rank the alternatives from 1 (the most important) to 5 (the least important):**

		N	Mean	Sta. Dev.	Median	Rng.
Bipedal humanoid	_________	15	3.2	1.7	3.5	1-5
Bipedal non-humanoid	_________	15	3.3	1.1	3.5	2-5
Quadruped	_________	15	2.3	1.2	2.0	1-5
Hexapod	_________	15	3.5	1.2	3.5	2-5
Hybrids	_________	15	2.9	1.8	3.0	1-5

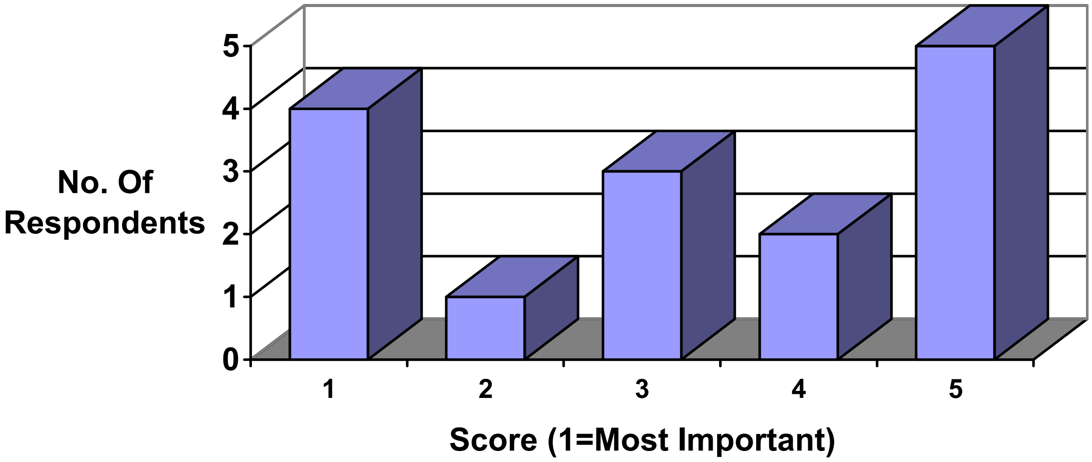

Military Usefulness Of Alternative Legged Robots
Mean Score (1=Most Important)
3.5
3
2.5
2
1.5
1
0.5
0
Quad
Hybrids
Bipedal H
Bip Non
Hex
Legged Types

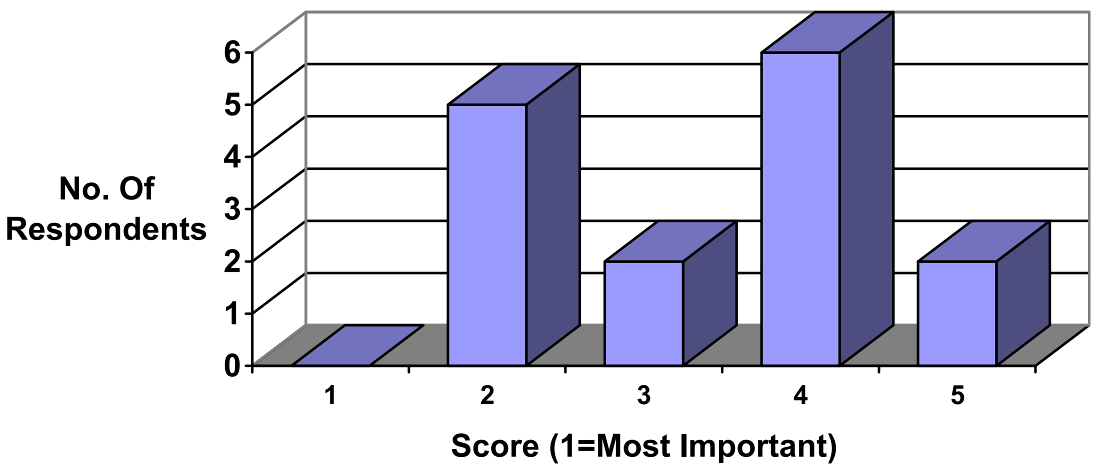

Military Usefulness Of Legged Robots: Quadruped
No. Of Respondents
5
4
3
2
1
0
1
2
3
4
5
Score (1=Most Important)

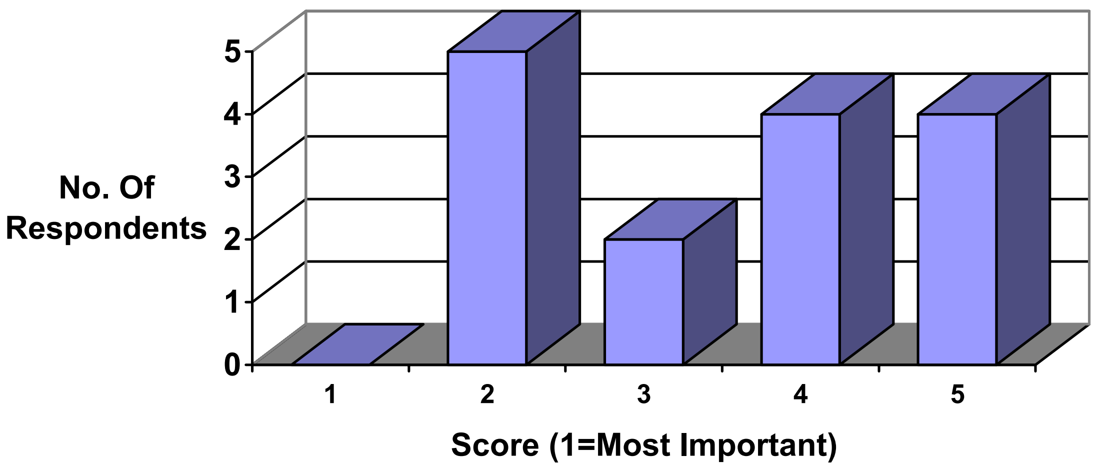
Military Usefulness Of Legged Robots: Hybrids



Military Usefulness Of Legged Robots: Bipedal Humanoid




Military Usefulness Of Legged Robots: Biped Non-Humanoid


Military Usefulness Of Legged Robots: Hexapod

Comments (if any): [The following are verbatim or edited responses].

- ☐ *Robots should be designed to best fulfill the mission for which they are intended. Soldiers perform the RSTA mission, but the human body is not optimized for that mission. Something which could move faster, closer to the ground, and perhaps telescope higher, would be better suited to the RSTA mission. But people are people and perform the mission despite our limitations. Robots should not be constrained by our limitations.*

- ☐ *The definition of "hybrid" is too wide open to adequately compare it with the other four configurations.*

- ☐ *I believe the rating indicated in my answers will be in line with the development of humanoid technology.*

- ☐ *A quadruped seems to be the easiest version to field. Load capacity and stability issues are simpler to address than for bipedal locomotion. A variant that could operate in either mode would seem optimal for MOUT and complex terrain situations.*

- ☐ *This is a very difficult area to quantify. Without seeing examples and understanding exact capabilities of each design it is nearly impossible to place one design over another. My answer is based on applicability to my background as an EOD Technician. We use a variety of tools, monitors and energetic "weapons" on our existing robot. Therefore a concern for us will be weight payload that the system can carry.*

- ☐ *This evaluation, in my opinion, is almost impossible to rate. If one knows the specific mission that a robotics application will be used for, then perhaps ranking them would be appropriate. I can see applications for all the platforms. Ranking them is very difficult.*

- ☐ *Stability in rough terrain and the ability to upright themselves is a major problem in robotic systems [including robotic vehicles].*

(7) Given that a tank can cost several million dollars each and a HMMWV can cost a hundred thousand dollars: What is your estimate of the acceptable unit *cost* (in today's dollars) of a militarily useful, supervised autonomous *humanoid* robot? Please insert your estimate of the unit cost (in dollars) for each case (your estimate of the optimistic, pessimistic, and most likely acceptable costs) below:

Optimistic cost ______________
Pessimistic cost ______________
Most likely cost ______________

TYPE COST	N	MEAN ($)	STA.DEV.	RANGE ($)
Optimistic	13	115,000	78,500	5,000-250,000
Pessimistic	12	895,800	569,100	200,000-2,000,000
Most Likely	12	351,870	226,860	45,000-750,000

Results: Using a Beta distribution assumption: **Expected (Mean) Unit Cost = $403,100; Standard Deviation = $130,100.**

Comments (if any): [The following are verbatim or edited responses].

- ☐ *Unit cost is not a good metric – what is the total ownership cost/capability?*

- ☐ *It depends very much on capabilities and quantities.*

- ☐ *My cost estimate assumes some high-production run quantities on the order of 50,000 to 75,000 robots, and it assumes the interoperability/exchange of components and sub-components among a family of hybrid robots.*

- ☐ *The cost of these humanoid robots will most likely be dependent on the capabilities associated with the robot, e.g., from a simple mobility platform to one that acts/thinks like a human.*

- ☐ *As production increases the cost would decrease, as with any equipment. The goal would be spiral development. Field it as soon as possible with development cost on the manufacturer, when possible, and use payloads that already exist to reach an 80% solution. Refine it with real-world experience.*

- ☐ *This is highly task-dependent. The above numbers could easily change by an order of magnitude (higher). Tasks requiring high reliability will require expensive robots. These costs need to be weighed against the training, feeding, housing, retirement, health care, etc. of a human being. This is how autonomous entities achieve cost benefits - one fully trained human supervising a number of potentially expensive robots. Total ownership cost for the entire system, human and robots, is less than if the task were performed entirely by humans.*

- ☐ *As technology advances, costs will drop.*

- ☐ *Obviously, unit cost is affected by capabilities, research costs and quantity ordered. Cost will dictate the applicability to each of the categories above. If each unit costs $2,000,000 or more, using this robot in an infantry type role will be cost prohibitive. To the contrary, if this robot is used in an Immediate Danger to Life and Health (IDLH) environment to perform sophisticated tasks, then perhaps a high unit cost will be warranted.*

- ☐ *Acceptable cost, verses realistic costs based upon today's technology, are two different things. The rating is based on what I feel the military would be willing to pay for production copies. This cost again is not a realistic figure. The complexity of the platform will be dependant upon the mission being conducted. There will be a positive correlation between the complexity of the mission and cost.*

- ☐ *The specific payload/package would add to the cost.*

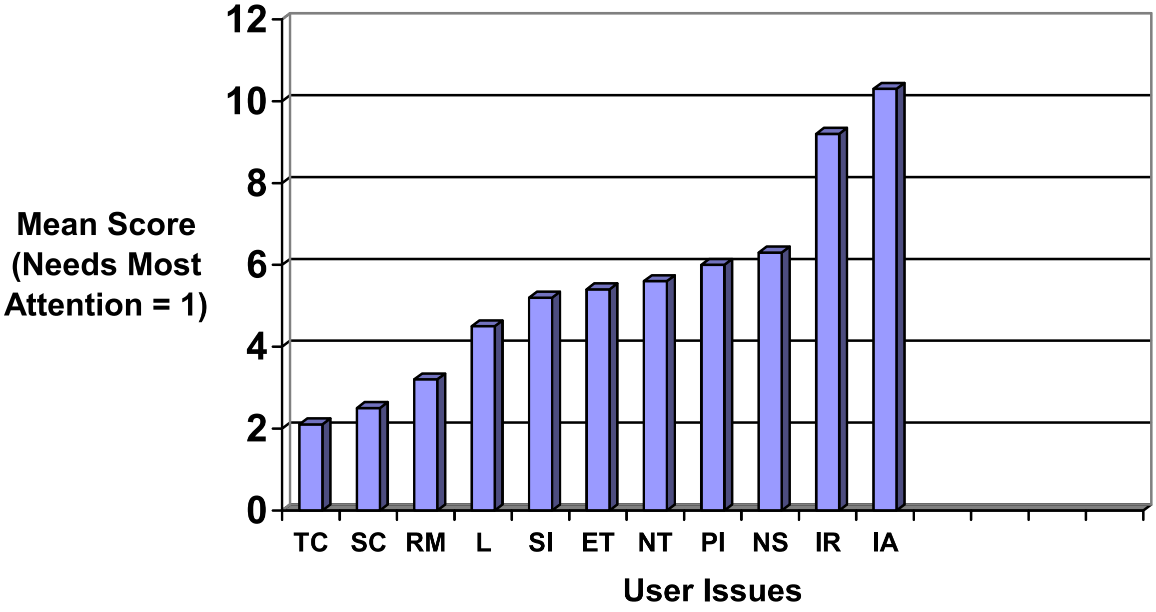
☐ *Robots are like cars, how fast do you want to go? It's all a question of money.*

(8) Which *key user issues* need the most *attention* in order for (supervised) autonomous humanoid robots to be useful in the U.S. military? Please score each of the choices from 1 (needs the *most* attention) to 11 (needs the *least* attention):

Technology concerns (e.g., effectiveness) _______________
Safety concerns _______________
Political/public relations issues _______________
Educating/training users on the systems _______________
Reliability/maintenance concerns _______________
Logistics concerns _______________
Integration with existing systems _______________
Need for new tactics _______________
Need for new strategy and doctrine _______________
Intra/inter service rivalry _______________
Issues with U.S. allied forces _______________
Other (please describe) _______________

Results Tabulated:

KEY USER ISSUE	N	MEAN	STA.DEV.	RANGE
Technology Concerns	16	2.1	1.5	1-6
Safety Concerns	16	2.5	2.5	1-10
Political/PR Issues	16	6.0	3.2	1-11
Educating/Training	16	5.4	3.4	1-11
Reliability/Maintenance	16	3.2	2.2	1-7
Logistics	16	4.5	2.9	1-9
Systems Integration	16	5.2	2.9	1-11
New Tactics	16	5.6	2.4	1-10
New Strategy & Doctrine	16	6.3	2.7	1-12
Intra/Inter Service Rivalry	16	9.2	2.5	2-15
Issues with U.S. Allies	16	10.3	1.3	9-15
Other	3	6.7	5.5	1-12

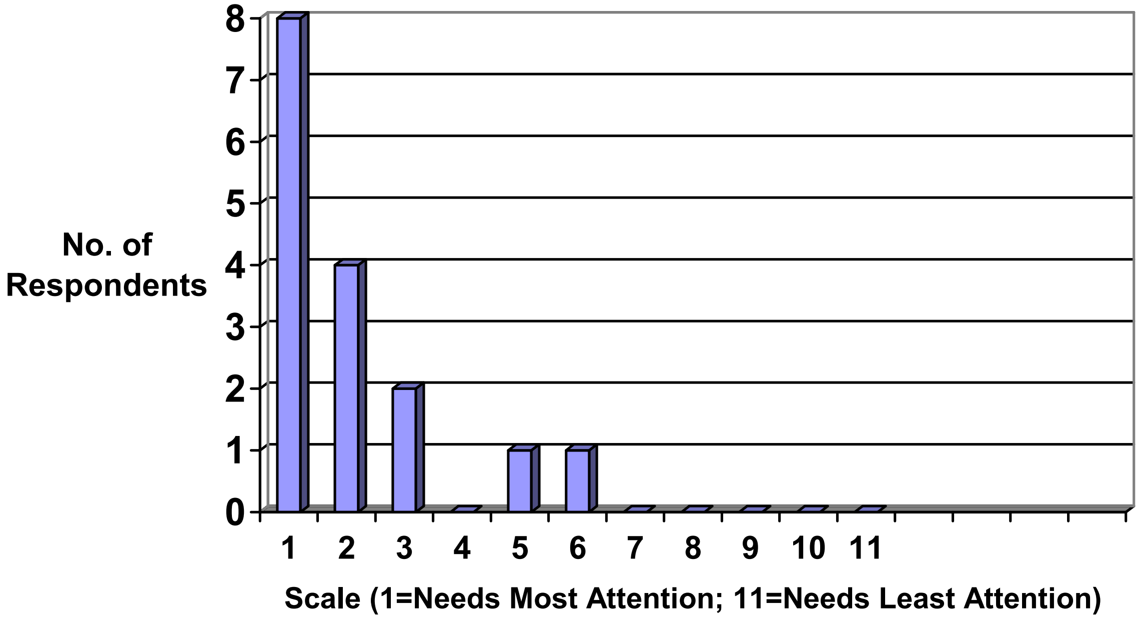


Key User Issues: Mean Scores

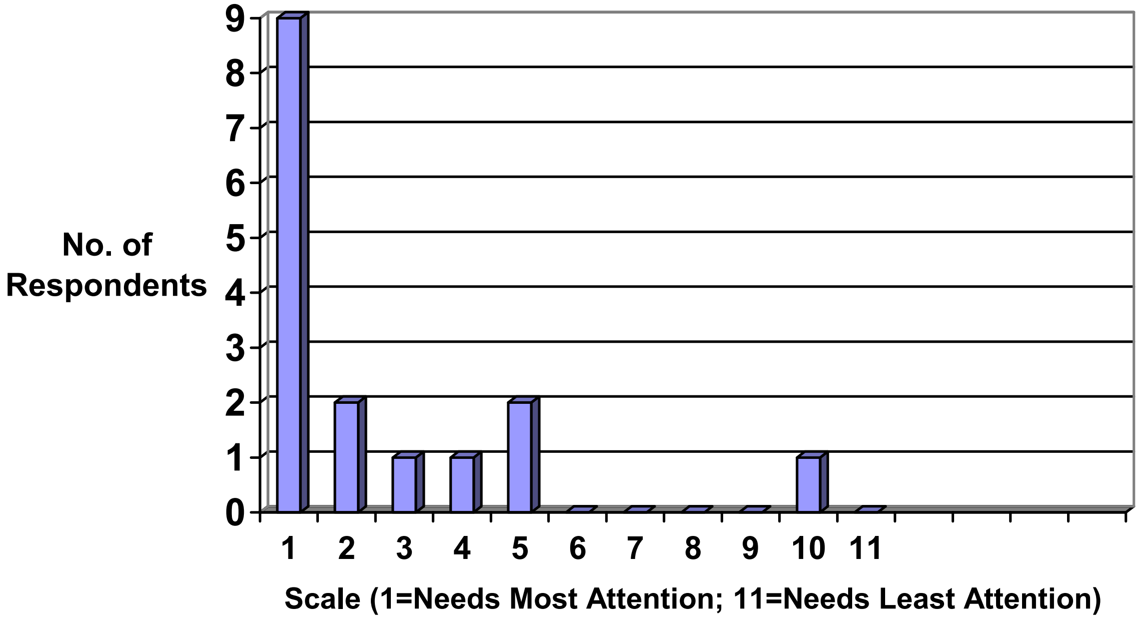
Key to User Issues on Chart

SC = Safety Concerns
TC = Technology Concerns
RM = Reliability/Maintenance
L = Logistics
ET = Education/Training
SI = Systems Integration
NT = New Tactics
PI = Political/PR Issues
NS = New Strategy/Doctrine
IR = Intra/Inter Service Rivalry
IA = Issues with U.S. Allies

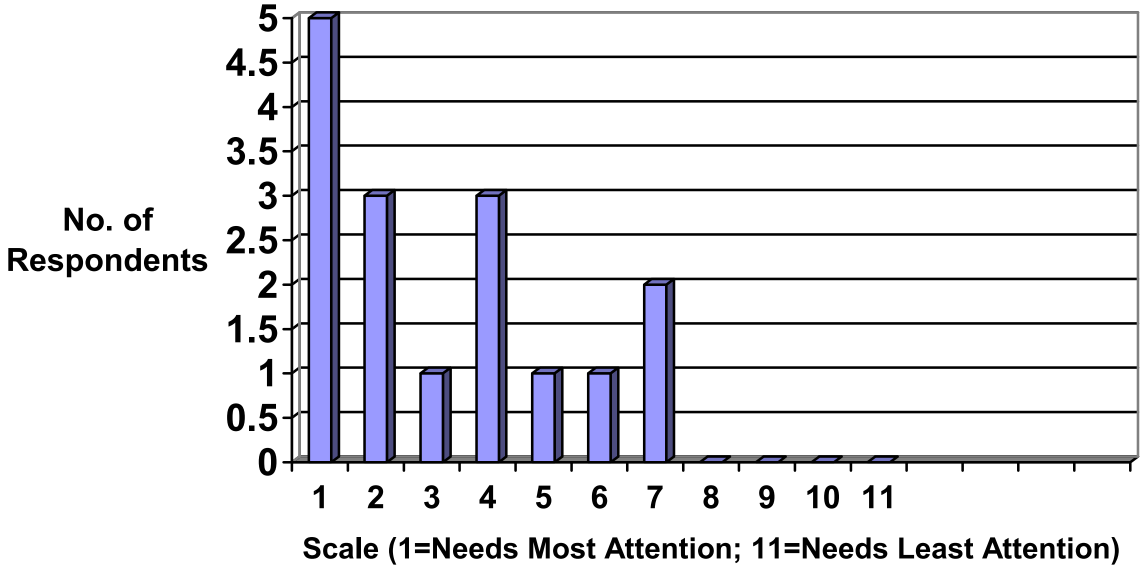
Key User Issues: Technology Concerns



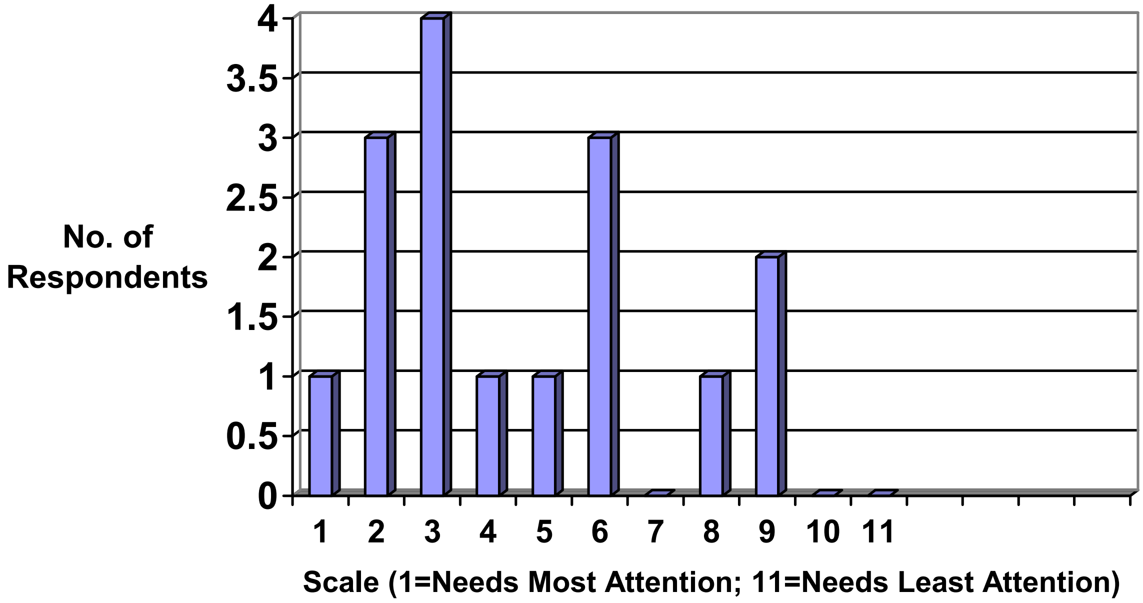
Key User Issues: Safety Concerns



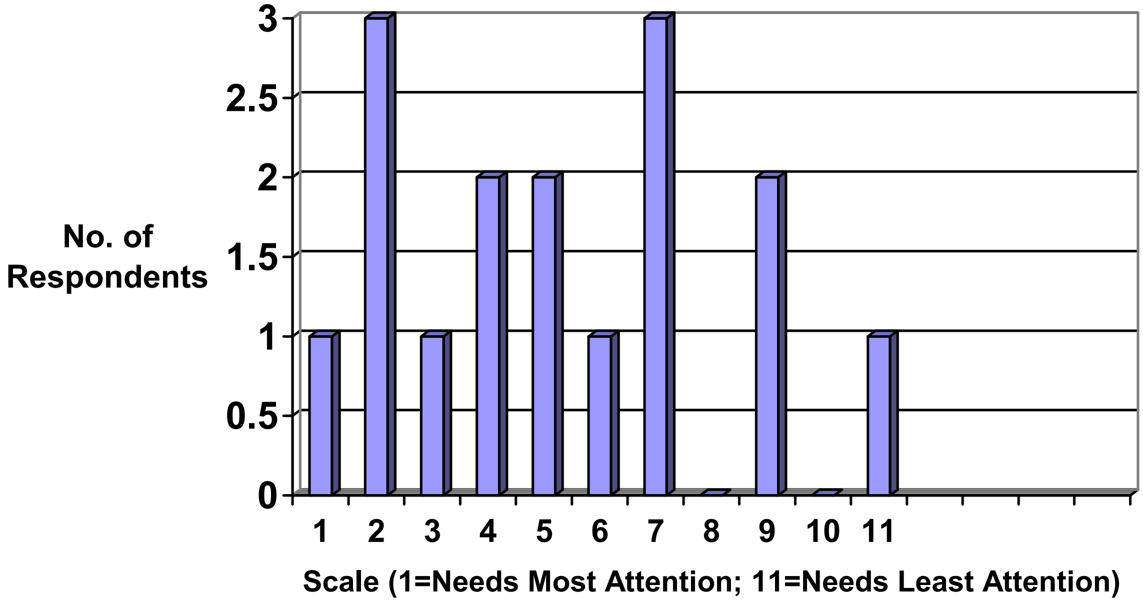
Key User Issues: Reliability & Maintenance Concerns



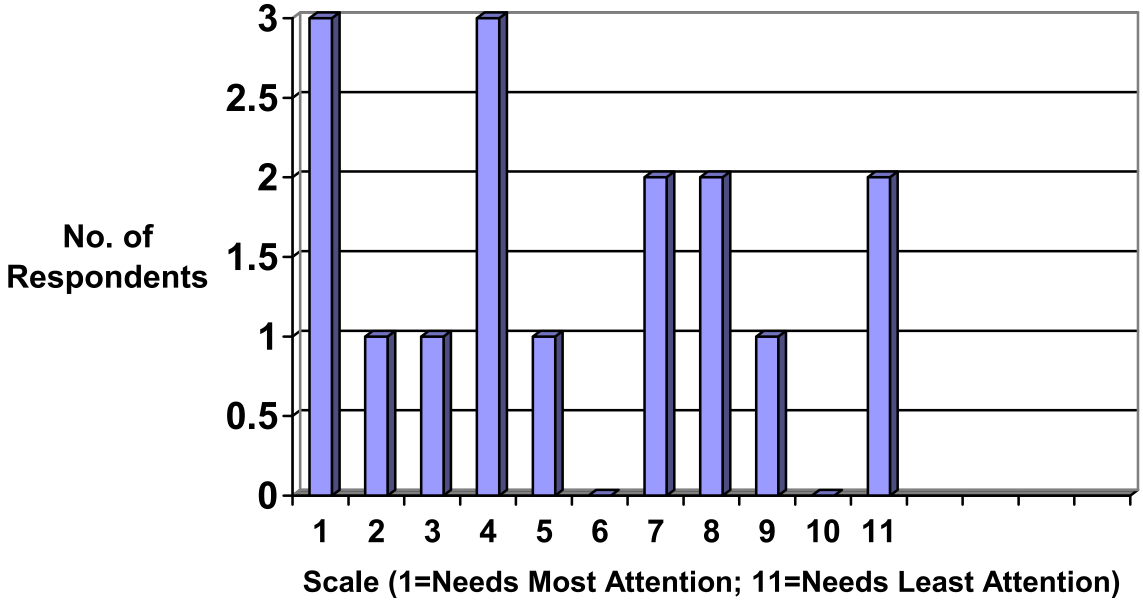
Key User Issues: Logistics Concerns



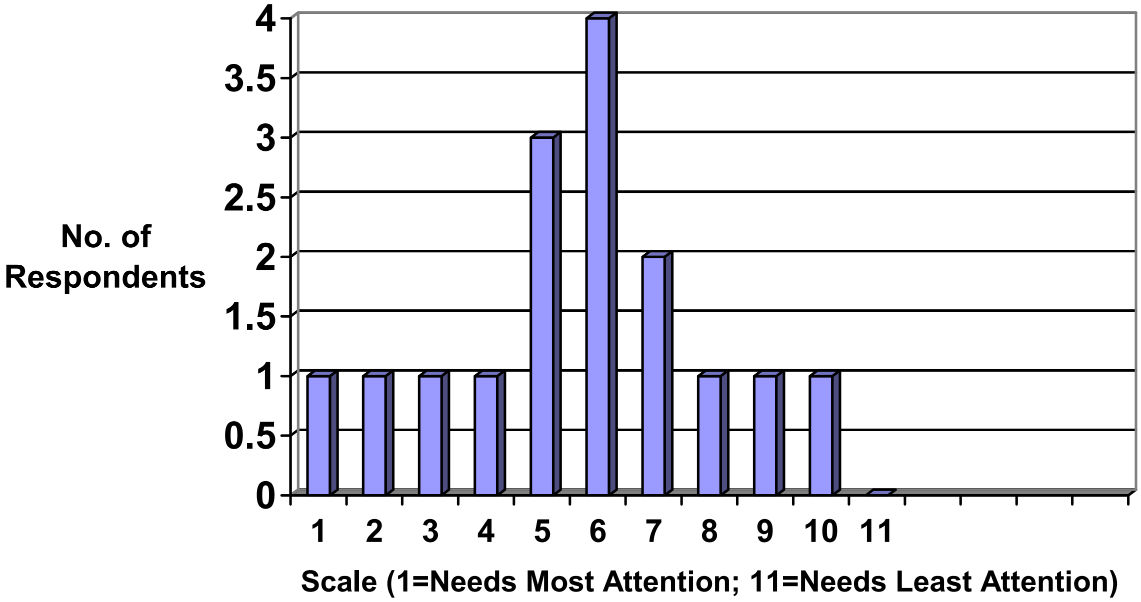
Key User Issues: Systems Integration Concerns



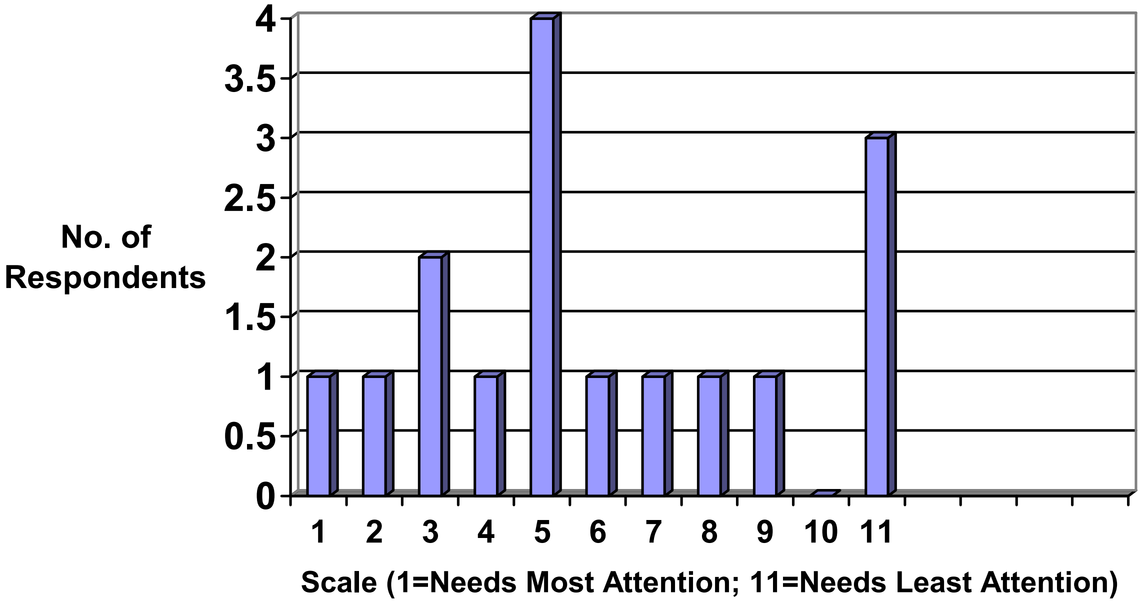
Key User Issues: Education/Training Concerns



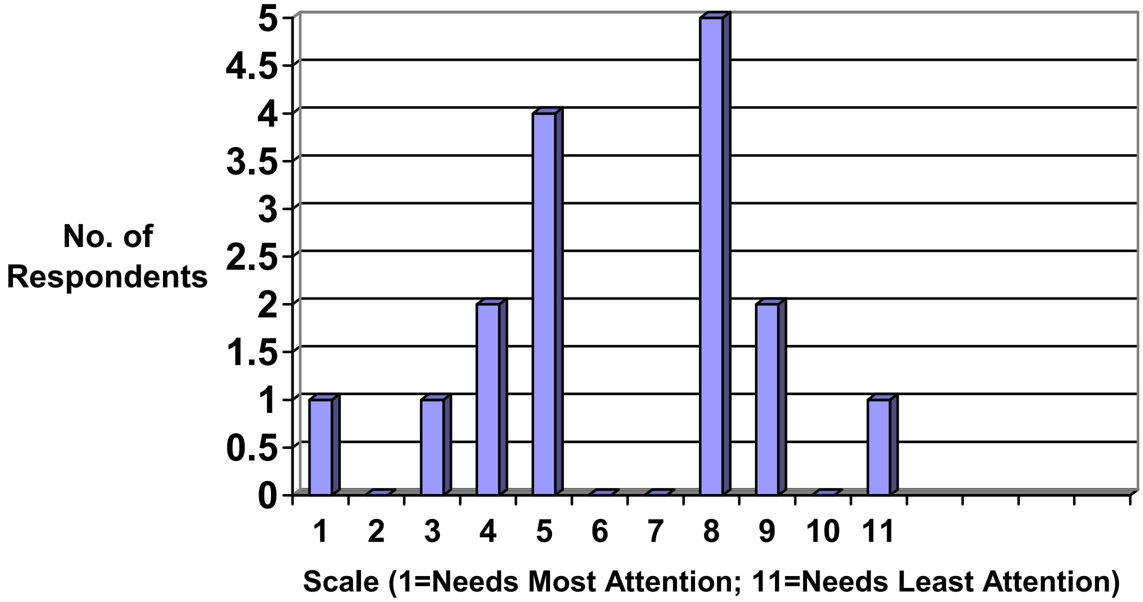
Key User Issues: New Tactics Concerns



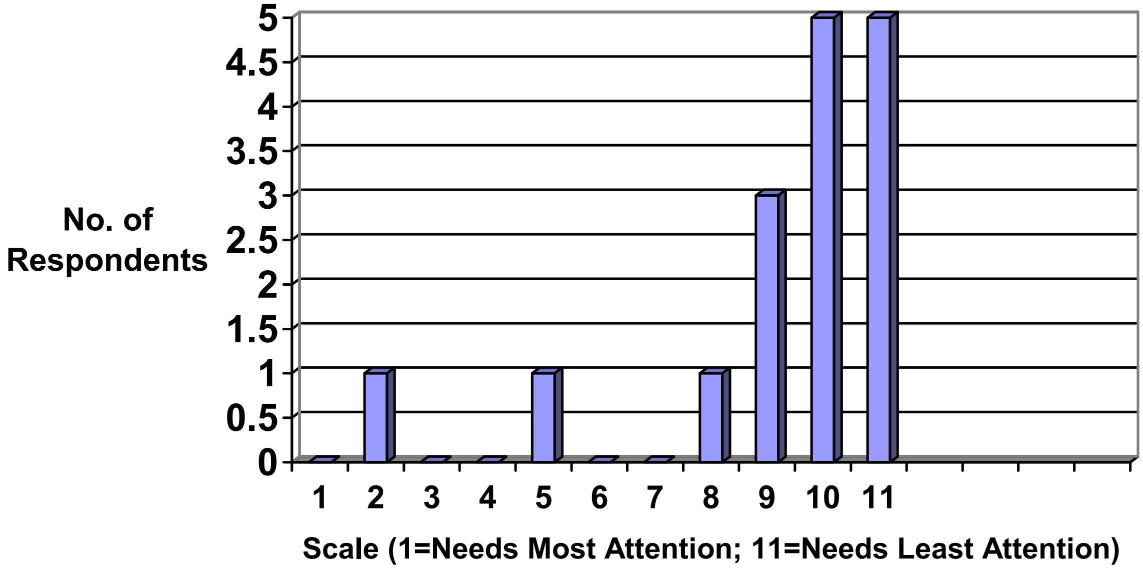
Key User Issues: Political/PR Concerns



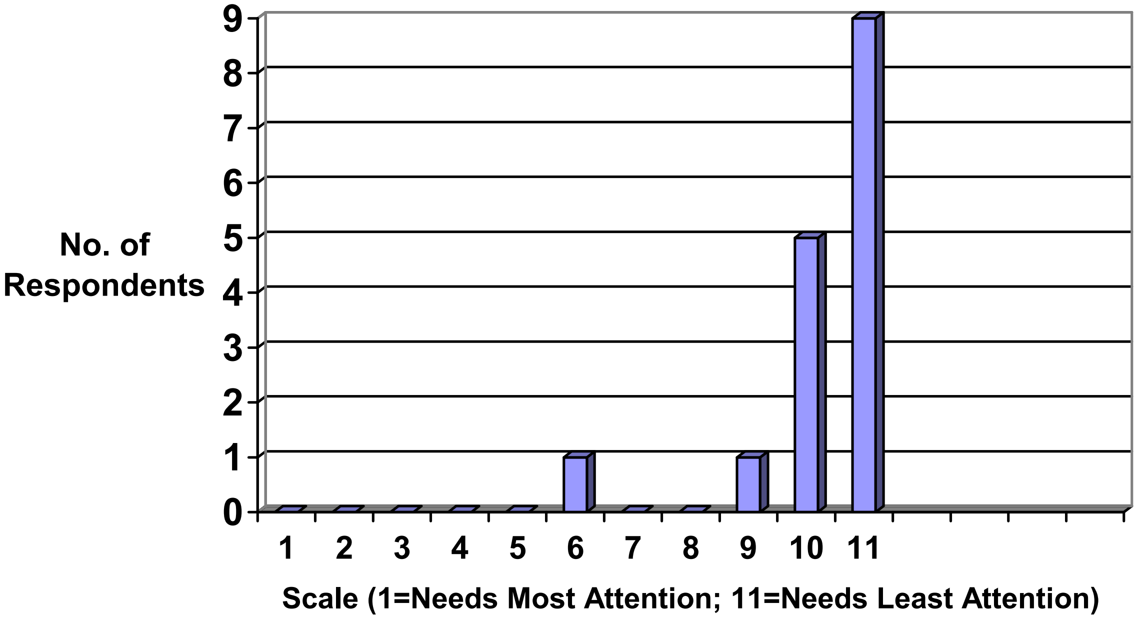
Key User Issues: New Strategy/Doctrine Concerns



Key User Issues: Intra/Inter Service Rivalry Concerns



Key User Issues: U.S. Allies



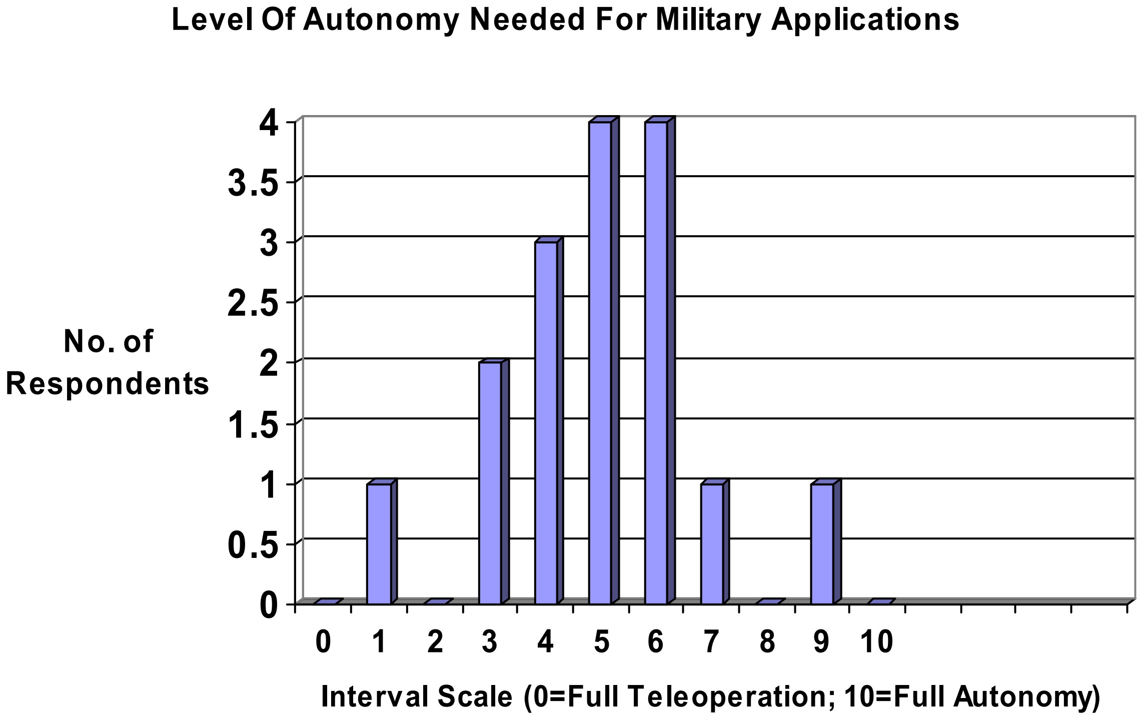
Comments (if any): [The following are verbatim or edited responses].

- ☐ *Need to invest in the technology of Cognitive Decision Aiding Software. To date, work has been laboratory and conceptual. There is a need to conduct realistic and evolutionary work to transition this into a measurable and valuable "thing".*
- ☐ *Two major components that must be improved before robotic systems become practical are remote power cell/battery life and communications range.*
- ☐ *The soldier will make the best use of any equipment you give him. Doctrine has not caught up to some systems that were fielded years ago, and it should be developed in conjunction with robotic applications. The "joint" world needs to be more forgiving of initial capabilities and concentrate on refinement, not ownership.*
- ☐ *Interesting question. Safety is always the biggest concern with any form of automation. Integration and effectiveness are probably the next big hitters with any type of new military system.*
- ☐ *Intra and inner service rivalry.*
- ☐ *Addressing public opinion.*
- ☐ *Counter-jamming and EMP shielding should be a major concern, as well as having a secure data link that cannot be co-opted.*

(9) Depending on the capability of the technology, humanoid robots may be completely controlled (at a distance) at all times by a dedicated operator (full teleoperation), or be fully autonomous (so that one human supervisor may supervise multiple robots), or be semi-autonomous, with various degrees of human intervention. In your opinion, what *minimum* level of autonomy is needed for most practical militarily applications of humanoid (or other legged) robots? Please place an "X" on the appropriate position along the scale:

/---------/---------/---------/---------/---------/--**X**------/---------/---------/---------/--------/
0 1 2 3 4 5 6 7 8 9 10
Full Teleoperation Semi-Autonomy Full Autonomy

Results: n = 16; **M = 5.3** Sta. Dev. = 1.8; **Median ~ 5**; Range = 1-9



Comments (if any): [The following are verbatim or edited responses].

- ☐ *Having a dedicated operator for each robot will not pass the common sense test. Experimentation conducted using soldiers to control unmanned systems have consistently shown that the operators cannot operate the platform, employ their weapon, walk through complex terrain, or understand the information being provided through the Operator Control Unit (OCU) all at the same time. In order to be effective, robotic platforms must provide the operator with some semi-autonomous capabilities that will allow the operator to conduct the other tasks as needed.*

☐ *Full autonomy does not truly exist. Some human must at least program in a mission with parameters for the robot to follow. Full teleoperation is time consuming and not making the best use of a very expensive asset. Semi-autonomy must be considered in any application. Repetitive actions are best completed by the platform, not the operator. The human must be in the link whenever needed. Ultimately, the robot relies on the human because it is a tool.*

☐ *The system needs to be flexible to allow a supervisor to manage many robots, but be able to interact when necessary. The phrase around here is "as autonomous as needed, as interactive as desired." Full teleoperation is practical for some dedicated tasks, such as the bomb disarming robots used today, but, in general, the robot-to-operator ratio will have to be much higher to achieve substantial cost savings.*

☐ *Full teleoperation for recon missions, but full autonomy for ambush tactics or mine clearance.*

☐ *I think there is a definite fear of completely autonomous robots. That said, a certain degree of autonomy would be useful, such as for terrain recognition/adaptation.*

☐ *This depends on the task, mission, or function the platforms are performing.*

(10) Given that a humanoid robot is a new military system (perhaps serving as a weapons system): In your opinion, what should be done, by robot developers, in order to earn full acceptance, by military users, of humanoid (or other legged) robots? Please respond below: [The following are verbatim or edited responses].

☐ *They should be able to surpass the mobility of a human soldier, be affordable, be able to perform for extended periods of time greater than four hours of continuous operation, and be easily maintainable by young soldiers who have numerous other tasks and distractions in the field and on the battlefield.*

☐ *They should be able to at least match the mobility of a human soldier, be able to perform for extended periods of time, be reliable, and be totally maintained and under control by their human handlers.*

☐ *Safety should be the number one priority. Failsafe systems should be implemented, along with fire control. Education and training are key elements, and reliability must be near 100%.*

☐ *Answer a basic question: why humanoid? Do we need to be building "R2D2" or "Commander Data"? First determine why a humanoid form is needed for a particular task then develop it. Why should it have a human shape?*

☐ *The robots should be: cheap, safe, suitable for quick training, accurate, effective, lightweight, portable, easy to maintain, easy to integrate.*

☐ *Identify and develop required capabilities and ensure reliability and military ruggedness.*

☐ *Predictable results from an autonomous software system that includes learning and adaptive thinking.*

☐ *Stop white paper robot companies. Whoever does the work – make sure the robot works. Make the robot fit the mission, not the mission fit the robot.*

☐ *Currently humanoid robots do not exist. However, we do have a variety of air and ground platforms being evaluated by the military. I believe that in order to gain acceptance by military users for these systems, we must first show the utility of these systems through experimentation and limited in the field-testing. The characteristics required would include:*
  - *Semi-autonomous operation (the robot must be able to operate unsupervised under certain conditions)*
  - *Operating range (for dismounted operations, at least 4-10 km)*
  - *User/robot interface (the OCU should be part of the soldier's uniform and not a separate box in his hands)*
  - *Quality of data provided by the system (data should be automatically summarized for the operator and the system should alert the operator of threat targets)*
  - *Speed (the robot should increase the tempo of the units' movement)*
  - *Mobility (the robot must be able to go where the soldier goes, or be able to rendezvous at a predetermined location on its own)*
  - *Power requirements (the operator should not be burdened with carrying extra batteries)*
  - *Dependability (in all weather/terrain)*
  - *Cost (the cost to purchase and maintain robots should be in line with future commercial robotic/vehicle systems)*

☐ *Start with simple high-risk missions (such as CBRN recon and countermine). Get the price down so that the loss of a few systems will not slow down programs (if it is not disposable, it should be repairable modularly). Get them in the field and out of the laboratory and let the soldiers show you how to use them. Men in cubicles who have never been in the military have a very different view of what the military does than the grunt in the foxhole.*

☐ *Engage the end users early and often. Trust is going to be the critical issue for effective use of autonomy in the future. If the operators do not understand or trust the system, they will never relinquish any authority to the autonomy and will therefore never step back into the supervisory role. For example, UAVs are currently being designed to fly missions similar to manned missions, employing the same tactics and procedures. Human operators are comfortable with this and it has become a necessary step to achieve trust in the autonomous system. Unfortunately, it is very expensive to replicate human behavior, when perhaps other behaviors may serve as well or better.*

☐ *There must be more than one type of robot for situations and tasks. The robots must be easy to deploy and use.*

☐ *Safety issues will be at the forefront of concerns of military users. As with all approved military equipment, numerous safety systems will need to be integrated into this technology. The key military application of robots is directly tied to reducing risks taken by soldiers. This is the needed focal point for robot developers. For example, in Afghanistan, we used the TALON robot to enter suspected enemy-held caves to perform reconnaissance, to limit soldier exposure to enemy fire. This was a great military application of robotic technology.*

☐ *It must be able to perform as stated; become a mission essential piece of equipment and not be a weight burden; and have enough power, enough mobility, modular, minimal logistics footprint and ample communications capability not put the operation at risk. It should preferably be dropped into place rather than emplaced.*

☐ *Demonstrate that it is failsafe against friendly fire and ensure total human control of robots.*

☐ *Model the control program after a video game, the kids will love it and half of the training and skill acquisition will be accomplished before they even enlist.*

(11) Additional comments (if any):

☐ *The sooner the better! Army Engineer tasks are dull, dirty, and dangerous. Unmanned systems are a must in order to keep Engineer soldiers out of harm's way.*

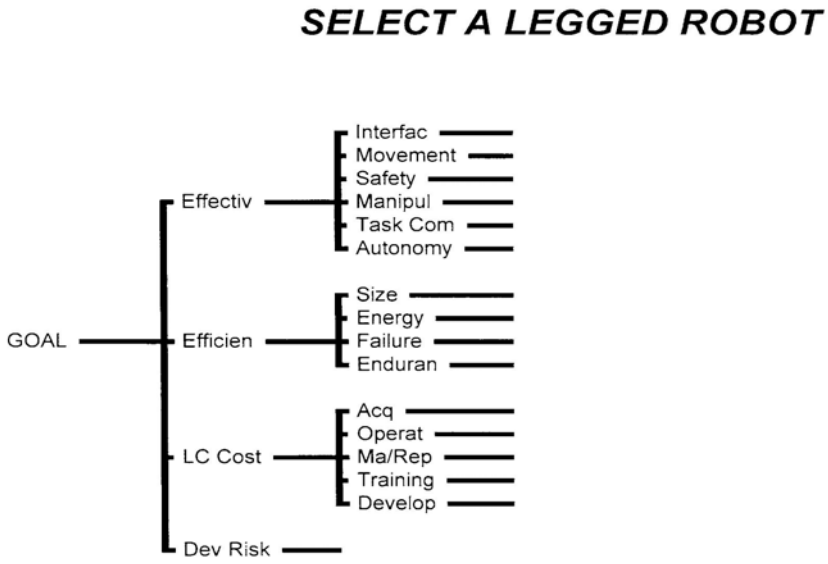
☐ *The Joint Service EOD community is interested in assessing humanoid/legged robots for EOD applications. We currently have tracked teleoperated systems fielded with all four services. EOD user representatives from each service reside locally at the Naval EOD Technology Division, Indian Head, Maryland. The users have recently submitted a needs document that extols the benefit of humanoid robots to EOD, and we would like to explore a possible collaboration to see where the technology currently stands.*

☐ *I believe that we (today) are the pioneers of the Star War systems of the future and that the decisions we make today will help determine how robotic systems will be employed by our current and future forces.*

☐ *Consider disposable attack robots, such as smart toys with explosive charges; items that can be deployed by the hundreds for area denial.*

☐ *Thank you for the opportunity to contribute.*
☐ *If you make it, make it right, and keep in close contact with the end users in the field for testing and input.*

APPENDIX G: METRICS FIGURES



Abbreviation	Definition
Acq	Acquisition Cost
Autonomy	Level Of Autonomy
Dev Risk	Development Risk
Develop	Development Cost
Effectiv	Effectiveness
Efficien	Efficiency
Enduran	Endurance For Designated Tasks
Energy	Rate Of Energy Expenditure For Designated Tasks
Failure	Expected Failure Rate
Interfac	Human/Robot Interface
LC Cost	Life Cycle Cost
Ma/Rep	Maintenance And Repair Cost
Manipul	Ability To Manipulate Objects Suitably For Designated Tasks
Movement	Ability To Move Appropriately On Suitable Surfaces
Operat	Operational Cost
Safety	Acceptably Safe
Size	Weight And Volume
Task Com	Ability To Complete Defined Tasks Successfully
Training	Training Cost

Figure G-1: Tree Diagram of Metrics and Submetrics

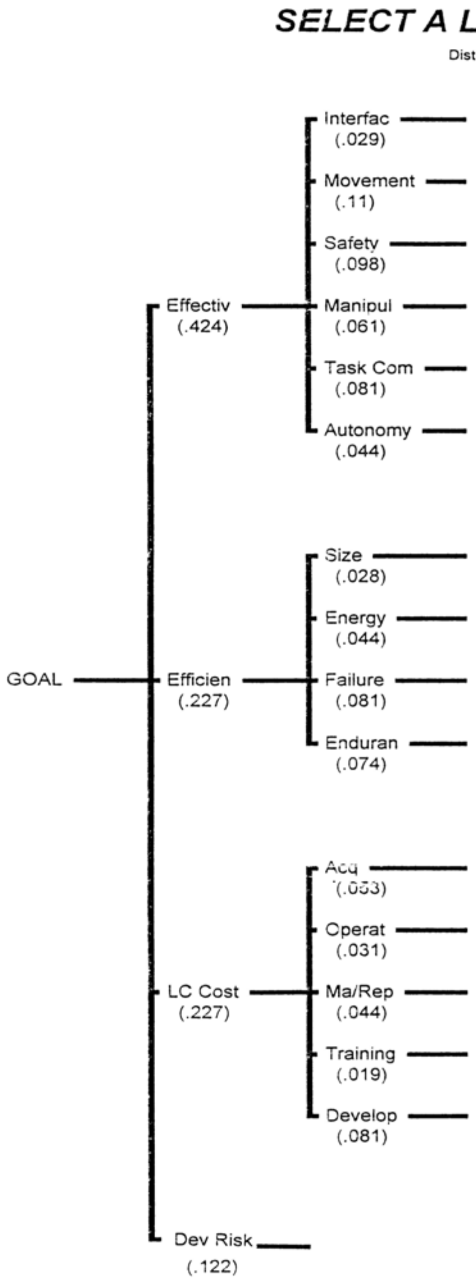


Figure G-2: Tree Diagram of Metrics and Submetrics with Synthesis of Results

SELECT A LEGGED ROBOT

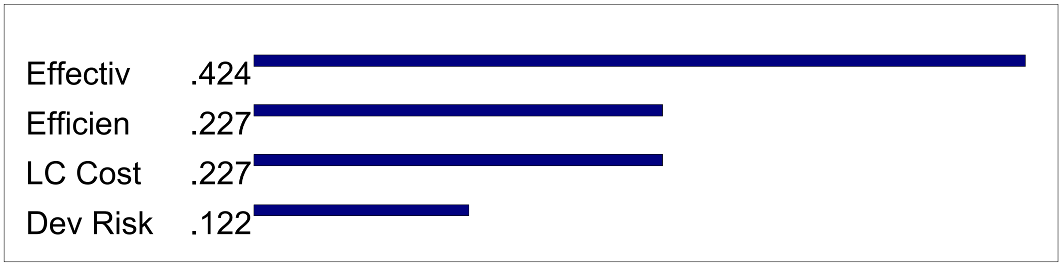
Node: 0

Compare the relative IMPORTANCE with respect to: GOAL

1=EQUAL 3=MODERATE 5=STRONG 7=VERY STRONG 9=EXTREME

1	Effectiv	9	8	7	6	5	4	3	[✓ 2]	**1**	2	3	4	5	6	7	8	9	Efficien
2	Effectiv	9	8	7	6	5	4	3	[✓ 2]	**1**	2	3	4	5	6	7	8	9	LC Cost
3	Effectiv	9	8	7	6	5	4	[✓ 3]	2	**1**	2	3	4	5	6	7	8	9	Dev Risk
4	Efficien	9	8	7	6	5	4	3	2	[✓ **1**]	2	3	4	5	6	7	8	9	LC Cost
5	Efficien	9	8	7	6	5	4	3	[✓ 2]	**1**	2	3	4	5	6	7	8	9	Dev Risk
6	LC Cost	9	8	7	6	5	4	3	[✓ 2]	**1**	2	3	4	5	6	7	8	9	Dev Risk

Abbreviation	**Definition**
Goal	SELECT A LEGGED ROBOT
Effectiv	Effectiveness
Efficien	Efficiency
LC Cost	Life Cycle Cost
Dev Risk	Development Risk



Inconsistency Ratio =0.0

Figure G-3: Evaluation of Goal Metrics

SELECT A LEGGED ROBOT

Node: 10000
Compare the relative IMPORTANCE with respect to: Effectiv < GOAL

1=EQUAL 3=MODERATE 5=STRONG 7=VERY STRONG 9=EXTREME

1	Movement	9	8	7	6	5	4	3	[✓ 2]	**1**	2	3	4	5	6	7	8	9	Safety
2	Movement	9	8	7	6	5	4	3	2	[✓ **1**]	2	3	4	5	6	7	8	9	Task Com
3	Movement	9	8	7	6	5	4	3	[✓ 2]	**1**	2	3	4	5	6	7	8	9	Manipul
4	Movement	9	8	7	6	5	4	3	[✓ 2]	**1**	2	3	4	5	6	7	8	9	Autonomy
5	Movement	9	8	7	6	5	4	[✓ 3]	2	**1**	2	3	4	5	6	7	8	9	Interfac
6	Safety	9	8	7	6	5	4	3	[✓ 2]	**1**	2	3	4	5	6	7	8	9	Task Com
7	Safety	9	8	7	6	5	4	3	[✓ 2]	**1**	2	3	4	5	6	7	8	9	Manipul
8	Safety	9	8	7	6	5	4	3	[✓ 2]	**1**	2	3	4	5	6	7	8	9	Autonomy
9	Safety	9	8	7	6	5	4	[✓ 3]	2	**1**	2	3	4	5	6	7	8	9	Interfac
10	Task Com	9	8	7	6	5	4	3	[✓ 2]	**1**	2	3	4	5	6	7	8	9	Manipul
11	Task Com	9	8	7	6	5	4	3	[✓ 2]	**1**	2	3	4	5	6	7	8	9	Autonomy
12	Task Com	9	8	7	6	5	4	3	[✓ 2]	**1**	2	3	4	5	6	7	8	9	Interfac
13	Manipul	9	8	7	6	5	4	3	[✓ 2]	**1**	2	3	4	5	6	7	8	9	Autonomy
14	Manipul	9	8	7	6	5	4	[✓ 3]	2	**1**	2	3	4	5	6	7	8	9	Interfac
15	Autonomy	9	8	7	6	5	4	3	[✓ 2]	**1**	2	3	4	5	6	7	8	9	Interfac

Abbreviation	**Definition**
Goal	SELECT A LEGGED ROBOT
Effectiv	Effectiveness
Movement	Ability To Move Appropriately On Suitable Surfaces
Safety	Acceptably Safe
Task Com	Ability To Complete Defined Tasks Successfully
Manipul	Ability To Manipulate Objects For Designated Tasks
Autonomy	Level Of Autonomy
Interfac	Human/Robot Interface

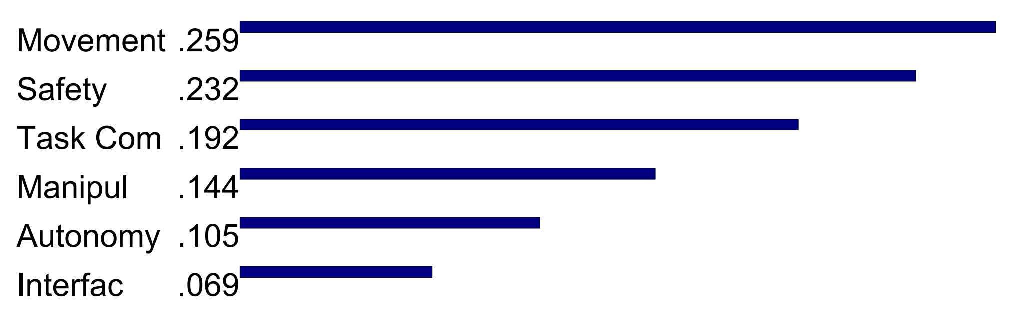


Figure G-4: Evaluation of Effectiveness Submetrics

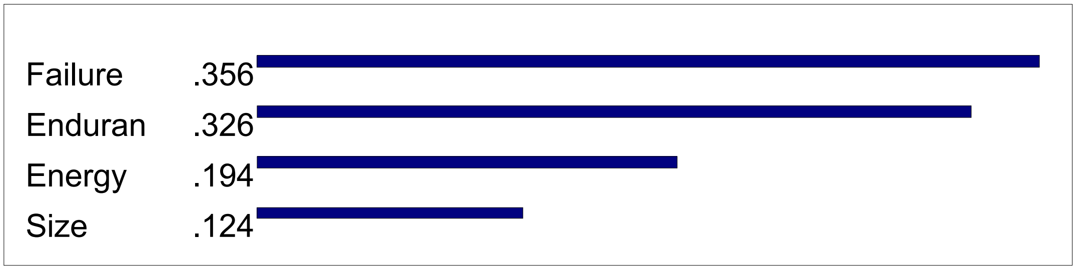
SELECT A LEGGED ROBOT

Node: 20000
Compare the relative IMPORTANCE with respect to: Efficien < GOAL

1=EQUAL 3=MODERATE 5=STRONG 7=VERY STRONG 9=EXTREME

1	Failure	9	8	7	6	5	4	3	2	[✓ **1**]	2	3	4	5	6	7	8	9	Enduran
2	Failure	9	8	7	6	5	4	3	[✓ 2]	**1**	2	3	4	5	6	7	8	9	Energy
3	Failure	9	8	7	6	5	4	[✓ 3]	2	**1**	2	3	4	5	6	7	8	9	Size
4	Enduran	9	8	7	6	5	4	3	[✓ 2]	**1**	2	3	4	5	6	7	8	9	Energy
5	Enduran	9	8	7	6	5	4	3	[✓ 2]	**1**	2	3	4	5	6	7	8	9	Size
6	Energy	9	8	7	6	5	4	3	[✓ 2]	**1**	2	3	4	5	6	7	8	9	Size

Abbreviation	**Definition**
Goal	SELECT A LEGGED ROBOT
Efficien	Efficiency
Failure	Expected Failure Rate
Enduran	Endurance For Designated Tasks
Energy	Rate Of Energy Expenditure For Designated Tasks
Size	Weight And Volume



Inconsistency Ratio =0.02

Figure G-5: Evaluation of Efficiency Submetrics

SELECT A LEGGED ROBOT

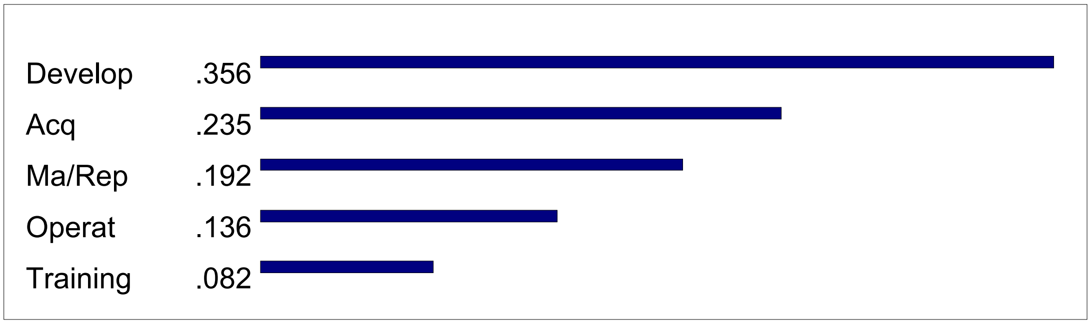
Node: 30000

Compare the relative IMPORTANCE with respect to: LC Cost < GOAL

1=EQUAL 3=MODERATE 5=STRONG 7=VERY STRONG 9=EXTREME

1	Develop	9	8	7	6	5	4	3	[✓ 2]	**1**	2	3	4	5	6	7	8	9	Acq
2	Develop	9	8	7	6	5	4	3	[✓ 2]	**1**	2	3	4	5	6	7	8	9	Ma/Rep
3	Develop	9	8	7	6	5	4	[✓ 3]	2	**1**	2	3	4	5	6	7	8	9	Operat
4	Develop	9	8	7	6	5	4	[✓ 3]	2	**1**	2	3	4	5	6	7	8	9	Training
5	Acq	9	8	7	6	5	4	3	[✓ 2]	**1**	2	3	4	5	6	7	8	9	Ma/Rep
6	Acq	9	8	7	6	5	4	3	[✓ 2]	**1**	2	3	4	5	6	7	8	9	Operat
7	Acq	9	8	7	6	5	4	3	[✓ 2]	**1**	2	3	4	5	6	7	8	9	Training
8	Ma/Rep	9	8	7	6	5	4	3	[✓ 2]	**1**	2	3	4	5	6	7	8	9	Operat
9	Ma/Rep	9	8	7	6	5	4	[✓ 3]	2	**1**	2	3	4	5	6	7	8	9	Training
10	Operat	9	8	7	6	5	4	[✓ 3]	2	**1**	2	3	4	5	6	7	8	9	Training

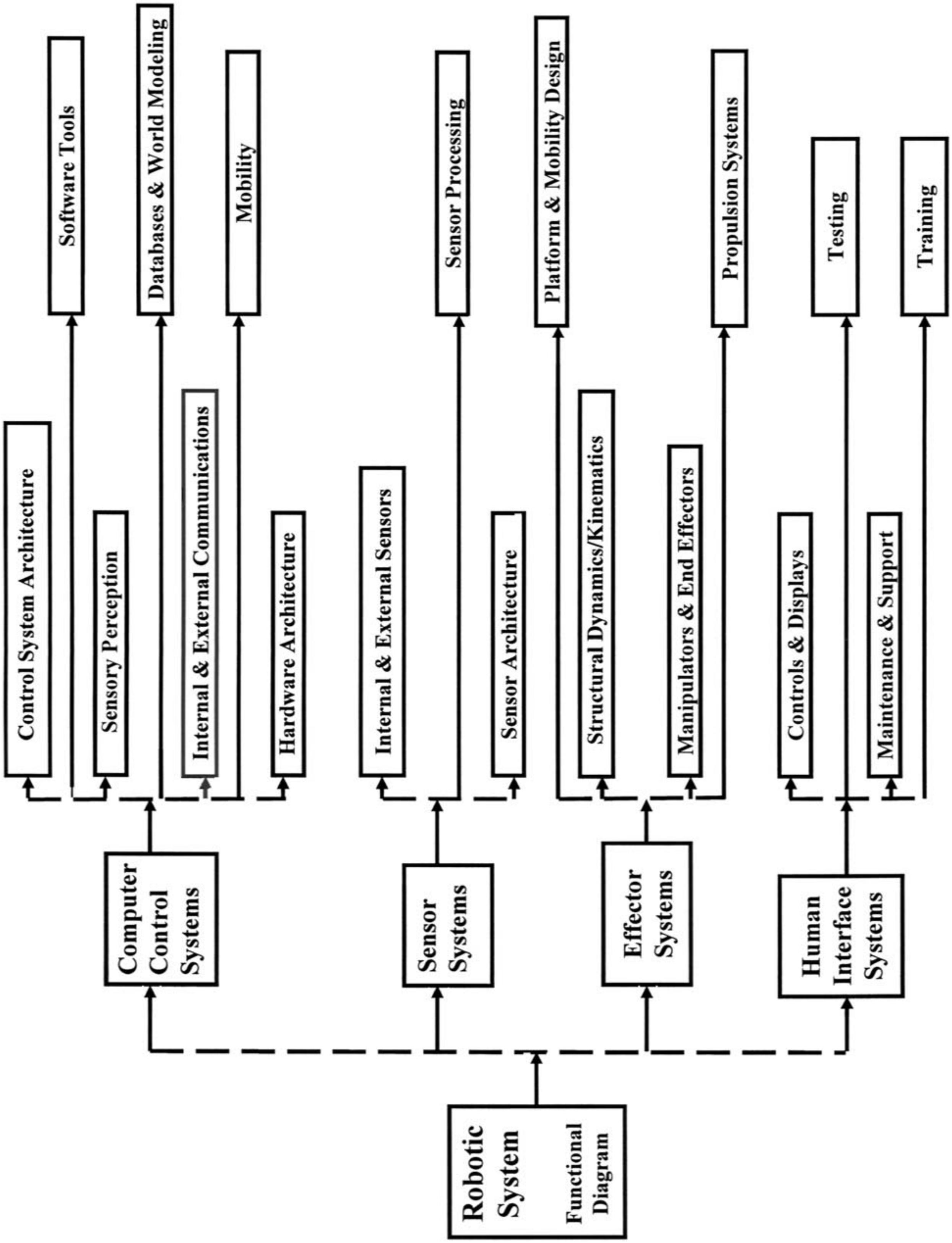
Abbreviation	Definition
Goal	SELECT A LEGGED ROBOT
LC Cost	Life Cycle Cost
Develop	Development Cost
Acq	Acquisition Cost
Ma/Rep	Maintenance And Repair Cost
Operat	Operational Cost
Training	Training Cost



Inconsistency Ratio =0.05

Figure G-6: Evaluation of Cost Submetrics

APPENDIX H: FUNCTIONAL DIAGRAM OF ANY LEGGED ROBOT



APPENDIX I: REFERENCES

(All references are available in the RTI library)

- Ackerman, Sandra, “Discovering the Brain,” National Academy Press, 1992.
- Adams, Bryan, et. al., “Humanoid Robots: A New Kind of Tool,” IEEE Intelligent Systems, July/August 2000, pp. 25-31.
- Aiyama, Y., et. al., “Cooperative Transportation by Two Four-Legged Robots with Implicit Communication,” Robotics and Autonomous Systems 29 (1999) 13-19.
- Albus, James, “Humanoid and Quadruped Robots,” private White Paper, Oct. 2002.
- Albus, James, “Brains, Behavior, & Robotics,” McGraw-Hill, 1981.
- Albus, James, “A Theory of Cerebellar Function,” Mathematical Biosciences 10: 25-61.
- Albus, James, et. al., “4D/RCS: A Reference Model Architecture for Unmanned Vehicle Systems, Version 2.0,” NISTIR 6910, August 2002.
- Albus, James, and Meystel, Alexander, “Engineering of Mind: An Introduction to the Science of Intelligent Systems,” John Wiley & Sons, 2001.
- Albus, J, Meystel, A., and Quintero, R., eds., “Intelligent Systems: A Semiotic Perspective,” Proceedings, Vols. I and II, NIST, 20-23 Oct. 1996.
- Aleksander, Igor, ed., “Neural Computing Architectures: The Design of Brain-Like Machines,” MIT Press, 1989.
- Alexander, Mc Neill R., “Exploring Biomechanics,” Scientific American Books, 1992.
- Allen-Mills, Tony, “Robots to Join US Battle in Baghdad,” London Sunday Times, P.21, 11 Aug. 2002.
- Allman, William, “Inside the Neural Network Revolution,” Bantam, 1989.
- Altendorfer, Richard, et. al., “Evidence for Spring Loaded Inverted Pendulum Running in a Hexapod Robot,” DARPA/SPAWAR
- Ambrose, Robert, et. al., “Robonaut: NASA’s Space Humanoid,” IEEE Intelligent Systems (July/Aug. 2000) 57-63.
- Ambrose, Robert, and Bluethman, Bill, “Articulated Upper Bodies for Dexterous Manipulation,” Briefing, NASA JCS, 2001.
- Antsaklis, Panos, and Passino, Kevin, “An Introduction to Intelligent and Autonomous Control,” Kluwer Academic Publishers, 1992.
- Arden, Bruce, ed., “What Can Be Automated?” MIT Press, 1981.
- Arkin, Ronald, “Behavior-Based Robotics,” MIT Press, 2000.
- Arkin, Ronald, et. al., “An Ethological and Emotional Basis for Human-Robot Interaction,” Robotics and Autonomous Systems 1042 (2003) 1-11.
- Arkin, Ronald, et. al., “Behavioral Models of the Preying Mantis as a Basis for Robot Behavior,” Robotics and Autonomous Systems 32 (2000) 39-60.
- Arkin, Ronald, and Bekey, George, “Robot Colonies,” Kluwer Academic Publ., 1997.
- Asada, Minoru, et. al., “Cognitive Developmental Robotics as a New Paradigm for the Design of Humanoid Robots,” Robotics and Autonomous Systems 37 (2001) 185-193.
- Ashby, Ross, “An Introduction to Cybernetics,” John Wiley & Sons, 1963.
- Ashby, Ross, “Design for a Brain,” Chapman & Hall, 1976.
- “Asimo, World’s Most Advanced Humanoid Robot, Begins Educational Tour, Will Visit Major U.S. Cities During 15-Month Period” Business Wire, 28 Jan. 2003.
- Atroley, Akansha, “Robowarriors: Terminator Now,” Computers Today, 15 Aug. 2001.

- ☐ Barr, Avron, and Feigenbaum, Edward, “The Handbook of Artificial Intelligence,” Heuristic Press, 1981.
- ☐ Bar-Yam, Yaneer, “Dynamics of Complex Systems,” Perseus Books, 1997.
- ☐ Beardsley, Tim, “Enter Robots, Slowly,” Scientific American, Vol. 281, No. 3, P.36, Sep. 1999.
- ☐ Beardsley, Tim, “Here’s Looking at You: a Disarming Robot Starts to Act Up,” Scientific American, Vol. 280, No. 1, P. 39, Jan. 1999.
- ☐ “Behold the Humanoid!” Malaysian Business, 1 Sep. 2002.
- ☐ Beutel, Allard, “Future Mars Rovers To Change Shape, Rappel Cliffs,” CNN Headline News, 21 Jan. 2002.
- ☐ Billard, Aude, “Robota: Clever Toy and Educational Tool,” Robotics and Autonomous Systems 1047 (2003) 1-11.
- ☐ Billard, Aude, and Mataric, Maja, “A Biologically Inspired Robotic Model for Learning by Imitation,” ACM, Agents 2000 Barcelona, Spain, 2000.
- ☐ Blackburn, Michael, “Autonomy and Intelligence: A Question of Definitions,” Proceedings of the Autonomous Intelligent Networks and Systems Symposium, UCLA, 8-9 May 2002.
- ☐ Bond, Alan, and Gasser, Les, “Readings in Distributed Artificial Intelligence,” Morgan Kaufman, 1988.
- ☐ “Boston Dynamics and Sony Develop Simulator for Humanoid Robot,” Press Release, Boston Dynamics.
- ☐ Bowden, Richard, et. al., “Jeremiah: The Face of Computer Vision,” ACM, Symposium on Smart Graphics, 11-13 June 2002.
- ☐ Brady, Michael, et. al., eds., “Robot Motion, Planning and Control,” MIT Press, 1986.
- ☐ Branwyn, Gareth, “Hey, Asimo, Bring Me a Beer!” Yahoo! Internet Life, P 92, Aug. 2001.
- ☐ Breazeal, Cynthia, and Scassellati, Brian, “Robots That Imitate Humans,” Trends in Cognitive Sciences, Vol. 6, No. 11, Nov. 2002, pp. 481-487.
- ☐ Brooks, Rodney, “From Earwigs to Humans,” Robotics and Autonomous Systems 20 (1997) 291-304.
- ☐ Brooks, Rodney, “Humanoid Robots,” Communications of the ACM, Vol. 45, No. 3, P. 33-38, March 2002.
- ☐ Brown, C.C., and Huissoon, J.P., “Temporal Gait Control of a Quadruped Robot,” Robotics and Autonomous Systems 30 (2000) 305-314.
- ☐ Buchbinder, David, “In Afghanistan a New Robosoldier Goes to War,” Christian Science Monitor, P. 1, 31 July 2002.
- ☐ Burnell, Scott, “Robots Not Replacing Troops Soon,” UPI, 13 May 2002.
- ☐ Cairns-Smith, A.G., “Evolving the Mind,” Cambridge University Press, 1996.
- ☐ Carter, Rita, “Mapping the Mind,” University of California Press, 1999.
- ☐ Capi, Genci, et. al., “Real Time Gait Generation for Autonomous Humanoid Robots: A Case Study for Walking,” Robotics and Autonomous Systems 42 (2003) 107-116.
- ☐ Capi, Genci, et. al., “Real-time Generation of Humanoid Robot Optimal Gait for Going Upstairs Using Intelligent Algorithms,” The Industrial Robot, Vol. 28, No. 6, P.489, 2001.
- ☐ Cerny, Jeff, “Combotoid: Telepresence, The Best of Two Worlds,” private White Paper, Feb. 2003.

- ☐ Chalmers, David, “The Conscious Mind: in Search of a Fundamental Theory,” Oxford University Press, 1996.
- ☐ Charniak, Eugene, et. al., “Artificial Intelligence Programming,” Lawrence Erlbaum Associates, Publishers, 1980.
- ☐ Cheng, Gordon, et. al., “Continuous Humanoid Interaction: An Integrated Perspective – Gaining Adaptivity, Redundancy, Flexibility – in One,” Robotics and Autonomous Systems 37 (2001) 161-183.
- ☐ Churchland, Patricia, “Neurophilosophy: Toward a Unified Science of the Mind/Brain,” MIT Press, 1988.
- ☐ Churchland, Paul, “Matter and Consciousness,” MIT Press, 1988.
- ☐ Coelho, Jefferson, et. al., “Developing Haptic and Visual Perceptual Categories for Reaching and Grasping with a Humanoid Robot,” Robotics and Autonomous Systems 37 (2001) 195-218.
- ☐ Conant, Roger, ed., “Mechanisms of Intelligence,” Intersystems Publications, 1981.
- ☐ Critchlow, Arthur, “Introduction to Robotics,” Macmillan Publ., 1985.
- ☐ Cruse, Holk, et. al., “Walknet – a Biologically Inspired Network to Control Six-Legged Walking,” Neural Networks, 11, (1998) 1435-1447.
- ☐ Damasio, Antonio, “Descarte’s Error: Emotion, Reason, and the Human Brain,” Putnam’s Sons, 1994.
- ☐ Damasio, Antonio, “Looking for Spinoza: Joy, Sorrow, and the Feeling Brain,” Harcourt, 2003.
- ☐ Davis, Lawrence, ed., “Handbook of Genetic Algorithms,” Van Nostrand Reinhold, 1991.
- ☐ Delcomyn, Fred, and Nelson, Mark, “Architectures for a Biomimetic Hexapod Robot,” Robotics and Autonomous Systems 30 (2000) 5-15.
- ☐ Denk, J., et. al., “Vision Guided Biped Walking: Step Sequence Planning, Visual Perception and Feedback,” Proceedings of the 5th International Conference on Climbing and Walking Robots (CLAWAR 2002), Paris France, pp. 163ff, Sept. 2002.
- ☐ Denk, J., and Schmidt, G., “Walking Primitive Synthesis for an Anthropomorphic Biped Using Optimal Control Techniques,” Proceedings of the 4th International Conference on Climbing and Walking Robots (CLAWAR 2001), Karlsruhe, Germany, 819-826, Sept. 2001.
- ☐ Dennett, Daniel, “Kinds of Minds,” Basic Books, 1996.
- ☐ Dennett, Daniel, “Consciousness Explained,” Little, Brown & Co., 1991.
- ☐ De Santos, P. Gonzalez and M.A. Jimenez, “Path tracking with Quadruped Walking Machines using Discontinuous Gaits,” Computers Elect. Engng, Vol/ 21, No. 6, P. 383-396, 1995.
- ☐ “Designed for Life,” New Scientist, 1 June 2002.
- ☐ Dinello, Dan, “We, Robots,” Salon.com, Inc., 21 June 01.
- ☐ Dougherty, Edward, and Giardina, Charles, “Mathematical Methods for Artificial Intelligence and Autonomous Systems,” Prentics Hall, 1988.
- ☐ “Dr. Doi’s Useless Inventions,” Economist, Vol. 357, No. 8202, P. 102, 23 Dec 2000.
- ☐ Duffy, Brian, “Anthropomorphism and the Social Robot,” Robotics and Autonomous Systems 1041 (2003) 1-14.
- ☐ Durkin, John, “Expert Systems: Design and Development,” Prentice Hall Publ., 1994.
- ☐ Dvorak, John, “Here Come the Robots Dept.,” PC Magazine, P.67, 13 Nov. 2001.

- “E-Business: Humanoid Helper,” Birmingham Post, P. 20, 14 Jan. 2003.
- Edelman, Gerald, “Bright Air, Brilliant Fire: On the Matter of the Mind,” Basic Books, 1992.
- Endo, Fumiko, “Coexistence of Humans and Robots; Robots Offer Learning Opportunity,” The Daily Yomiuri (Tokyo), P. 10, 1 Jan. 2003.
- Engelberger, Joseph, “Robotics In Service,” MIT Press, 1989.
- Engelberger, Joseph, “Futurespeak,” American Demographics, Vol. 23, Issue 7, P.58, July 2001.
- Engelke, Roger, “MIT Humanoid Robot Project Takes Exciting Steps Forward,” Electronic Design, Vol. 46, No. 9, P.27, 20 April 1998.
- “Enter the Kung Fu-bot,” Design Engineering, P. 9, Nov. 2001.
- Espenschied, Kenneth, et. al., “Biologically Based Distributed Control and Local Reflexes Improve Rough terrain Locomotion in a Hexapod Robot,” Robotics and Autonomous Systems 18 (1996) 59-64.
- Ferrell, Cynthia, “A Comparison of Three Insect-Inspired Locomotion Controllers,” Robotics and Autonomous Systems 16 (1995) 135-159.
- Finkelstein, Robert, “Combat Robotics: From the Kaiser to the New World Order,” Defense Year Book, Brassy’s Publ., 1992.
- Finkelstein, Robert, “Combat Robotics and Values, or How Should a Robot Decide Between Chocolate and Vanilla,” Unmanned Systems 5(4): 8, 11.
- Finkelstein, Robert, “Terrorism, Ants, and Unmanned Vehicles,” Unmanned Systems 4(1): 45-46.
- Finkelstein, Robert, “Robot Morality,” Unmanned Systems 3(1): 10-11.
- Finkelstein, Robert, “Robotic Vehicles for the Future Combat System (FCS),” NA1341-01-U-0081, NIST, Feb. 2001.
- Finkelstein, Robert, “Robotic Air and Ground Vehicles: Synergy,” 43NANB911338, NIST, Dec. 1999.
- Finkelstein, Robert, “Metrics: Evaluating the Performance of Intelligent Systems, the Example of Robots in Urban Search and Rescue,” 43NANB009812, NIST, June 2000.
- Finkelstein, Robert, “A Method for Evaluating the “IQ” of Intelligent Systems,” Proceeding of the Performance Metrics for Intelligent Systems Workshop, NIST, DARPA, IEEE, NASA, 14-16 Aug. 2000.
- Finkelstein, Robert, “Analysis of Robotics for the Future Combat System: Expected Operational Utility of Robots,” Boeing, May 2001.
- Finkelstein, Robert, “Robotic Analysis for the Future Combat System,” Boeing, May 2001.
- Finkelstein, Robert, “Historical Lessons Learned: A Cautionary tale for Unmanned Air and Ground Vehicles,” Boeing, Sept. 2002.
- Finkelstein, Robert, and Shaker, Steven, “Unmanned Vehicle Systems: military and Civil Robots for the 21st Century and Beyond,” Pasha Publications, 1994.
- Fischler, Martin, and Firschein, Oscar, “Intelligence: the Eye, the Brain, and the Computer,” Addison-Wesley, 1987.
- Foerst, Anne, “Artificial Sociability: From Embodied AI toward New Understanding of Personhood,” Technology in Society 21 (1999) 373-386.
- Foerst, Anne, “COG, a Humanoid Robot, and the Question of the Image of God,” Zygon, Vol. 33, No. 1, P.91-111, March 1998.

- Foerst, Anne, “Response: Embodied AI, Creation, and COG,” Zygon, Vol. 33, No. 3, P.455-461, Sep. 1998.
- Foerst, Anne, “Birthing the ‘Bot,” Forbes ASAP, P.73, 4 Oct. 1999.
- Fowler, Jonathan, “U.N. Says Robot Sales Down In U.S.,” Associated Press, 2 Oct. 2002.
- “Fujitsu’s Microelectronics and Components Groups Plan Major Exhibit at Convergence 2002 in Detroit (HOAP-1 Humanoid Robot),” PR Newswire, 21 Oct. 2002.
- “Full-size Humanoid Stands Up By Itself,” The Nikkei Weekly, 7 Oct. 2002.
- Furuta, T., et. al., “Design and Construction of a Series of Compact Humanoid Robots and Development of Biped Walk Control Strategies,” Robotics and Autonomous Systems 37 (2001) 81-100.
- Gallagher, John, et. al., “Application of Evolved Locomotion Controllers to a Hexapod Robot,” Robotics and Autonomous Systems 319 (1996) 95-103.
- Gardner, Howard, “Intelligence Reframed: Multiple Intelligences for the 21st Century,” Basic Books, 1999.
- Gasser, Les, and Huhns, Michael, eds., “Distributed Artificial Intelligence,” Morgan Kaufmann, Publ., 1989.
- Gazzaniga, Michael, “Mind Matters: How the Mind and Brain Interact to Create Our Conscious Lives,” Houghton Mifflin Co., 1988.
- Gazi, Veysel, et. al., “The RCS Handbook,” John Wiley & Sons, 2001.
- Geduld, Harry, and Gottesman, Ronald, “Robots, Robots, Robots,” Little, Brown, & Co., 1978.
- Gerhart, Mary, and Russell, Allan, “COG is to Us as We Are to God: A Response to Anne Foerst,” Zygon, Vol. 33, No. 2, P. 263-269, June 1998.
- Gershenfeld, Neil, “When Things Start to Think,” Henry Holt & Co., 1999.
- Gevarter, William, “Intelligent Machines,” Prentice Hall Publ., 1985.
- Giarratano, Joseph, and Riley, Gary, “Expert Systems: Principles and Programming,” PWS Publ., 1994.
- Gibilisco, Stan, ed., “The McGraw-Hill Encyclopedia of Robotics & Artificial Intelligence,” McGraw-Hill, 1994.
- Giszter, Simon, et. al., “Neurobiological and Neurorobotic Approaches to Control Architectures for a Humanoid Motor System,” Robotics and Autonomous Systems 37 (2001) 219-235.
- Glassie, John, “Flesh, Robots, and God,” Salon.com, 25 February 2002.
- Goldberg, David, “Genetic Algorithms,” Addison-Wesley Publ., 1989.
- Golden, Frederic, “A Robot Out of Cyberspace,” Time, Vol. 156, No. 11, P. 47, 11 Sep. 2000.
- Golubitsky, Martin, et. al., “A Modular Network for Legged Locomotion,” Physica D 115 (19989) 546-72.
- Gonzalez DeSantos, P., and Jimenez, M.A., “Path Tracking with Quadruped Walking Machines Using Discontinuous Gaits,” Computers Elect. Engng, Vol. 21, No. 6, P.383-396, 1995.
- Gould, James, and Gould, Carol, “The Animal Mind,” Scientific American Books, 1994.
- Gove, Alex, “The Bloodiest Edge: Surgical Robots Take Up Residence in the Operating Room,” May 1998.
- Graham-Rowe, Duncan, and Crystall, Ben, “Jobs for the Bots,” New Scientist, 10 Feb. 2001.

- ☐ Gregg, Lee, ed., “Knowledge and Cognition,” John Wiley & Sons, 1974.
- ☐ Gregory, Richard, ed., The Oxford Companion to the Mind,” Oxford University Press, 1987.
- ☐ Griffen, Donald, “Animal Minds,” University of Chicago press, 1992.
- ☐ Grossberg, Stephen, ed., “Neural Networks and Natural Intelligence,” MIT Press, 1988.
- ☐ Guttenplan, Samuel, ed., “A Companion to the Philosophy of the Mind,” Blackwell Publ., 1994.
- ☐ Hampden-Turner, Charles, “Maps of the Mind,” Macmillan, 1981.
- ☐ Hara, Yoshiko, “Soccer-Playing Bots Advance Researcher’s Goals,” Electronic Engineering Times, P.18, 17 June 2002.
- ☐ Hara, Yoshiko, “Fujitsu Offers Kit for Making Humanoid Robot,” Electronic Engineering Times, P.22, 17 Sept. 2001.
- ☐ Hara, Yoshiko, New Industry Awaits Human-Friendly Bipeds – Personal Robots Get Ready to Walk on the Human Side,” Electronic Engineering Times, P.A157, 16 Sep. 2002.
- ☐ Hara, Yoshiko, “Pino Walks, the Tiny Robot with Big Aspirations,” Electronic Engineering Times, P.26, 27 May 2002.
- ☐ Harbron, Patrick, “The Future of Humanoid Robots,” Discover, Vol. 21, no. 3, P.84, March 2000.
- ☐ Hawaleshka, Danylo, “Robot Renaissance,” Macleans, Vol. 113, No. 34, P.20, 21 Aug. 2000.
- ☐ Hayden, Thomas, and Hadfield, Peter, “The Age of Robots,” U.S. News and World Report, Vol. 130, No. 16, P.45, 23 April 2001.
- ☐ Hayes-Roth, Frederick, et. al., eds., “Building Expert Systems,” Addison Wesley Publ., 1983.
- ☐ Hecht-Nielsen, Robert, “Neurocomputing,” Addison-Wesley Publ., 1990.
- ☐ Hedman, K., et. al., “Sensing and Direction in Locomotion Learning with a Random Morphology Robot,” Proceedings of the Genetic and Evolutionary Computation Conference, GECCO 2002 (pp.1297). New York, 9-13 July 2002. Morgan Kaufmann.
- ☐ Herbert, Nick, “Elemental Mind: Human Consciousness and the New Physics,” Dutton, 1993.
- ☐ “High-Tech Love Story: Robots,” Nightline Transcript, 19 Aug. 2002.
- ☐ Hirai, Kazua, “The Honda Humanoid Robot: Development and Future Perspective,” The Industrial Robot, Vol. 26, No. 4, P. 260-266, 1999.
- ☐ Holland, John, “Adaptation in Natural and Artificial Systems,” MIT Press, 1993.
- ☐ Horn, Berthold, “Robot Vision,” MIT Press, 1986.
- ☐ “Honda Develops New Humanoid Robot,” Xinhua General News Service, 5 Dec. 2002.
- ☐ “Honda Develops New Robot that Can Interpret Postures of Humans,” Deutsche Presse-Agentur, 5 Dec. 2002.
- ☐ “Honda Improves Robot Asimo’s Communication Ability,” Jiji Press Ticker Service, 5 Dec. 2002.
- ☐ “Honda Releases More Intelligent Asimo Humanoid Robot,” Japan Economic Newswire, 11 Dec. 2002.
- ☐ “Honda Robot is a Wonder,” Western Morning News (U.K.), P.6, 7 Feb. 2003.
- ☐ “Honda to Launch Improved Version of Asimo Humanoid Robot from Next Jan.,” AFX Asia, 5 Dec. 2002.

- “Honda’s Humanoid Robot Asimo Starts Educational Tour in U.S.,” Japan Economic Newswire, 28 Jan 2003.
- Hubel, David, “Eye, Brain, and Vision,” Scientific American Books, 1988.
- “Humanlike Robots,” CBS Sunday Morning Transcript, 12 May 2002.
- “Humanoid Moves with Uncanny Grace,” The Nikkei Weekly, 3 Feb. 2003.
- “Humanoid Robot Really Digs the Job,” The Nikkei Weekly, 6 Jan. 2003.
- “Humanoid Robots Taking Big Strides in Evolution,” The Nikkei Weekly, 24 Dec. 2002.
- “Humanoids Striding into Daily Life in Japan,” The Industrial Robot, Vol. 28, No. 3, P.186, 2001.
- Ibidapo-Obe, O., and Alonge, A.B., “On Active Controls for a Biped Mechanism,” Applied Mathematics and Computation 69:159-183 (1995).
- Inaba, Masayuki, et. al., “Vision-Based Adaptive and Interactive Behaviors in Mechanical Animals Using the Remote-Brained Approach,” Robotics and Autonomous Systems 17 (1996) 35-52.
- Inaba, Masayuki, et. al., “Design and Implementation of a 35 D.O.G. Full-Body Humanoid That Can Sit, Stand Up and Grasp an Object,” Advanced Robotics, Vol. 12, No. 1, P.1-14, 1998.
- “Isamu, the First Humanoid Robot, Runs Under Linux Wireless Internet,” Control Engineering Europe, P.10, Nov. 2001.
- Ishiguro, Hiroshi, “Toward Interactive Humanoid Robots,” ACM, AAMAS 02 Bologna, Italy, 2002.
- Ishiguro, Hiroshi, et. al., “Robovie: An Interactive Humanoid Robot,” The Industrial Robot, Vol. 28, No. 6, P. 498, 2001.
- Itoko, Toshiyuki, and Kobayashi, Masami, “Teleoperation Master System for a Humanoid Robot with Kinesthetic Sensation,” Advanced Robotics, Vol.15, No. 3, P.313-316, 2001.
- “Japanese Humanoid Robot Can Operate Power Excavator in Rain,” Asia Pulse, 20 Dec. 2002.
- “Japan’s Kawada Develops Life-Sized Humanoid Robot with 6-Kg Load,” Asia Pulse, 10 Dec. 2002.
- Jaynes, Julian, “The Origins of Consciousness in the Breakdown of the Bicameral Mind,” Houghton Mifflin Co., 1990.
- Jenkins, Odest, and Mataric, Maja, “Deriving Action and Behavior Primitives from Human Motion Data,” Proceedings of 2002 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS-2002), P. 2551-2556, Lausanne, Switzerland, 30 Sep.- 4 Oct. 2002.
- Jimenez, M.A., and de Santos, P. Gonzales, “Attitude and Position Control for Realistic Legged Vehicles,” Robotics and Autonomous Systems 18 (1996) 345-354.
- Johnstone, Bob, “Japan’s Friendly Robots,” Technology Review, Vol. 102, No. 3, P.64-69, May/June 1999.
- “Joint Robotics Master Plan,” Department of Defense, 2002.
- Jones, Joseph, and Flynn, Anita, “Mobile Robots,” A.K. Peters Ltd, 1993.
- Kakiuchi, Youhei, et. al., “Extending Humanoid Mobility with a Skating Tool Based on an On-Line Motion Adjusting System,” Advanced Robotics, Vol. 13, No. 3, P.347-348, 1999.

☐ Kawamura, Kazuhiko, et. al., “Development of a Cognitive Model of Humans in a Multi-Agent Framework for Human-Robot Interaction,” ACM, AAMAS02, 15-19 July 2002.

☐ Kiesler, Sara, “Mental Model of Robotic Assistants,” ACM, CHI 2002, 20-25 April 2002.

☐ Khatib, Oussama, et. al., “Robotics and Interactive Simulation,” Communications of the ACM, vol. 45, No. 3, March 02.

☐ Kim, Munsang, et. al., “Task Planning for Humanoid Robots Using Look-Up Table,” Robotics and Autonomous Systems 40 (2002) 205-212.

☐ Kirsner, Scott, “Making Robots, with Dreams of Henry Ford,” NY Times, 26 Dec. 2002.

☐ “Korea Unveils Its First Humanoid Robot,” Computergram International, 9 Aug. 99.

☐ Kitano, Hiroaki, et. al., “Designing a Humanoid Head for RoboCup Challenge,” ACM, Agents 2000 Barcelona, Spain, 2000.

☐ Kotosaka, Shin’ya, et. al., “Humanoid Robot for Brain Research,” Advanced Robotics, Vol. 14, No. 5, P 419-421, 2000.

☐ Koza, John, “Genetic Programming,” MIT Press, 1992.

☐ Krane, Jim, “Will Robots Demand Human Rights?” Associated Press, 8 July 2001.

☐ Laddaga, Robert, Swinson, Mark, and Robertson, Paul, “Seeing Clearly and Moving Forward,” IEEE Intelligent Systems, Nov/Dec. 00.

☐ Loh, Deborah, “Asimo the Humanoid Enthralls, Inspires Visitors,” New Straits Times – Management Times (Malaysia), 11 Jan. 2003.

☐ Lorek, Laura, “March of the A.I. Robots,” Interactive Week, 30 April 2001.

☐ Lowe, Sue, “Now the Clucky Get Clackity,” Sydney Morning Herald, P.2, 23 Dec. 2002.

☐ Mahoney, Diana, “From Human to Humanoid,” Computer Graphics World, P.20, April 2001.

☐ “Man or Machine,” Electronic Times, 5 March, 01.

☐ Maney, Kevin, “The Latest Roving Reporter on Battlefields Could be a Robot,” USA Today, P.3B, 20 March 2002.

☐ Manna, Zohar, “Mathematical Theory of Computation,” McGraw-Hill, 1974.

☐ Martinez, Elisa, and Torras, Carme, “Qualitative Vision for the Guidance of Legged Robots in Unstructured Environments,” Pattern Recognition 43 (2001) 1585-1599.

☐ Martins-Filho, L.S., and Prajoux, R., “Locomotion Control of a Four-Legged Robot Embedding Real-Time Reasoning in the Force Distribution,” Robotics and Autonomous Systems 32 (2000) 219-235.

☐ Mataric, Maja, et. al., “Movement Control Methods for Complex, Dynamically Simulated Agents: Adonis Dances the Macarena,” CAN, Autonomous Agents 98, Minneapolis, MN, 1998.

☐ McMahon, Thomas, and Bonner, John, “On Size and Life,” Scientific American Books, 1983.

☐ Medsker, Larry, “Hybrid Intelligent Systems,” Kluwer Academic Publishers, 1998.

☐ Nakamura, Yoshiko, et. al., “Humanoid Robot Simulator for the METI HRP Project,” Robotics and Autonomous Systems 37 (2001) 101-114.

☐ Mendola, Joseph, “Human Thought,” Kluwer Academic Publishers, 1997.

☐ Messina, E.R. and Meystel, A.M., eds., “Measuring the Performance and Intelligence of Systems: Proceedings of the 2001 PerMIS Workshop, NIST, DARPA, NASA, IEEE, 4 Sep. 2001.

☐ Messina, E.R. and Meystel, A.M., eds., “Measuring the Performance and Intelligence of Systems: Proceedings of the 2002 PerMIS Workshop, NIST, DARPA, NASA, IEEE, 13-15 Aug. 2002.
☐ Meystel, Alexander, and Albus, James, “Intelligent Systems: Architecture, Design, and Control,” John Wiley & Sons, 2002.
☐ Meystel, Alexander, and Messina, Elena, “The Challenge of Intelligent Systems,” Proceedings of the IEEE Intelligent Control Symposium, 17-19 July 2000.
☐ Meystel, A., ed., “Proceedings of the 1997 International Conference on Intelligent Systems and Semiotics,” NIST, IEEE, NSF, ARO, 1997.
☐ “Military Robots Well Trained for War,” Associated Press, 13 Jan. 2003.
☐ Minsky, Marvin, and Papert, Seymour, “Perceptrons,” MIT Press, 1969.
☐ Minsky, Marvin, “The Society of Mind,” Simon & Schuster, 1986.
☐ Mithen, Stevem, “The Prehistory of the Mind,” Thames and Hudson, 1996.
☐ Miyakawa, Mikiko, “Robots May Storm World – But First, Soccer,” The Daily Yomiuri (Tokyo), P.11, 1 Jan. 2003.
☐ “Mobile Robotics: The Next Revolution,” ActivMedia Research, 2001.
☐ Moravec, Hans, “Robot: Mere Machines to Transcendent Mind,” Oxford University Press, 1999.
☐ Moravec, Hans, “Mind Children: the Future of Robot and Human Intelligence,” Harvard University Press, 1988.
☐ Mulhauser, Gary, “Mind Out of Matter,” Kluwer Academic Publishers, 1998.
☐ Murphy, Robin, “Introduction to AI Robotics,” MIT Press, 2000.
☐ Natale, Lorenzo, et. al., “Development of Auditory-Evoked Reflexes; Visuo-Acoustic Cues Integration in a Binocular Head,” Robotics and Autonomous Systems 39 (2002) 87-106.
☐ Negoita, Constantin, “Expert Systems and Fuzzy Systems,” Benjamin/Cummings Publ., 1985.
☐ “New Military Technology Robots Being Tested To Do Some Of The Dangerous Duties For Soldiers,” ABC Good Morning America Transcript, 4 Dec. 2002.
☐ Nicolescu, Monica, and Mataric, Maja, “A Hierarchical Architecture for Behavior-Based Robots,” Proceedings of the First International Joint Conference on Autonomous Agents and Multi-Agent Systems, Bolgna, Italy, July 15-19, 2002.
☐ Nicolescu, Monica, and Mataric, Maja, “Learning and Interacting in Human-Robot Domains,” Special Issue of IEEE Transactions on Systems, Man, and Cybernetics, Part A: Systems and Humans, Vol. 31, No. 5, P. 419-430, Sep. 2001.
☐ Nilsson, Nils, “Principles of Artificial Intelligence,” Tioga Publ., 1980.
☐ Ngui, Clarence, “Asimo Talks, Walks and Dances with Ease,” New Straits Times Press (Malaysia), 1 Sep. 2002.
☐ Nolfi, Setfano, and Floreano, Dario, “Evolutionary Robotics,” MIT Press, 2000.
☐ “Open Architecture Control for the Robotics Industry,” Proceedings, NIST & Robotics Industry Association, 9-10 Feb. 2000.
☐ Nordin, Peter, and Wolff, Krister, “Evolution of Efficient Gait with Humanoids Using Visual Feedback,” Institute of Physical Resource Theory, 2001.
☐ Ornstein, Robert, “The Evolution of Consciousness,” Prentice Hall Press, 1991.
☐ O’Shea, Tim, and Eisenstadt, Marc, “Artificial Intelligence: Tools, Techniques, and Applications,” Harper & Row Publ., 1984.

- Overby, Stephanie, “Bringing Up Robo-Baby,” CIO, P.52, 15 Sep. 2001.
- “Not Clever Enough: Will Intelligent Humanoid Robots Ever Exist?” Economist, Vol. 339, No. 7966, P.81, 18 May 1996.
- Parker, Gary, “Co-evolving Model Parameters for Anytime Learning in Evolutionary Robotics,” Robotics and Autonomous Systems 33 (2000) 13-30.
- Penrose, Roger, “The Emperor’s New Mind: Concerning Computers, Minds, and the Laws of Physics,” Oxford University Press, 1989.
- Penrose, Roger, “Shadows of the Mind: A Search for the Missing Science of Consciousness,” Oxford University Press, 1994.
- Penrose, Roger, “The Large, the Small, and the Human Mind,” Cambridge University Press, 1997.
- “Perfect Child: Walks, Talks, Does What It Is Told,” The Advertiser, P. 1, 13 Dec. 2002.
- Pfeiffer, Friedrich, et. al., “Six-legged Technical Walking Considering Biological Principles,” Robotics and Autonomous Systems 14 (1995) 223-232.
- Pfeiffer, Rolf, and Schier, Christian, “Understanding Intelligence,” MIT Press, 2000.
- Pinker, Steven, “How the Mind Works,” Norton, 1997.
- Pomplun, M. & Mataric, M.J., “Evaluation Metrics and Results of Human Arm Movement Imitation,” Proceedings of the First IEEE-RAS International Conference on Humanoid Robots (Humanoids-2000), MIT, Cambridge, MA.
- Port, Otis, “Pele, Hamm, and Now…C3PO?” Business Week, P.85, 13 May 2002.
- Porter, Bruce, “Honda’s Latest Asimo Humanoid Features Intelligence Technology,” Japan Corporate News Network, 6 Dec. 2002.
- Posner, Michael, and Raichle, Marcus, “Images of Mind,” Scientific American Books, 1994.
- Pratihar, Dilip, et. al., “Optimal Path gait Generations Simultaneously of a Six-Legged Robot Using a GA-Fuzzy Approach,” Robotics and Autonomous Systems 41 (2002) 1-20.
- “Proceedings of the 1998 IEEE International Symposium on Intelligent Control Held Jointly with the IEEE International Symposium on Computational Intelligence in Robotics and Automation and the Intelligent Systems and Semiotics Conference,” IEEE, NIST, 14-17 Sep. 1998.
- “Putting a Robot to Work (A Humanoid Controls the Arm of an Earth Mover),” Newsday, P.A34, 20 Dec. 2002.
- Raibert, Marc, and Hodgins, Jessica, “Animation of Dynamic Legged Motion,” Computer Graphics, Vol. 25, No. 4, P. 349-358, July 1991.
- Raman, Prasanna, :Humanoid Robots,” New Straits Times (Malaysia), P.2, 10 Feb. 2003.
- “Readings from Scientific American: Animal Engineering,” W.H. Freeman & Co., 1974.
- “Readings from Scientific American: The Nature and Nurture of Behavior,” W.H. Freeman & Co., 1973.
- “Readings from Scientific American: The Mind’s Eye,” W.H. Freeman & Co., 1986.
- Reich, Helmut, “COG and God: A Response to Anne Foerst,” Zygon, Vol. 33, No. 2, P.255-262, June 1998.
- Reif, John, and Wang, Hongyan, “Social Potential Fields, A Distributed Behavioral Control for Autonomous Robots,” Robotics and Autonomous Systems 27 (1999) 171-194.
- Restak, Richard, “The Modular Brain,” Charles Scribner’s Sons, 1994.

- ☐ Restak, Richard, “The Brain,” Bantam Books, 1984.
- ☐ Restak, Richard, “The Mind,” Bantam, 1988.
- ☐ Rich, Elaine, “Artificial Intelligence,” McGraw-Hill Book Co., 1983.
- ☐ “Robotics: An Emerging Technology in Portugal [RoboCup],” Internet Wire, 31 Oct. 2002.
- ☐ Rock, Irvin, “Perception,” Scientific American Books, 1984.
- ☐ Roker, Al, “Corey Greenberg of Beststuff.Com Shows the New Robot from Honda, Asimo,” Transcript, NBS Today, 27 Jan. 2003.
- ☐ Rosch, Winn, “Networks Key to Waging Robot Wars,” The Plain Dealer, 20 June 2002.
- ☐ Rosenfeld, Israel, “The Invention of Memory: A New View of the Brain,” Basic Books, 1988.
- ☐ “Send in the Bots: Taking Dangerous Positions,” GPS World, Vol. 13, No. 8, P.10, Aug. 2002.
- ☐ Ross, Rachel, “Home Robot Can Check Up On Kids,” The Guelph Mecury, P.A11, 30 Oct. 2002.
- ☐ Ross, Rachel, “Your Wish Is Robot’s Command: For No More Than $3,100 You Buy Lot’s of Brainpower,” Windsor Star, P.B9, 1 Nov. 2002.
- ☐ Ross, Rachel, “Ontario Firm Develops an Affordable Security Robot: The 60-cm Tall Humanoid Roams Around the House to Make Sure Everything is Safe,” Edmonton Journal, P.J4, 2 Nov. 2002.
- ☐ Schaal, Stefan, “Is Imitation Learning the Route to Humanoid Robots?” Trends in Cognitive Science, Vol. 3, No. 6, June 1999, P.233-242.
- ☐ Schank, Roger, and Colby, Kenneth, “Computer Models of Thought and Language,” W.H. Freeman & Co., 1973.
- ☐ Schulte, Bret, “Asimo: Honda’s New Compact Comes in Peace,” Washington Post, 3 Aug. 02, P.C01.
- ☐ Scott, Alwyn, “Stairway to the Mind,” Copernicus, 1995.
- ☐ “Sentience in Robots: Applications and Challenges,” IEEE Intelligent Systems, Sept./Oct. 2001, P.66-69.
- ☐ Sforza, Daniel, “A Robot’s Baby Steps; Honda Touting Humanoid as Helpmate of the Future,” The Record (Bergen County, NJ), P.B01, 29 Jan. 2003.
- ☐ Shachtman, Noah, “A War of Robots: All Chattering on the Western Front,” NY Times, P.G5, 11 July 2002.
- ☐ Shank, Roger, “The Cognitive Computer,” Addison-Wesley, Publ., 1984.
- ☐ Shaw, Dave, “Boston Dynamics and Sony Present Running AIBO in Joint Presentation at Robodex 2002, Press Release, Boston Dynamics, 5 April 2002.
- ☐ Sheridan, Thomas, and Ferrell, William, “Man-Machine Systems,” MIT Press, 1981.
- ☐ Shibata, T., and Schaal, S., “Biomimetic Gaze Stabilization Based on Feedback-Error-Learning with Nonparametric Regression Networks,” Neural Networks 14 (2001) 201-216.
- ☐ Simon, Herbert, “The Sciences of the Artificial,” MIT Press, 1999.
- ☐ Singh, Surya, and Thayer, Scott, “ARMS: Autonomous Robots for Military Systems,” CMU-RI-TR-01-16, The Robotics Institute, Carnegie Mellon University, 2001.
- ☐ Slagle, James, “Artificial Intelligence: the Heuristic Programming Approach,” McGraw-Hill Book Co., 1971.

- Sowa, J.F., “Conceptual Structures: Information Processing in Mind and Machine,” Addison-Wesley Publ., 1984.
- “Space ‘Bot,” Technology Review, P. 26, Nov./Dec. 1999.
- Squeo, Anne, “Meet the Newest Recruits: Robots,” Wall Street Journal, 13 Dec. 2001, P.B1.
- Stoica, Adrian, “Robot Fostering Techniques for Sensory-Motor Development of Humanoid Robots,” Robotics and Autonomous Systems 37 (2001) 127-143.
- Sukhatme, Gaurav, and Mataric, Maja, “Robots: Intelligence, Versatility, Adaptivity,” Communications of the ACM, Vol. 45, No. 3, P.30-32, March 2002.
- Swinson, Mark, “Humanoids,” private White Paper, 2002.
- Swinson, Mark, “Humanoid Robotics,” private White Paper, 12 Feb. 2003.
- Swinson, Mark, “Humanoid Robots,” private White Paper, 2001.
- Takeda, Kenro, et. al., “ACORBA-Based Approach for Humanoid Robot Control,” The Industrial Robot, Vol. 28, No. 3, P.242, 2001.
- Tachi, Susumu, “Telexistance and R-Cubed,” The Industrial Robot, Vol. 28, No. 6, P.498, 2001.
- Tajima, Ryosuke, et. al., “Development of Soft and Distributed Tactical Sensors and the Application to a Humanoid Robot,” Advanced Robotics, Vol. 6, No. 4, P.381-397, 2002.
- Takanishi, Atsuo, et. al., “Physical Interaction Between a Human and Humanoid Through hand Contact,” Advanced Robotics, Vol. 13, No. 3, P.303-305, 1999.
- “Technology Development for Army Unmanned Ground Vehicles,” National Research Council, National Academies Press, 2002.
- Trefil, James, “Are We Unique?” John Wiley & Sons, 1997.
- Turchin, Valentine, “A Cybernetic Approach to Human Evolution,” Columbia University Press, 1977.
- Tye, Michael, “Ten Problems of Consciousness: a Representational Theory of the Phenomenal Mind,” MIT Press, 1995.
- Ude, Ales, et. al., “Real-time Visual System for Interaction with a Humanoid Robot,” Robotics and Autonomous Systems 37 (2001) 115-125.
- Veloso, Manuela, “Entertainment Robotics,” Communications of the ACM, Vol. 45, No. 3, P.59-63, March 2002.
- Wade, Nicholas, ed., “The Science Times Book of the Brain,” The Lyons Press, 1998.
- Wang, Paul, ed., “Computing With Words,” John Wiley & Sons, 2001.
- Waterman, Talbot, “Animal Navigation,” Scientific American Books, 1989.
- Winston, Patrick, “Artificial Intelligence,” Addison-Wesley Publ., 1979.
- Winston, Patrick, ed., The Psychology of Computer Vision,” McGraw-Hill, 1975.
- Winston, Patrick, and Brown, Richard, eds., “Artificial Intelligence: An MIT Perspective,” Vols. 1 and 2, MIT Press, 1979.
- Wolff, Krister, and Nordin, Peter, “Evolution of Efficient Gait with an Autonomous Biped Robot Using Visual Feedback,” Proceedings of the 2nd IEEE-RAS International Conference on Humanoid Robots, Humanoids 2001 (pp. 99-106). Waseda University, Tokyo, Japan.
- Wolff, Krister, and Nordin, Peter, “Walking Humanoids for Robotics Research,” Proceedings of the Second International Workshop on Epigenetic Robotics: Modeling Cognitive Development in Robotic Systems, August 10-11, 2002, Edinburgh, Scotland.

- Woolridge, Dean, “Mechanical Man: The Physical Basis of Intelligent Life,” McGraw-Hill, 1968.
- Yamaguchi, Jin’ichi, et. al., “Development of a Bipedal Humanoid Robot Presupposing Various Whole Body Motions,” Advanced Robotics, Vol. 13, No. 3, P.297-299, 1999.
- Zachary, Katherine, “Learning from a Light, Lithe Biped,” Ward’s Auto World, P.61, Dec. 2001.
- Ziegler, Jens, et. al., “Constructing a Small Humanoid Walking Robot as a Platform for the Genetic Evolution of Walking,” 5th International Conference on Climbing and Walking Robots (CLAWAR) , 2002.
- Ziemke, Tom, “On the Epigenesis of Meaning in Robots and Organisms: Could a Humanoid Robot Develop a Human(oid) Umwelt?” Sign Systems Studies, 30.1, 2002.

“The only joy in the world is to begin,” … Cesare Pavese (1908-1950).