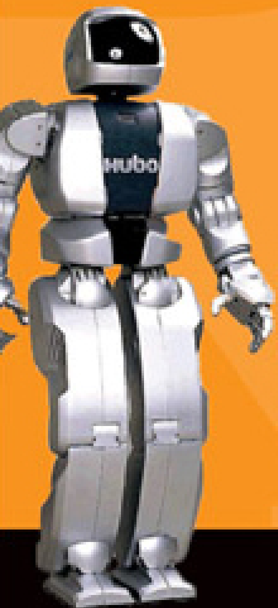

ROBOTICS

STATE OF THE ART AND FUTURE CHALLENGES

George Bekey • Robert Ambrose
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Imperial College Press

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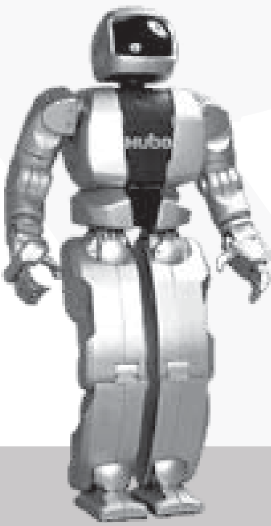

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State of the Art and Future Challenges

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CONTENTS

Chapter 1

INTRODUCTION

Robotics is an extremely dynamic field with thriving advancement in its technology. Along with other emerging technologies such as information technology, biotechnology, and nanotechnology, robotics will contribute to increasing opportunities for economic growth and greatly affect future generations with substantial social and economic impacts.

To assess the status of robotics R&D in the world and to compare the US efforts with those of other countries in terms of quality, scope, and funding, an international study on the status of robotics was conducted during 2004–2005 with grants from the National Science Foundation (NSF) and National Aeronautics and Space Administration (NASA) and some additional funding from the National Institute of Biomedical Imaging and Bioengineering (NIBIB). This book presents the state of the art and future challenges in the major areas of robotics, based on the international study report from the World Technology Evaluation Center (WTEC, http://wtec.org/robotics).

Under the leadership of Junku Yuh (who was at the time the Director of the Robotics and Computer Vision Program at NSF), David Lavery from NASA Headquarters and Y. T. Chien, the Director of Research for WTEC, a study team was formed. The study team consisted of two NASA scientists and four university faculty members, representing a broad cross-section of experience in the robotics field. In alphabetical order, the team members were:

- Robert Ambrose, NASA Johnson Space Center
- George Bekey, University of Southern California (Chair)
- Vijay Kumar, University of Pennsylvania
- Arthur Sanderson, Rensselaer Polytechnic Institute
- Brian Wilcox, NASA Jet Propulsion Laboratory
- Yuan Zheng, Ohio State University

To assess the status of robotics R&D in the United States and to provide a baseline for comparisons with efforts in other countries, a workshop was held at NSF on 21–22 July 2004. This invitational workshop was attended by some 100 researchers from universities, research laboratories, government, and industry, who presented "Status Reports" in a number of areas of robotics, including technology areas such as actuators and mechanisms, robot control, intelligence and learning, human–robot interaction, multirobot systems, and humanoid robots, and applications in such fields as entertainment, education, medicine and rehabilitation, military, space, and underwater. The materials presented at the workshop are available at http://wtec.org/robotics/us_workshop. Following the workshop, it was decided to narrow the scope of the international study into the following six areas: robotic vehicles; space robotics; humanoid robots; industrial, service and personal robots; robotics in biology and medicine; and networked robots.

In October 2004, the team traveled to Japan and South Korea, visiting 29 laboratories. In April 2005, an additional 21 laboratories were visited in France, Germany, Italy, Spain, Sweden, Switzerland, and the United Kingdom. In addition, a "virtual site visit" to Australia was conducted through e-mail. While there are significant works in robotics in other countries (such as Belgium, China, Russia, and others) the itinerary was constrained by time and budget. Based on extensive discussions among team members, consultation with sponsors, and e-mail discussions with colleagues throughout the world, visits were restricted to the specific countries listed above. The complete list of all sites visited is given in Table 1.1.

Most visits were completed in half a day. Even so, in order to visit 20 laboratories in Japan in 1 week, it was necessary to split the team into two subgroups. The number of sites visited in Europe was so large that the team was divided into three subgroups. Fortunately, these smaller groups were augmented by the following representatives from NASA, NSF, and WTEC who participated in the visits and assisted significantly in the gathering of information: David Lavery, NASA Headquarters; Minoo Dastoor; NASA Headquarters; Junku Yuh, NSF; Y. T. Chien, WTEC; Hassan Ali, WTEC; and Masanobu Miyahara, WTEC.

In order to focus the discussions in the various laboratories, the host engineers and scientists were provided with a set of questions prior to the visits. While the discussion did not necessarily follow the specific questions,

Table 1.1. Sites visited in Asia and Europe.

Site	Panelists	Date
Europe		
France		
Centre National d'Etudes Spatiales de Toulouse	Ambrose, Chien, Dastoor, Wilcox	25 April 2005
Cybernétix	Ali, Sanderson, Yuh, Zheng	27 April 2005
Institut Français de Recherché pour l'Exploitation de la Mer (IFREMER)	Ali, Sanderson, Yuh, Zheng	27 April 2005
Institut National de Recherche en Informatique et en Automatique (INRIA)	Ali, Sanderson, Yuh, Zheng	28 April 2005
Laboratoire d'Analyse et d'Architecture des Systèmes — Centre National de la Recherche Scientifique (LAAS/CNRS)	Ambrose, Chien, Dastoor, Lavery, Wilcox	26 April 2005
Germany		
Charite Hospital	Ambrose, Chien, Dastoor, Lavery, Wilcox	28 April 2005
DLR German Aerospace Center	Ambrose, Bekey, Chien, Kumar, Lavery, Wilcox	27 April 2005
Fraunhofer Institute — Production Systems and Design Technology (IPK)	Ambrose, Chien, Lavery, Wilcox	28 April 2005
Karlsruhe University	Bekey, Kumar	28 April 2005
Technical University Berlin	Ambrose, Chien, Dastoor, Lavery, Wilcox	28 April 2005
Technical University Munich	Ambrose, Bekey, Chien, Dastoor, Kumar, Lavery, Wilcox	27 April 2005
Italy		
Università di Genova	Ali, Yuh, Zheng	29 April 2005
Scuola Superiore Sant'Anna	Ali, Sanderson, Yuh, Zheng	29 April 2005
Spain		
Universitat de Girona	Sanderson, Yuh	22 April 2005
Sweden		
ABB Laboratory	Ambrose, Bekey, Chien, Kumar, Wilcox	29 April 2005
Kungl Teknisha Hogskolan (KTH)	Bekey, Kumar	28 April 2005
Switzerland		
École Polytechnique Fédérale de Lausanne (EPFL)	Bekey, Kumar	26 April 2005

Table 1.1. (*Continued*).

Site	Panelists	Date
Swiss Federal Institute of Technology (ETH)	Bekey, Kumar	25 April 2005
University of Zürich	Bekey, Kumar	25 April 2005
United Kingdom		
Heriot-Watt University	Ali, Sanderson, Yuh, Zheng	25 April 2005
Oxford University	Ali, Sanderson, Yuh, Zheng	26 April 2005
Asia		
Japan		
National Institute of Advanced Industrial Science and Technology (AIST)	Ambrose, Bekey, Lavery, Wilcox, Yuh, Zheng	6 Oct 2004
AIST — Intelligent Systems Research Institute	Ambrose, Chien, Wilcox	8 Oct 2004
ATR Computational Neuroscience Laboratories	Chien, Dastoor, Sanderson	5 Oct 2004
ATR Intelligent Robotics and Communication Laboratories	Chien, Dastoor, Sanderson	5 Oct 2004
FANUC	Chien, Kumar, Zheng	8 Oct 2004
Fujitsu Autonomous Systems Lab	Ambrose, Chien, Kumar, Lavery, Wilcox,Yuh	5 Oct 2004
Japan Agency for Marine Earth Science and Technology (JAMSTEC)	Chien, Kumar, Sanderson, Yuh, Zheng	4 Oct 2004
Keio University — Kawasaki Campus	Ambrose, Bekey, Kumar, Miyahara, Wilcox, Yuh, Zheng	5 Oct 2004
Keio University — Shonan Fujisawa Campus	Chien, Kumar, Miyahara, Yuh, Zheng	4 Oct 2004
Ministry of Economy, Trade, and Industry (METI)	Sanderson, Yuh	8 Oct 2004
Nagoya University	Chien, Dastoor, Sanderson	7 Oct 2004
NEC/Toshiba Space Systems Division	Ambrose, Bekey, Chien, Lavery, Wilcox	7 Oct 2004
Osaka University	Chien, Dastoor, Sanderson	6 Oct 2004
Ritsumeikan University	Chien, Dastoor, Sanderson	6 Oct 2004
Sony Corporate R&D Laboratory	Ambrose, Bekey, Kumar, Lavery, Wilcox, Zheng	5 Oct 2004
Tokyo Institute of Technology	Ambrose, Chien, Wilcox	4 Oct 2004
University of Tokyo — Department of Mechano Informatics	Sanderson, Yuh	8 Oct 2004
University of Tokyo — Underwater Technology Research Center	Ambrose, Lavery, Wilcox, Yuh	9 Oct 2004

Table 1.1. (*Continued*).

Site	Panelists	Date
Tsukuba University	Ambrose, Bekey, Lavery, Wilcox, Yuh	9 Oct 2004
Waseda University	Ambrose, Bekey, Kumar, Miyahara, Sanderson, Wilcox, Yuh, Zheng	7 Oct 2004
Korea		
Electronic and Telecommunications Research Institute (ETRI)	Ambrose, Bekey, Chien, Zheng	12 Oct 2004
Hanool Robotics	Ambrose, Bekey, Chien, Kumar, Sanderson, Weber, Wilcox, Yuh, Zheng	12 Oct 2004
Korea Advanced Institute of Science and Technology (KAIST)	Ambrose, Bekey, Chien, Wilcox, Yuh	12 Oct 2004
Korea Institute of Science and Technology (KIST)	Ambrose, Wilcox, Yuh, Zheng	12 Oct 2004
Korea Research Institute of Ships and Ocean Engineering (KRISO)/Korea Ocean Research & Development Institute (KORDI)	Sanderson, Wilcox, Yuh	12 Oct 2004
Pohang Science and Technical University (POSTECH)	Ambrose, Chien, Sanderson, Wilcox, Yuh, Zheng	13 Oct 2004
Samsung Mechatronics Center	Ambrose, Chien, Wilcox, Yuh, Zheng	12 Oct 2004
Seoul National University	Bekey, Chien, Sanderson, Weber	11 Oct 2004
Sungkyunkwan University	Bekey, Chien, Sanderson, Weber	11 Oct 2004

they provided a general framework for the discussions. The questions were the following:

1. How long has your laboratory been in existence?
2. What fraction of the work in this lab concerns robotics?
3. How is your work supported — Government, university, or industry funds?
4. Is the level of support adequate for the work you plan to do?
5. What interactions do you have with academia, government, and industry, and with the labs in other countries?
6. What are the other major research groups *in your country* that are working in your area of research?

7. What are the other major research groups *outside of your country* that are working in your area of research?
8. How do you assess robotics research in the United States as compared to your country? In your field of robotics, do you think your country is leading the United States?

In September 2005, the results of the study were presented to the nation at a press conference and workshop held at NSF. In January 2006, "virtual site visits" were conducted with two leading laboratories in Australia. The directors of these laboratories submitted replies to the questions from the team and provided pictures of the robots they developed. The final report was published by WTEC in February 2006 (http://wtec.org/robotics).

Based on the study, it was concluded that:

- Robotics is a very active field, worldwide.
- Japan, Korea, and the European Community invest significantly larger funds in robotics research and development for the private sector than the United States.
- There are numerous start-up companies in robotics, both in the United States and abroad. Venture capital appears to be available.
- The United States currently leads in such areas as robot navigation in outdoor environments, robot architectures (the integration of control, structure, and computation), and in applications to space, defense, underwater systems, and some aspects of service and personal robots.
- Japan and Korea lead in technology for robot mobility, humanoid robots, and some aspects of service and personal robots including entertainment.
- Europe leads in mobility for structured environments, including urban transportation. Europe also has significant programs in eldercare and home service robotics.
- Australia leads in commercial applications of field robotics, in such areas as cargo handling and mining, and in the theory and application of localization and navigation.
- In contrast with the United States, Korea and Japan have national strategic initiatives in robotics; the European community has EC-wide programs. In the United States, there is coordination only in military robotics. The US Department of Defense has a Joint Robotics Program (JRP) Master Plan. The United States lost its pre-eminence in industrial robotics at the end of the 1980s, so that nearly all robots for

welding, painting, and assembly are imported from Japan or Europe; it may lose its leading position in other aspects of robotics as well.

Some examples of funding disparities: In the United States, NSF funding for robotics is about $10 million per year. Annual funding for military robotics in the United States is estimated to be more than $200 million per year. In Japan, robotics useful in home and town was selected as one of the 62 Priority Technologies selected by Japanese Government's Council for Science and Technology Policy (CSTP) for Japan's Third S&T Basic Plan and its Priority Technologies, JFY2006-2010. In Korea, robotics has been selected as one of the 10 areas of technology to be "engines for economic growth"; the total funding for robotics is about $80 million per year. In Europe, a new program called "Advanced Robotics" has been funded at about $100 million for 3 years.

A summary of the areas of major strength in various aspects of robotics in the United States, Asia, and Europe is given in Table 1.2. The "INPUT" section refers to the kinds of resources and organizations that produce R&D, while "OUPUT" refers to the outcomes of research, into key robotic products or applications.

Table 1.2. Qualitative robotics comparison chart.

Area	Degree or Level of Activity			
	United States	Japan	Korea	Europe
Input				
Basic, university-based research (Individual, groups, centers)	*****	***	***	***
Applied, industry-based research (corporate, national labs)	**	*****	****	****
National or multinational research initiatives or programs	**	*****	*****	****
University–industry–government partnerships; entrepreneurship	**	*****	*****	****
Output				
Robotic vehicles: military and civilian	****	**	**	**
Space robotics	***	**	N/A	***
Humanoids	**	*****	****	**
Industrial robotics: manufacturing	**	*****	**	****
Service robotics: nonmanufacturing	***	***	****	***
Personal robotics: home	**	*****	****	**
Biological and biomedical applications	****	**	**	****

A number of trends in technology are expected to have a major impact on robotics in the near future. The DARPA Grand Challenge in the United States in 2005 and 2007 demonstrated the ability of autonomous vehicles to travel at average speeds in excess of 30 mph over unknown terrain, and in the presence of a number of hazards and obstacles. The winning vehicles integrated sensors (including GPS), complex and intelligent vision systems, and sophisticated navigation algorithms to accomplish the task. These and other aspects of the so-called "Intelligent Vehicle Technology" are expected to influence the development of autonomous robotic vehicles in the near future. Developments in nanotechnology may lead to *nanorobotic systems*, capable of self-assembly or perhaps manipulation of individual molecules for research in genetics and related areas. We have cited robotic surgery as a major current area of application. We expect that in the future, increasingly autonomous systems will be able to operate within the body to identify and perhaps remove tumors. New imaging techniques, like fMRI, combined with nanorobotics, may make possible dramatically new and different studies of brain function. Networks of sensors distributed throughout the environment may allow distributed robotic systems to interact and function as a collective system in the solution of environmental and other problems. This is just a sampling of the exciting potential of robotics. Clearly, this is the age of robotics and we expect it to have an increasingly important effect on our lives, both as individuals and as societies.

The remainder of this book is organized into six chapters concerned with specific major application areas. Each chapter:

- defines the area;
- indicates why it is important;
- describes the major technologies required;
- points out major applications with examples;
- outlines the major challenges, both present and future;
- summarizes major activities in the United States, Korea, Japan, and the European countries visited; and
- provides a qualitative comparison between R&D activities in these regions.

The specific topics are:

Chapter 1: Introduction
Chapter 2: Robotic vehicles
Chapter 3: Space robotics

Chapter 4: Humanoid robots
Chapter 5: Industrial, service, and personal robots
Chapter 6: Robotics in biology and medicine
Chapter 7: Networked robots

The Appendix contains short biographies of the members of the study team, who are also the authors of this volume.

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Chapter 2

ROBOTIC VEHICLES

2.1. Introduction

2.1.1. *What are robotic vehicles?*

The field of robotics encompasses a broad spectrum of technologies in which computational intelligence is embedded in physical machines, creating systems with capabilities far exceeding the core components alone. Such robotic systems are then able to carry out tasks that are unachievable by conventional machines, or even by humans working with conventional tools. The ability of a machine to move by itself, i.e., "autonomously," is one such capability that opens up an enormous range of applications that are uniquely suited to robotic systems. This chapter describes such unmanned and autonomous vehicles and summarizes their development and application within the international perspective of this study.

Robotic vehicles are machines that move "autonomously" on the ground, in the air, undersea, or in space. Such vehicles are "unmanned," in the sense that no humans are on board. In general, these vehicles move by themselves, under their own power, with sensors and computational resources onboard to guide their motion. However, such "unmanned" robotic vehicles usually integrate some form of human oversight or supervision of the motion and task execution. Such oversight may take different forms, depending on the environment and application. It is common to utilize so-called "supervisory control" for high-level observation and monitoring of vehicle motion. In other instances, an interface is provided for more continuous human input constituting a "remotely operated vehicle" (ROV). In this case, the ROV is often linked by cable or wireless communications in order to provide higher bandwidth communications of operator input. In the evolution of robotic vehicle technology that has been observed in this study, it is clear that a higher level of autonomy is an important trend of emerging technologies, and the ROV mode of operation is gradually being replaced by supervisory control of autonomous operations.

2.1.2. *Why are robotic vehicles important?*

First, robotic vehicles are capable of traveling where people cannot go, or where the hazards of human presence are great. To reach the surface of Mars, a spacecraft must travel more than 1 year, and on arrival the surface has no air, water, or resources to support human life. While human exploration of Mars may someday be possible, it is clear that robotic exploration is a fundamental step that provides enormous scientific and technological rewards enhancing our knowledge of other planets. The National Aeronautics and Space Administration (NASA) Mars rover shown in Fig. 2.1 is a robotic vehicle that has successfully achieved these goals, becoming a remote scientific laboratory for exploration of the Martian surface. The Mars rover is an example of a robotic vehicle under supervisory control from the earth, and capable of local autonomous operation for segments of motion and defined scientific tasks.

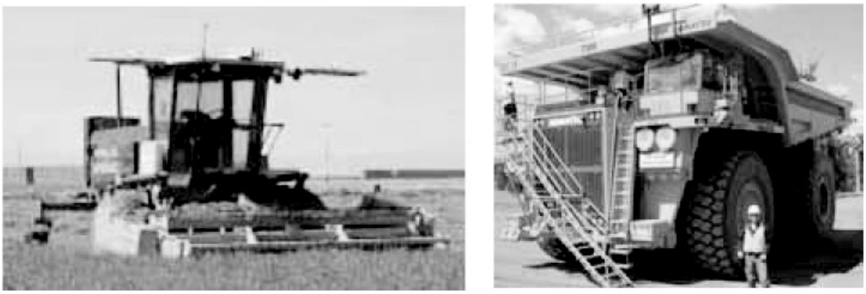
Another example of a hostile and hazardous environment where robotic vehicles are essential tools of work and exploration is the undersea world. Human divers may dive to a depth of 100 m or more, but pressure, light,

Fig. 2.1. NASA Mars rover (NASA Jet Propulsion Laboratory (JPL)).

Fig. 2.2. IFREMER ASTER autonomous underwater vehicle.

currents, and other factors limit such human exploration of the vast volume of the earth's oceans. Oceanographers have developed a wide variety of sophisticated technologies for sensing, mapping, and monitoring the oceans at many scales, from small biological organisms to major ocean circulation currents. Robotic vehicles, both autonomous and ROV types, are an increasingly important part of this repertoire, and provide information that is unavailable in other ways. Figure 2.2 shows an autonomous underwater vehicle (AUV) called ASTER under development at Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER), the French National Institute for Marine Science and Technology. ASTER will be used for coastal surveys up to 3000 m in depth and is capable of carrying a wide variety of instrumentation for physical, chemical, and biological sensing and monitoring. In research in the US, the evolution of remotely operated vehicles for deep ocean exploration enabled the discovery of the sunken Titanic and the ability to explore that notable shipwreck.

In addition to space and oceans, there are many applications where human presence is hazardous. Nuclear and biological contamination sites must often be explored and mapped to determine the types and extent of contamination, and provide the basis for remediation. Military operations incorporate many different autonomous and remotely operated technologies for air, sea, and ground vehicles. Increasingly, security and defense systems may use networks of advanced mobile sensors that observe and detect potential events that may pose threats to populations.



(a) (b)

Fig. 2.3. (a) Agricultural robotic vehicle (International Harvester, the United States). (b) Mining haul truck (ACFR, Australia).

In a second class of applications, robotic vehicles are used in routine tasks that occur over spaces and environments where machine mobility can effectively replace direct human presence. For example, large-scale agriculture requires machines to cultivate, seed, irrigate, and harvest very large areas of terrain. The ability to track an autonomous vehicle using global positioning systems (GPS), sensing the soil and plant conditions in the field, encourages the implementation of robotic vehicles for agricultural or "field" applications. Figure 2.3a shows an example of an agricultural robotic vehicle under development in the United States. Figure 2.3b shows a large autonomous mining haul truck developed in Australia.

Similar challenges occur in areas of environmental monitoring, where mobile vehicles may move through air, water, or ground to observe the presence of contaminants and track the patterns and sources of such pollutants. In large manufacturing facilities, mobility is essential to transport components and subassemblies during the manufacturing process and a variety of robotic guided vehicles are utilized in these domains.

A third class of applications of robotic vehicles occurs in the support of personal assistance, rehabilitation, and entertainment for humans. A robotic wheelchair may provide mobility for a human who would otherwise not be able to move about. The integration of sensors, computational intelligence, and improved power systems have made such personal robotic aids increasingly capable and practical for everyday use. An example of a wheelchair that utilizes emerging robotic technologies for guidance and balance is shown in Fig. 2.4. More details on medical robotics and robotic aids to the handicapped will be described in Chap. 6.

Fig. 2.4. IBOT advanced wheel chair (DEKA, the United States).

Other examples of such personal aids include vehicles that support elderly care through feeding, household tasks, and emergency notification. Many daily household tasks may benefit from enhanced mobile robotics, and there are rapid commercial developments of vacuum cleaners and lawn mowers that utilize advanced sensor and navigation systems. Also, advanced entertainment systems will incorporate robotic vehicles including locomotion of humanoids and biomimetic pets that entertain and provide interactive companions. The Japanese development of humanoids and robotic pets with sophisticated locomotion systems, as shown in Fig. 2.5, is a major topic of this international comparative study. While Sony no longer manufactures robots like the QRIO shown in Fig. 2.5(a), it is included here since it was one of the most advanced humanoid entertainment robots at the time of this study. More detailed examples of personal and entertainment robotic vehicles will be described in Chap. 5, and of humanoid robots in Chap. 4.

2.1.3. *How do robotic vehicles work? What are the key technologies for mobility?*

Robotic vehicles move on the ground, through the air, and on and under the water. To achieve these various modes of propulsion, a large number of different technological solutions have been proposed and investigated.

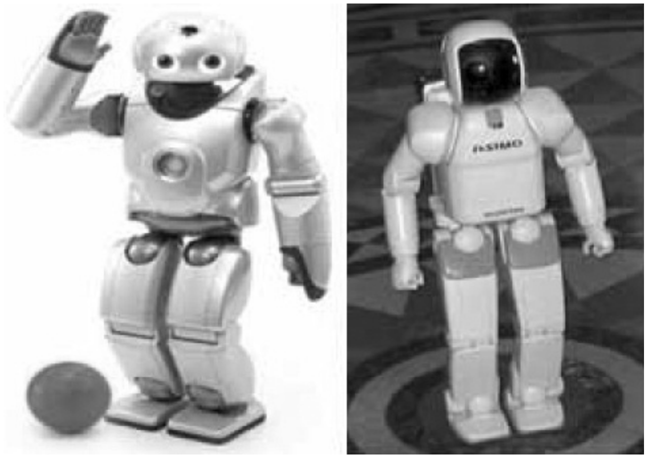


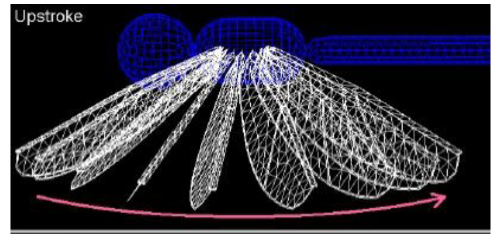
Fig. 2.5. Humanoid robots with locomotion (left: Sony, right: Honda).

As illustrated in Table 2.1, there are two major approaches to the evolution of these technologies in the robotics research field.

(a) "Wheels and props" strategy.
Engineering solutions are borrowed from the evolution of technologies that have been developed over many centuries for transportation. Robotic ground vehicles are developed with wheels and treads, much like automobiles. Robotic air vehicles are developed with propellers, or jet engines, and stationary wings (or rotating wings, such as helicopters). Robotic undersea vehicles utilize propellers and control surfaces.

(b) "Running and flapping" strategy.
In the evolution of robotics, there is a long tradition of utilizing biological systems as inspiration and models for new technological solutions. The Japanese research laboratories have been particularly interested and effective in these efforts toward "biomimetics." There has been a community of international researchers that has worked on the development of legged locomotion systems, including bipedal locomotion that resembles human walking and running. Similarly, there have been robotic snakes that slither, birds and insects that flap their wings, and fish and eels that swim using undulating motions. There has even been recent work on hybrid systems, such as "Whegs," combining attributes of wheels and legs.

Table 2.1. Types of robotic mobility systems.

	Engineering design	Biomimetic design
Air		
Ground		 
Sea		

Biomimetics research has two important broad goals. First, these efforts to replicate the motion of biological organisms will teach us about the natural world. Therefore, the engineering of an artificial swimming fish will help us to understand the physical process, the energetics, and the control systems used by these creatures. Second, these studies provide insight into practical systems that may have advantages over the engineering solutions mentioned earlier. For example, one may argue that legged locomotion is much better suited to rough terrain where foot placement may be used more efficiently than wheels. Similarly, there is evidence that the energy efficiency of some biological organisms including flying insects and fish exceeds that of engineering systems, and therefore important new developments could emerge. These goals may also intersect in applications such as personal robotics where robotic pets or entertainment devices may resemble biological creatures in both physical and behavioral manner.

2.2. Research Challenges

Historically, there have been examples of technologies that could be controlled through remote mechanical linkages (e.g., mechanically coupled manipulators for handling dangerous chemicals), and other technologies that provided preprogrammed motions (e.g., missiles and torpedoes). However, only with the development of microelectronics and embedded computation it has been possible to design systems that combine both mobility and autonomy. Four major research challenges have dominated these developments, and they continue to represent the key themes observed in this international study.

2.2.1. *Mechanisms and mobility*

As described above, both engineering and biomimetic approaches have been taken to design mobile robotic vehicles, and current research efforts continue to follow both of these strategies. Key research themes include the following:

Principles of motion. Basic studies of kinematics and dynamics of motion in all domains (ground, air, and water) continue to examine fundamental issues of devices that contact and interact with the forces around them. A primary example of this work is the study of bipedal locomotion and the distinction between “quasistatic” walking and “dynamic” walking. Algorithms used in recent full-humanoid prototypes exhibit very sophisticated motion and balance, but still do not achieve all of the characteristics of human dynamic balance. New theories and experiments continue to impact this research. Similarly, such studies have a direct effect on different walking patterns, such as trotting and running gaits, and how these may be executed on two-legged and multi-legged robotic vehicles.

Materials properties and design. Materials considerations are also of primary interest for new mechanisms, and uses of light and strong materials, with controllable compliance, are the current research topics.

2.2.2. *Power and propulsion*

The long-term autonomy of vehicles is directly impacted by the available power and the energy efficiency of motion. These considerations are of additional importance in remote domains, such as planetary and undersea deployments, where recovery or refueling is impractical. While battery technologies are of primary interest for all such vehicles, from vacuum cleaners to spacecraft, there are premiums obtained by efficient motion and even sharing of tasks among multiple vehicles. In addition, there are several strategies for energy storage (e.g., fuel cells, and microfuel cells), as well as strategies for energy harvesting in many forms (e.g., solar cells, ocean temperature gradients and currents, wind, and biological batteries), and energy management using sophisticated control techniques to improve energy budgets. Figure 2.6 shows a solar-powered autonomous underwater vehicle capable of recharging on the surface and diving for 6–8 h of continuous underwater operation.

Biomimetic approaches to create artificial muscles using specialized materials and methods of micro and nanofabrication are also a topic of current research.

2.2.3. *Computation and control*

The introduction of microcomputation has enabled the use of embedded computer systems that are small, light, and energy efficient. Such embedded computational systems have been instrumental in the development of robotic vehicles with sophisticated computer architectures that organize sensor-based feedback and control actions onboard. Much of the current research internationally is focused on advanced computer architectures and implementations that coordinate these tasks. There are two fundamental

Fig. 2.6. Solar-powered AUV (Autonomous Undersea Systems Institute (AUSI), FSL, Rensselaer Polytechnic Institute (RPI), the United States).

strategies that are often integrated into these systems — hierarchical and behavioral control structures.

Hierarchical (or deliberative) control structures. In a complex system, engineers are often led to define hierarchies representing different levels of functions of the system. From the engineering perspective, they hope to simplify design principles and criteria in a manner that will permit more consistent and verifiable designs. Such an engineering approach often supports systematic techniques for error detection, service, and support as well as formal approaches to analysis and optimization of the system. As suggested in Fig. 2.7, one such hierarchy might represent a strategic plan (e.g., "go to the stone") defining a high-level task. The strategic plan might then generate a navigation plan (e.g., "first, go to the corner, then turn left"), followed by a supervisory control (e.g., "pick a point 10 m away with no likely collisions"), and a first simple motion control (e.g., "move the wheel motors at one revolution per minute").

Behavioral control structures. The behavioral control architecture may be thought of as a biomimetic analog to the nervous system of animals. Biological creatures seem to incorporate many sensor-based feedback systems that evolve in a behavioral context. These systems seem to provide a stable and context-sensitive response to complex situations, without constructing an explicit and detailed internal representation of

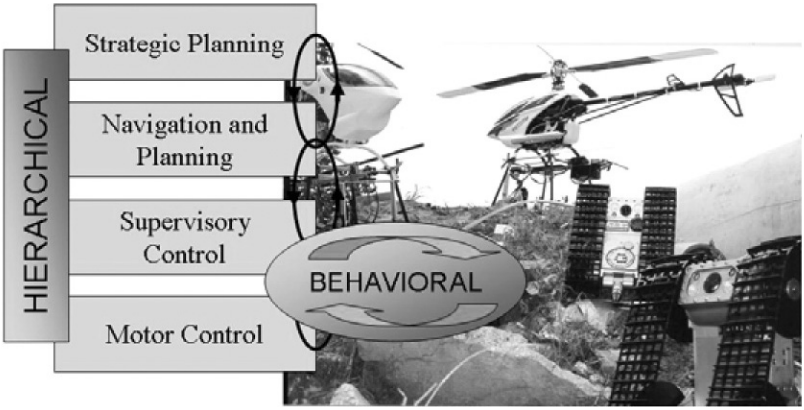


Fig. 2.7. Integration of hierarchical and behavior control architectures in a search-and-rescue domain (Center for Robot-Assisted Search and Rescue (CRASAR), University of South Florida (USF), the United States).

the environment at all levels. Such behavioral feedback loops may also integrate learning procedures and mechanisms that permit the system to adapt to changing conditions and to preferentially react to environmental conditions that are significant to the task or behavior at hand. For example, a robotic vehicle might approach a door using an algorithm to maximize the observed opening area. This algorithm moves the robot closer to the door, as well as perpendicular to the door opening. The vehicle could move through the door using this implicit sensory feedback without computing an explicit representation of geometries and distances.

Both hierarchical and behavioral architectures are active areas of research and many practical vehicles integrate some features of both approaches. Trade-offs occur where hierarchical architectures may be more provably robust since formal analytical methods may be applied, while behavioral systems may be more efficient to implement and computationally faster, and may support adaptive methods more naturally. On the implementation side, all computational and control architectures for sophisticated vehicles require careful and disciplined software engineering to implement and maintain. Integration of such embedded software systems is a major key to the success and longevity of vehicle prototypes and products. In addition, advances in communication technologies provide information links for command and control and have a strong role in multivehicle and distributed architectures.

2.2.4. *Sensors and navigation*

Recent advances in successful robotic vehicle technologies for ground, air, and water have been tied to the development of improved sensors and sensor networks. Such sensors serve two major purposes on robotic vehicles:

(a) Sensors are used to monitor the environment and to control interactive tasks. For example, an underwater vehicle might detect the presence of biological contaminants in the water, map the distribution, and support analyses that would identify the source. One area of technology advancement is the development of microelectronics and micro-electromechanical systems technologies for specific sensors in air and water. For example, detection of nitrogen compounds in air, and detection of dissolved oxygen in water, support valuable environmental applications.

(b) Sensors are essential for the navigation of a robotic vehicle. Each vehicle must sense its surroundings and utilize the relative locations of events and landmarks in order to answer questions: Where am I? Do I have a map of this area? How do I move in order to accomplish my task? New sensor technologies include laser-based techniques, such as Light Detection and Ranging (LIDAR), which generate depth maps of solid objects, permitting the robot to detect both obstacles and landmarks and integrate them into their navigation strategies.

Navigation and localization have been very important topics in the research community over the past 10 years. The problem of simultaneous localization and mapping (SLAM), also called cooperative mapping and localization (CML), is a research field with significant outcomes that have directly influenced the reliability and practicality of robotic vehicle deployments in real applications. Important results, particularly in the United States, Europe, and Australia, have derived algorithms that enable a vehicle to efficiently learn a "map" of its environment, then utilize that map as the basis for planning navigation leading to the accomplishment of goals. Such algorithms are now commonly implemented in some form on most prototype and production vehicles, ranging from vacuum cleaners, to underwater vehicles, to planetary explorers and agricultural devices.

The principle of the SLAM algorithms is a sophisticated and elegant mathematical formulation that represents the detected features of the environment by probability distributions. By moving a vehicle, or using several vehicles, to observe the same features, the consistency of these probability distributions is resolved into a small number of feasible maps that describe the world being explored. Currently these methods are used to efficiently and reliably resolve two-dimensional domains of modest size, such as a building layout or a local outdoor setting. Research is still being pursued to enlarge the size of these domains, improve the consistency required to resolve rarer events that occur at large scales, and extension of the basic approach to enable computational efficiency of these methods in three dimensions.

SLAM algorithms provide an example of the importance of basic analytical research that stimulates advances in practical applications. As an example, in military applications the integration of ground, air, and water sensors and vehicles is essential to fully interpret the activities in a theater of operations. As suggested in Fig. 2.8, the complexity of dynamic coordination of large-scale operations using sensor feedback and real-time assessment is extremely complex. Algorithms such as SLAM

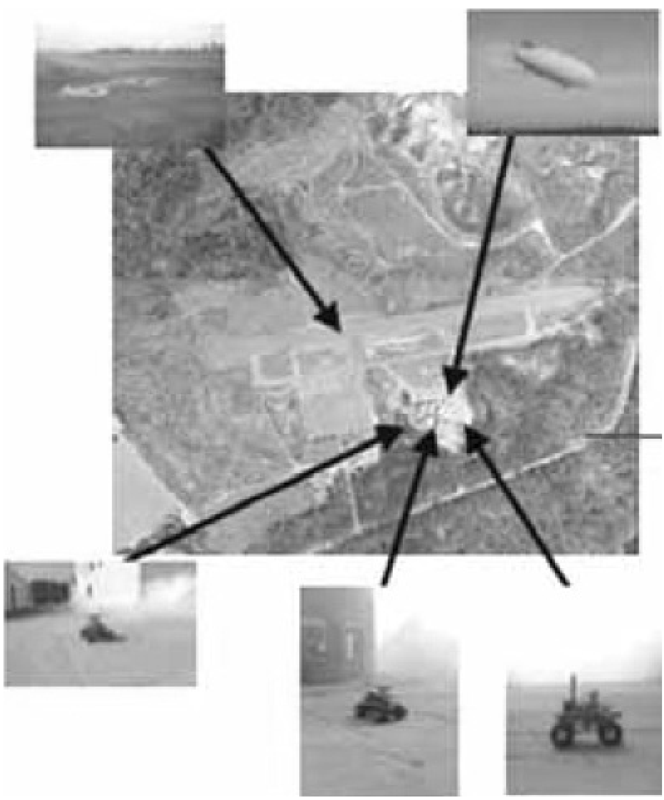


Fig. 2.8. Integration of sensor and navigation in a military application (U. Penn, the United States).

define fundamental principles that underlie the consistent interpretation of such complex activities, and support the development of reliable implementations.

2.3. International Survey

Robotic vehicles have been a principal theme of robotics research in many of the laboratories that were visited in this international survey. In many cases, the emphasis on the types of vehicles, the approaches to design, and the applications of interest have varied among these different international communities. This section summarizes these observations.

2.3.1. *Research on robotic vehicles — the United States*

In the United States, research on robotic vehicles has emphasized work in the following five areas.

2.3.1.1. *Military and defense systems*

The US federal government investment in robotic vehicle research has strongly emphasized the development of ground, air, and underwater vehicles with military applications. As shown in Fig. 2.9, there have been significant accomplishments in these areas in which large development programs have resulted in capable and reliable vehicle systems. Many of these systems are deployed in a "remotely operated" mode, i.e., a human controller works interactively to move the vehicle and position it, based on visual feedback from video or other types of sensors. In addition, there is a strong emphasis on integration of autonomous probes and observers with other parts of the military tactical system. The integration of sophisticated computer and communications architectures is an essential feature of these systems, and the use of algorithms such as SLAM to interpret complex scenes is an important contribution to these systems. The United States is generally acknowledged as the world leader in military applications of robotic vehicle technologies. As indicated in Chap. 1, in 2004 and 2005 the US Department of Defense conducted competitive Grand Challenge events in which autonomous robotic vehicles navigated and drove over 200 km in off-road desert conditions; in 2007 they navigated in an urban area.

2.3.1.2. *Space robotic vehicles*

The field of space robotics was identified as a topic for separate focus in this study and the major results of that effort will be presented in Chap. 3.

Fig. 2.9. Examples of the US military and defense robotic vehicles.

In the context of vehicle technologies, the recent Mars rover programs have uniquely demonstrated perhaps the most successful deployment of robotics vehicle technologies to date in any domain of applications. The rovers have landed and explored the surface of Mars and have carried out important scientific experiments and observations that have dramatically enhanced human understanding of that planet and its natural history. This US NASA effort has been the only successful demonstration of interplanetary vehicle space technology and is clearly recognized as the world leader in this domain.

2.3.1.3. *Field robotics*

Robotic vehicles developed for both military and space applications are intended for use in rough terrain, i.e., without roads or cleared areas. In this context, the experience of off-road robotic vehicles in the United States has also provided a basis for research in field robotics, the application of robotic vehicles to other unstructured domains, such as agriculture, mining, construction, and hazardous environments. In addition, the US industrial companies active in these areas have invested in prototype developments for these applications. Figure 2.3(a) is an example of such a prototype vehicle.

2.3.1.4. *Undersea robotics*

The United States has supported research in several different types of applications of underwater vehicles. These include:

(a) *Military and defense applications* As described in 'Military and Defense Systems,' the US defense technologies have included many fundamental prototypes and products that provide both ROV and AUV technology for the military. Figure 2.9 shows several of these vehicles.
(b) *Coastal security and environmental monitoring systems.* AUV systems may be used as surveillance and observance of the systems with both defense and environmental implications. Figure 2.10 shows an overview of the autonomous oceanographic sensor network (AOSN) systems, deployed as an experiment at the Monterey Bay Aquarium Research Institute (MBARI) in California, which integrate many different robotic and sensor resources.
(c) *Scientific mission and deep ocean science.* AUV and ROV technologies are the only means to actively explore large portions of the ocean volume. The study of ocean currents, ocean volcanoes, tsunami detection, deep-sea biological phenomena, and migration and changes

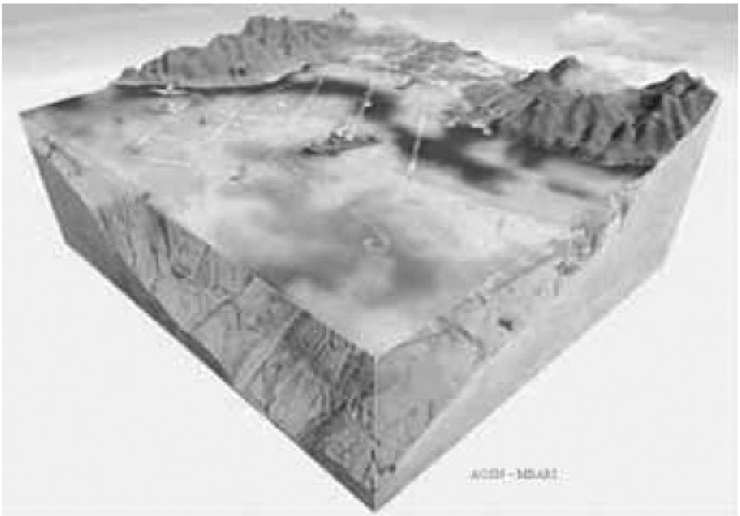


Fig. 2.10. Advanced oceanographic sensor network (MBARI, the United States).

in major ecosystems are all examples of topics that are studied with these systems. Several of the major scientific laboratories in the world are located in the United States and are leaders in these fields. A new project, HROV, is funded by the National Science Foundation (NSF) to develop a new hybrid remotely operated vehicle for underwater exploration in extreme environments, capable of operation at 11,000-m depth as shown in Fig. 2.11.

2.3.1.5. *Search-and-rescue robotics*

In recent years, there has been an increased emphasis on effective response to natural disasters, from earthquakes to hurricanes, in addition to other events, including terrorist activity. Robotic vehicles provide a means to explore such hazardous sites at times of extreme danger, providing information to support other responses and guiding search-and-rescue activity at the site. Rapid and reliable response and effective links to human interaction are essential features of these systems. An example of a search-and-rescue robotic vehicle system is shown in Fig. 2.12.

2.3.2. *Research on robotic vehicles — Japan and South Korea*

In Japan and South Korea, there is a long history of research on robotic vehicles with an emphasis on biomimetic systems and their applications to

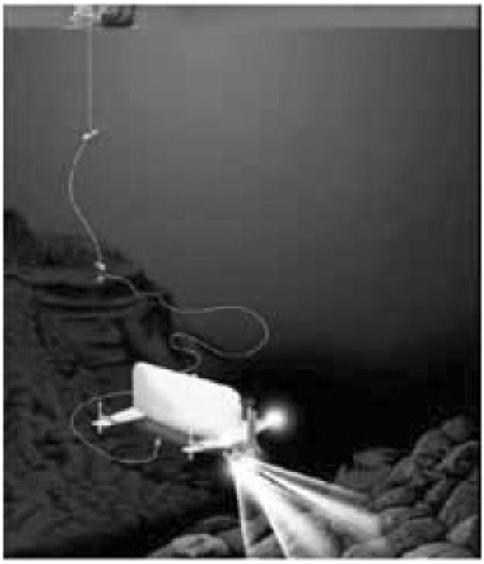


Fig. 2.11. HROV (Hybrid ROV) project (Johns Hopkins University (JHU) and Woods Hole (WHOI), the United States).

Fig. 2.12. Search-and-rescue robotics (CRASAR, USF, the United States).

personal and service systems. In addition, there is significant research in underwater vehicles.

2.3.2.1. *Personal and service robotic vehicles*

In Japan and South Korea there have been broad national initiatives that have shaped the course of research activities. Projections of the economic value of robotics technology have suggested that personal and service applications, including entertainment, are major opportunities for Japanese industry to build international markets. In this context, Japanese researchers have identified applications areas in household, eldercare, security and surveillance, and entertainment robotics as the areas of opportunity. Examples of household robotic vehicles include vacuum cleaners, as shown in Fig. 2.13, with projections of significant economic markets developing in the next ten years. Eldercare robotics is viewed as a high priority in both Japan and South Korea where aging populations suggest a need for service and support technologies. These technologies and markets will be discussed further in Chap. 5, but mobility is a primary requirement for many of these markets and both wheeled and legged ground vehicles are important constituents of the development efforts. Japan is viewed as a world leader in developing personal, service, and entertainment robots with potential international markets.

2.3.2.2. *Biomimetic mobility*

In both Japan and South Korea, there has been significant research effort in the development of mechanisms and systems that mimic biological mobility

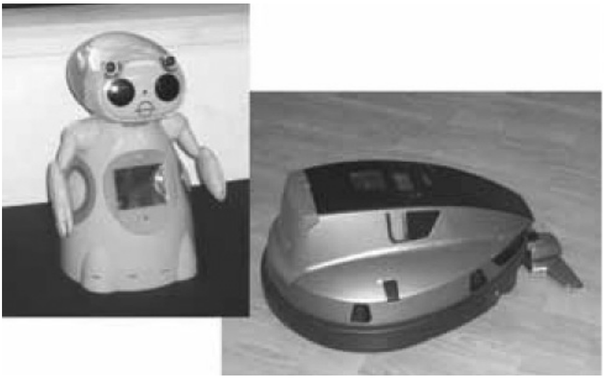


Fig. 2.13. Personal and service robots (Hanool, South Korea).

systems. These projects range from flying insects to snakes and swimming fish, and include both two-legged and multi-legged locomotion. Studies from a flying insect project in Japan are shown in Fig. 2.14a. A robotic swimming fish from South Korea is shown in Fig. 2.14b, while a brachiation robot (swinging between tree limbs) is shown in Fig. 2.14c.

Humanoid walking and bipedal locomotion have been a major focus of development in conjunction with recent humanoid projects in Japan and South Korea (see Chap. 4). As shown in Fig.2.5, these humanoid robots are sophisticated and have achieved significant results in bipedal locomotion, including stair climbing.

2.3.2.3. *Undersea robotics*

In both Japan and South Korea there are significant research efforts in underwater robotics. Sites of particular interest include:

The Japan Agency for Marine-Earth Science and Technology (JAMSTEC) has developed very sophisticated deep-sea vehicles for ocean science and exploration of ocean resources. Figure 2.15 shows the URASHIMA vehicle, which is 10 m long and will be powered by fuel cell technology.

The Ura Laboratory, University of Tokyo, has developed a series of underwater vehicles that are used in ocean research, and have also been used in environmental monitoring experiments in fresh water environments (Lake Biwa Research Institute). Figure 2.16 shows the photo of a vehicle from the University of Tokyo laboratory.

The national laboratory Korean Ocean Research and Development Institute (KORDI) has developed undersea vehicle technology that is used in ocean science and monitoring ocean resources.

2.3.3. *Research on robotic vehicles — Europe*

European research laboratories have emphasized the development of fundamental capabilities of robotic vehicles, including navigation systems and architectures, as well as applications in areas such as transportation systems, personal and service robotics, and undersea vehicles.

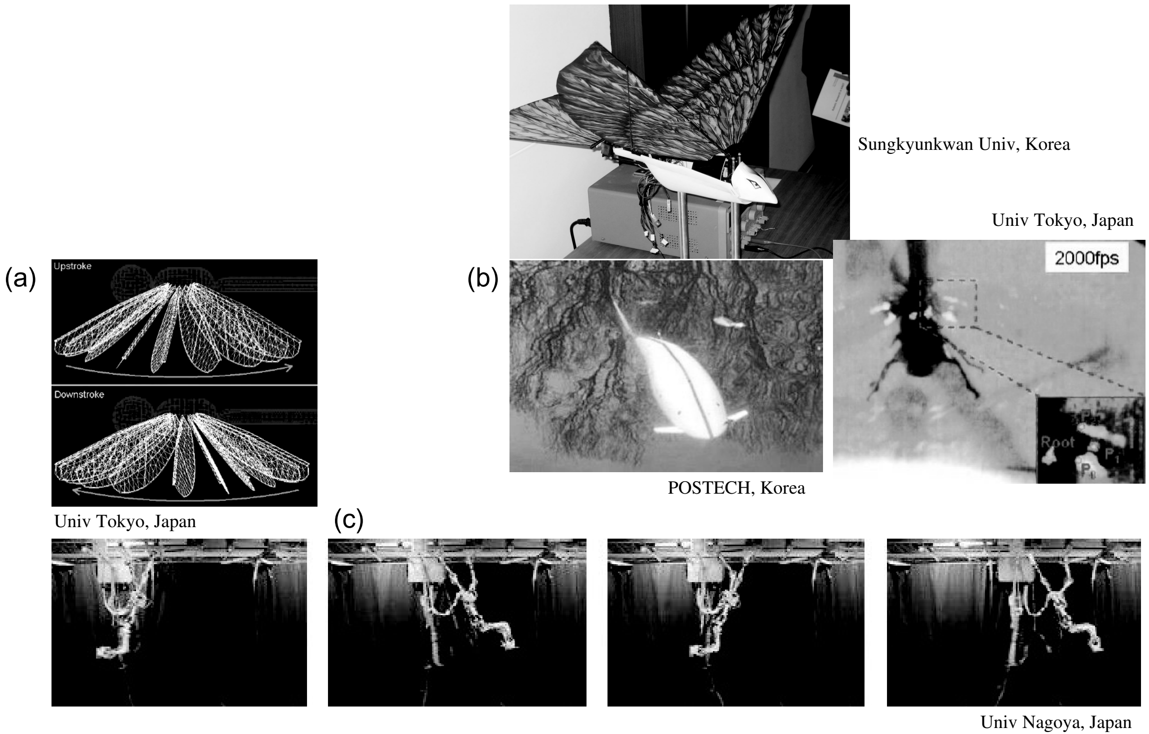


Fig. 2.14. Projects in biomimetic robot design. (a) Insect flight studies (Uno, U. Tokyo, Japan). (b) Robotic fish (Pohang Univ. of Science & Technology (POSTECH), South Korea). (c) Brachiation robot (U. Nagoya, Japan).

Fig. 2.15. URASHIMA AUV (JAMSTEC, Japan).

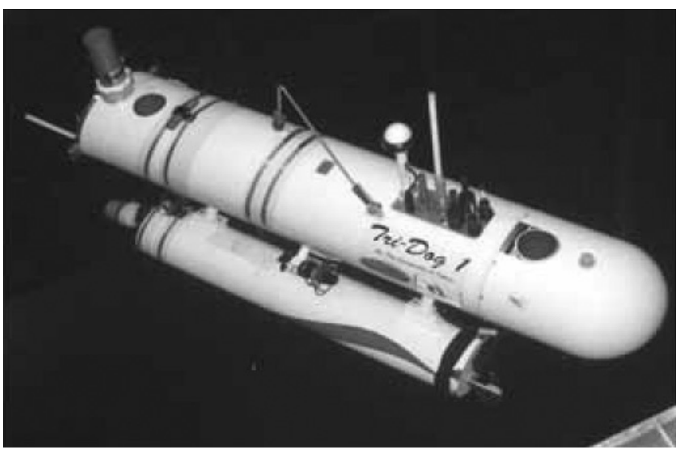


Fig. 2.16. Tri-Dog AUV with sensor guidance (U. Tokyo, Japan).

2.3.3.1. *Navigation and architectures*

Significant fundamental research has been carried out at several laboratories, including the Laboratoire d'Analyse et d'Architecture des Systèmes (LAAS) laboratory in Toulouse, France, the Robotics Laboratory at the University of Oxford, the United Kingdom, and the University of Karlsruhe, Germany, on computational architectures and communications in support of algorithms for navigation and mapping. These programs have

Fig. 2.17. Sensor-based mapping and localization using SLAM algorithms (U. Oxford, the United Kingdom).

contributed significantly to the international community in sensor-based navigation and vehicle control systems. An example of sensor-based map building from the University of Oxford is shown in Fig. 2.17. European laboratories have been among the leaders in international research in these fundamental areas.

2.3.3.2. *Transportation systems*

In European community programs, there has been investment in the development of robotic vehicles that could contribute to transportation systems and be used in urban environments. Figure 2.18 shows an example of the CYBERCar at l'Institut National de Recherche en Informatique et en Automatique (INRIA) Sophia-Antipolis, France, demonstrating vision-based following control. Figure 2.19 shows the implementation of vehicle-based vision systems for vehicle following and road following at high speed at the University of Braunschweig, Germany. European programs have demonstrated unique capabilities in these urban applications of robotic vehicle technologies.

2.3.3.3. *Personal and service robotics*

A number of European programs have also addressed the issues of personal and service robotics, including household robots, rehabilitation and eldercare robotics, and search-and-rescue robotics. Figure 2.20 shows

Fig. 2.18. CYBERCar prototype (INRIA, France).

Fig. 2.19. Autonomous road following and vehicle following at high speed (U. Braunschweig, Germany).

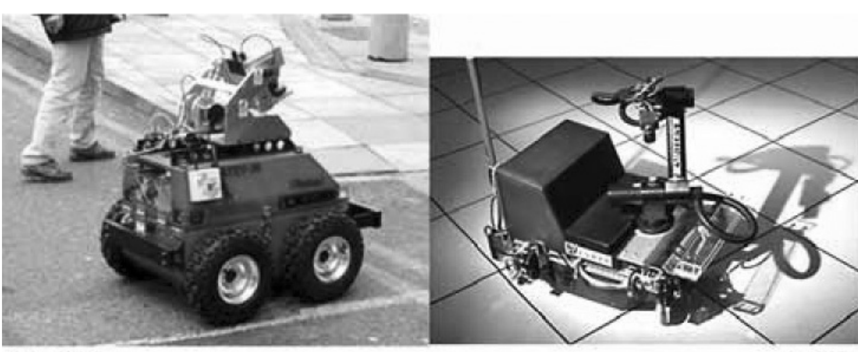


Fig. 2.20. Prototype vehicles used in urban and indoor settings.

mobile robots that have been developed for urban and indoor settings. Related medical and rehabilitation applications will be described in more detail in Chap. 6.

2.3.3.4. *Undersea robotics*

European programs have been very active in undersea robotics research. Programs at the Heriot-Watt University in Edinburgh, the United Kingdom, Southampton University in the United Kingdom, IFREMER in Toulon, France, Cybernétix in Marseille, France, and the University of Girona, Spain, all have significant research programs with prototype vehicles and systems that contribute to international collaborative projects. Figure 2.21 shows several prototypes and products including the ALIVE AUV developed by Cybernétix in conjunction with IFREMER and Heriot-Watt University. Figure 2.20 also shows the Garbí AUV used in experiments at the University of Girona. Research at Heriot-Watt University brings a strong systems capability (supporting software systems) that contributes to effective navigation and task control of AUVs.

2.4. Comparative Review of Programs

Based on the visits described in this book and the review of national programs in this international community in the area of robotic vehicles, a number of research priority areas have become clear. These research priorities are summarized in Table 2.2.

Table 2.2. International research priorities in robotic vehicles.

Region	Research priorities
The United States	Outdoor vehicular mobility: ground, air, undersea Navigation and mapping in complex outdoor environments
Japan and South Korea	Indoor mobility using humanoid locomotion Novel mechanisms of locomotion *Key applications:* service, entertainment, commercial
Europe	Mobility in urban and built environments Sensor-based navigation with maps *Key applications:* Infrastructure support and transportation

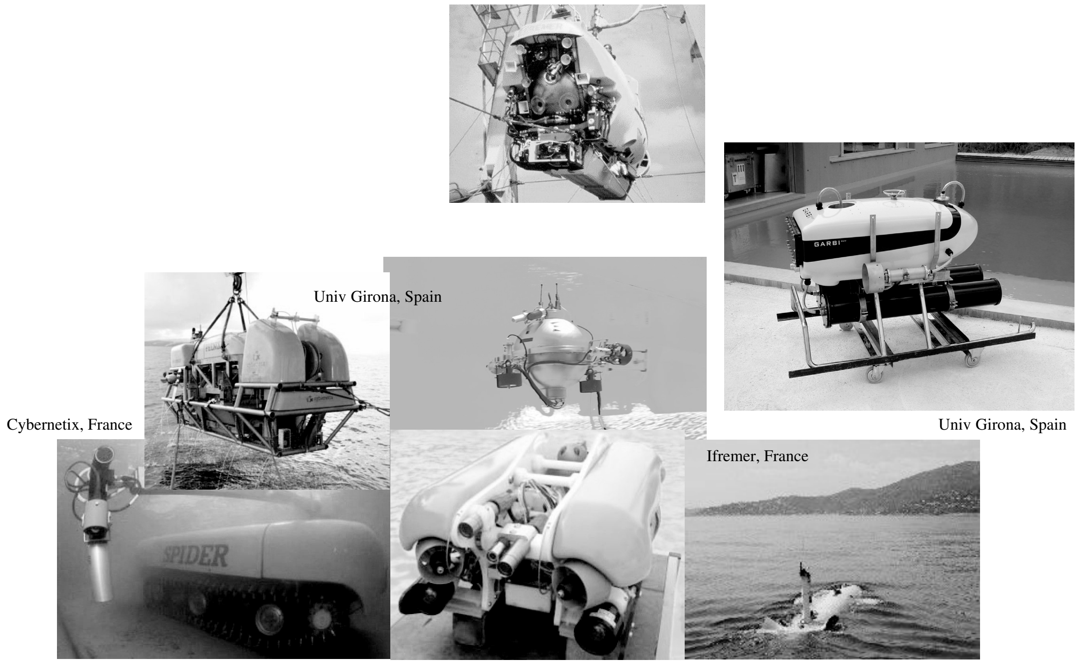


Fig. 2.21. Undersea robotic vehicles.

In summary, in the area of research in robotic vehicles, this study concludes:

- The US leadership in robotic vehicles has been strongly dependent on federal mission-oriented programs (DOD, NASA, and other agencies), and continuity of investment in basic research will be critical.
- The United States lags in the identification of strategic priorities that could translate vehicle capabilities to innovation and commercial, industrial, and civil infrastructure applications.
- Japan and Korea have aggressive national plans and investment to develop mobile robots supporting personal and service applications, including healthcare and eldercare.
- The European Community has developed strategic plans that coordinate vehicle programs and emphasize civilian and urban infrastructure, as well as some space applications.
- Other countries, particularly Australia, have made significant contributions to both theory and implementation of these technologies. International capabilities will continue to grow and more countries will demonstrate capability to build both prototype and commercial systems meeting applications needs.

Key future challenges in robotic vehicle research will include:

- Multivehicle systems.
  - Distributed sensor networks and observatories.
- Long-term reliable deployment.
- Micro and nanoscale mobility.
- Efficient and independent power.
- Human–robot vehicles.
- Interactions.
  - Service and entertainment.

2.5. Further Readings

The following recent books provide an overview of research progress in the field of robotic vehicles, and related topics in computational architectures, navigation, and mapping algorithms.

1. R. C. Arkin, *Behavior-Based Robotics* (MIT Press, Cambridge, MA, 1998).
2. G. A. Bekey, *Autonomous Robots: From Biological Inspiration to Implementation and Control* (MIT Press, Cambridge, MA, 2005).
3. T. Braunl, *Embedded Robotics: Mobile Robot Design and Applications with Embedded Systems* (Springer-Verlag, New York, 2001).
4. H. Choset, K. Lynch, S. Hutchinson, G. Kantor, W. Burgard, L. Kavraki and S. Thrun. *Principles of Robot Motion: Theory, Algorithms, and Implementations* (MIT Press, Cambridge, MA, 2005).
5. G. Dudek and M. Jenkin, *Computational Principles of Mobile Robotics.* (Cambridge University Press, Cambridge, MA, 2000).
6. D. Kortenkamp, R. P. Bonasso and R. Murphy, *Artificial Intelligence and Mobile Robotics: Case Studies of Successful Robot Systems* (AAAI, New York, 1998).
7. R. Madhavan, E. R. Messina and J. S. Albus, *Intelligent Vehicle Systems* (Nova Science Publishers, Hauppauge, NY, 2007).
8. R. Murphy, *An Introduction to AI Robotics* (MIT Press, Cambridge, MA, 2000).
9. U. Nehmzow, *Scientific Methods in Mobile Robotics: Quantitative Analysis of Agent Behavior* (Springer, New York, 2006).
10. R. Siegwart and I. R. Nourbakhsh, *Introduction to Autonomous Mobile Robots* (MIT Press, Cambridge, MA, 2004).
11. S. Thrun, W. Burgard and D. Fox, *Probabilistic Robotics* (MIT Press, Cambridge, MA, 2005).

Chapter 3

SPACE ROBOTICS

3.1. What is Space Robotics?

Space robotics is the process of developing general-purpose machines that are capable of surviving (for a time, at least) the rigors of the space environment, and performing exploration, assembly, construction, maintenance, servicing, or other tasks that may or may not have been fully understood at the time of the design of the robot. Humans control space robots either "locally," from a control console (e.g., with essentially zero speed-of-light delay, as in the case of the Space Shuttle robot arm (Fig. 3.1) controlled by astronauts inside the pressurized cabin) or "remotely" (e.g., with non-negligible speed-of-light delays, as in the case of the Mars Exploration Rovers (Fig. 3.2) controlled by human operators on Earth). Space robots are generally designed to do multiple tasks, including unanticipated tasks, within a broad sphere of competence (e.g., payload deployment, retrieval, or inspection; planetary exploration).

Space robots are important to our overall ability to operate in space because they can perform tasks less expensively or on an accelerated schedule, with less risk and occasionally with improved performance over humans doing the same tasks. They operate for long durations and are often "asleep" for long periods before their operational mission begins. They can be sent into situations that are so risky that humans would not be allowed to go. Indeed, every space robot mission beyond Earth orbit has been a "suicide mission" in that the robot is left in space when it stops operating, since the cost of return-to-Earth is (literally) astronomical (and that cost would be better spent in the return of scientific samples in almost every case). Missions to distant targets such as Titan (a moon of Saturn thought to have liquid hydrocarbon lakes or rivers) presently require a significant fraction of human lifetime for the transit from Earth to the destination (Fig. 3.3). Access to space is expensive (currently about

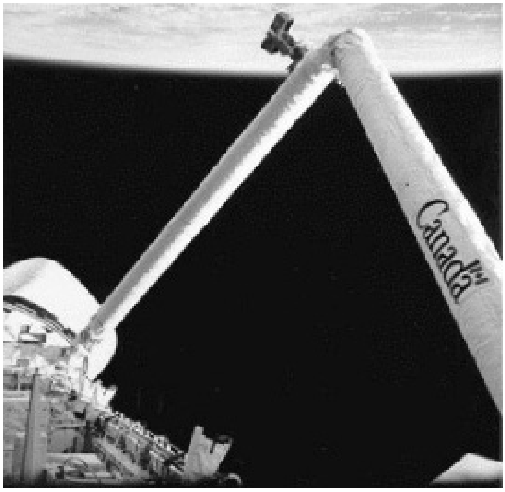


Fig. 3.1. Space Shuttle robot arm developed by Canadian Space Agency.

Fig. 3.2. Mars Exploration Rover.

$10,000 for every kilogram lofted into Low Earth Orbit (LEO)), implying that, for certain jobs, robots that are smaller than human and require much less infrastructure (e.g., life support) makes them very attractive for broad classes of missions (Fig. 3.4).

Fig. 3.3. Artist's conception of Robot blimp on Titan.

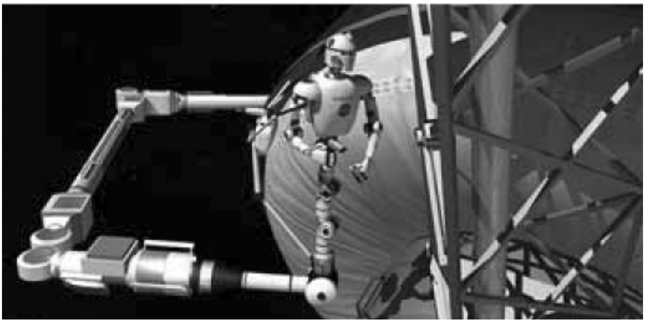


Fig. 3.4. Artist's conception of "Robonaut" (an "astronaut-equivalent" robot) performing space assembly.

3.2. Issues in Space Robotics

3.2.1. *How are Space Robots created and used? What technology for space robotics needs to be developed?*

There are four key issues in Space Robotics. These are **Mobility** — moving quickly and accurately between two points without collisions and without putting the robots, astronauts, or any part of the worksite at

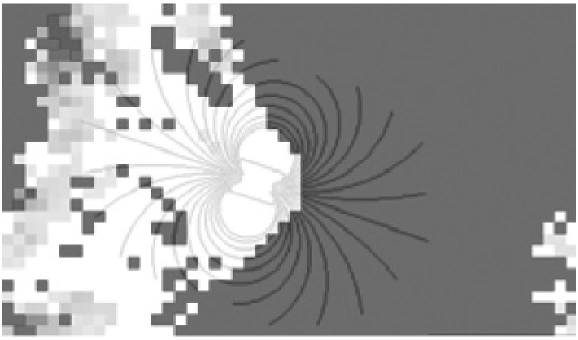


Fig. 3.5. MER path planner evaluates arcs through sensed terrain (gray levels indicate traversability; pattern, unknown terrain).

risk; **Manipulation** — using arms, hands, and tools to contact worksite elements safely, quickly, and accurately without accidentally contacting unintended objects or imparting excessive forces beyond those needed for the task; **Time Delay** — allowing a distant human to effectively command the robot to do useful work; and **Extreme Environments** — operating despite intense heat or cold, ionizing radiation, hard vacuum, corrosive atmospheres, very fine dust, etc.

A path planner for the Mars Exploration Rover (MER), which permits the vehicles to plan their own safe paths through obstacle fields, eliminating the need for moment-to-moment interaction with humans on Earth, is shown in Fig. 3.5. The "supervisory control" provided by human operators is at a higher level, allowing the vehicle to stay productive even though humans give only one set of commands each day. This approach to managing the time delay works for both mobility and for manipulation — commands are given to move either the vehicle or the arm through nominal waypoints, avoiding any impending collisions detected by on-board sensors. Expectations are generated for what sensors should read (e.g., overall vehicle pitch, roll, motor currents), and any deviations outside the expected range will cause the vehicle to stop and "call home" for help. These approaches are still in their infancy — better sensing is needed to detect impending unsafe conditions or possible collisions, especially for manipulation. The ability to manage contact forces during manipulation is also very primitive. Shown in Fig. 3.6 is a computer-aided design (CAD) rendering of the Ranger system developed by the University of Maryland to demonstrate advanced space manipulation in the payload bay of the space shuttle. These systems were extensively developed in underwater

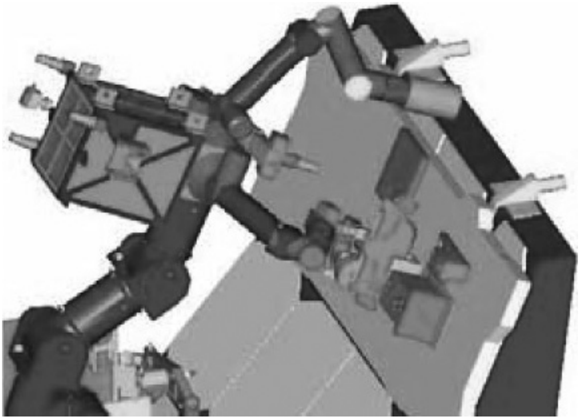


Fig. 3.6. Ranger (U. MD) robot was developed to demonstrate advanced robotics in the space shuttle payload bay.

neutral-buoyancy tests to demonstrate useful task-board operations despite several seconds of speed-of-light round-trip between the human operator on the ground and the robot.

All space robots share a need to operate in extreme environments. Generally, this includes increased levels of ionizing radiation, requiring noncommercial electronics that have been specially designed and/or qualified for use in such environments. The thermal environment is also generally much different from terrestrial systems, requiring minimum systems that are cooled not by air or convection, but by conduction and radiation. Many space environments routinely get significantly hotter or colder than the design limits for normal commercial or military components. In such cases, the space robot designer faces a choice of whether to put those components into a special thermal enclosure to maintain a more moderate environment, or to attempt to qualify components outside their recommended operating conditions. Both approaches have been used with success, but at significant costs.

The Mars Exploration Rover created by the Jet Propulsion Laboratory is a good example of a space robot. The twin MER rovers “Spirit” and “Opportunity” have collectively taken hundreds of thousands of images and millions of spectra since arriving on Mars in January 2004. Figure 3.7 shows one of the MER robot arms placing an instrument against a rock. The arm carries multiple instruments to get different sorts of spectra, and also a Rock Abrasion Tool that can grind the rock surface to expose a fresh face of unweathered rock.

Fig. 3.7. Robot arm on Mars Exploration Rover.

Fig. 3.8. Robonaut performing dexterous grasp.

Robonaut (Fig. 3.8) is an "astronaut-equivalent" robot being developed at the Johnson Space Center. The central premise of robonaut is of the same size, strength, and dexterity as a suited astronaut, and will be able to use all the same tools, handholds, and implements as the astronaut, and so will be able to "seamlessly" complement and supplement human astronauts. The robonaut prototypes have five-fingered anthropomorphic hands each with 14 degrees of freedom (DOF) (e.g., different motors), sized to match the strength and range-of-motion of a gloved hand of an EVA astronaut (Figs. 3.9 and 3.10).

Fig. 3.9. Robonaut using handrails designed for human astronauts in simulated zero-g (using air-bearing floor).

Fig. 3.10. Robonaut engaged in cooperative truss assembly task with human astronaut in lab.

Fundamental research challenges for space robotics include solving the basic questions of mobility: where am I, where is the "goal," where are the obstacles or hazards, and how can I get from where I am to where I want to be? Figure 3.11 shows some results from stereocorrelation, a process where images taken from stereoscopic cameras are matched together to calculate

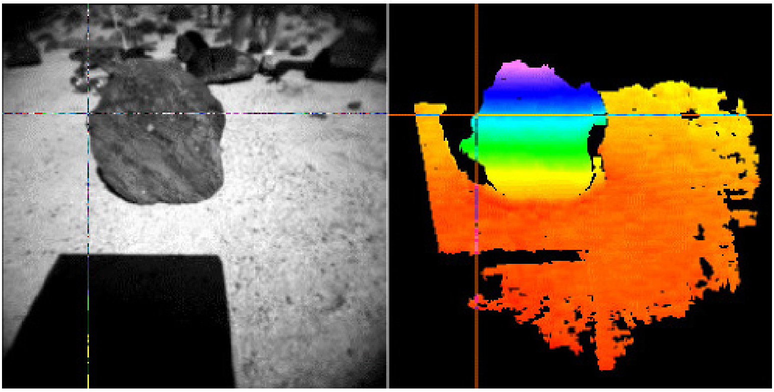


Fig. 3.11. Stereocorrelation example.

the range to each point in the image. This range map, along with the known camera-viewing geometry, can be transformed into an elevation map that is used to identify obstacles and other forms of hazards. Defining a coordinate frame in which hazards and objects of scientific interest can be localized is important. With the original Mars Rover Sojourner, the coordinate frame was fixed to the lander, and the rover always moved within sight of the lander mast-mounted cameras. However, with the MER rovers, the landers were left far behind and could not serve as a stationary reference point. So, it is very important to accurately measure the motion of each vehicle so that the updated position of previously seen objects can be estimated. In Fig. 3.12 is shown a result from "visual odometry," a process where distinctive points in an image are located and tracked from frame to frame so that the motion of the camera in a stationary scene can be accurately estimated. Vehicle "dead reckoning" (e.g., using only its compass and odometer to navigate) typically results in errors of about 10% of distance traveled in estimating its new position. With visual odometry, this error drops to well under 1%.[1] While stereovision and visual odometry allow a vehicle to autonomously estimate and track the position of rocks, craters, and other similar hazards, they are not able to estimate the load-bearing strength of the soil. Shown in Fig. 3.13 is "Purgatory Dune," a soft soil formation on Mars, where the rover Opportunity got stuck for 5 weeks in the spring of 2005. Shown in Fig. 3.14 are the tracks leading to Purgatory Dune, showing that the visual appearance of Purgatory Dune was not distinctively different from that of the small dunes, which had been successfully traversed for many kilometers previously. Detecting very soft soil conditions requires additional research and may also require specialized sensors.

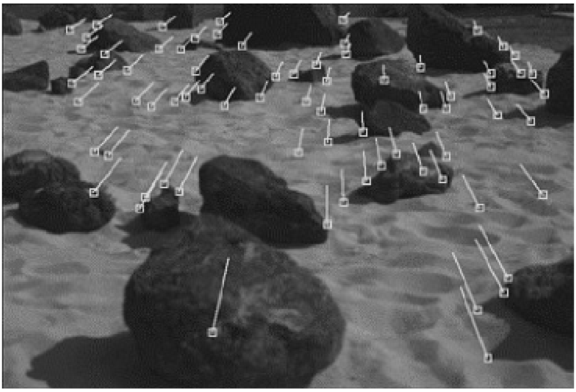


Fig. 3.12. Visual odometry example.

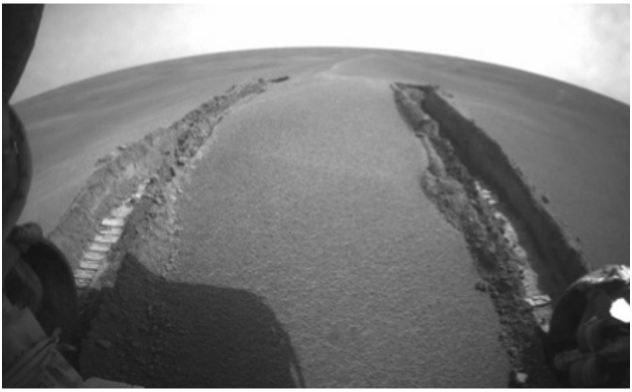


Fig. 3.13. Opportunity Rover image of Purgatory Dune after extraction.

Another area of fundamental research for space robotics relates to manipulation (see Fig. 3.15). Traditional industrial robots move to precise pre-planned locations to grasp tools or workpieces, and generally they do not carefully manage the forces they impart on those objects. However, space hardware is usually very delicate, and its position is often only approximately known in terms of the workspace of the arm. Large volumes of the workspace may be occupied by natural terrain, by spacecraft components, or by astronauts. If the robot arm is strong enough to perform useful tasks, and is fast enough to work cooperatively with human astronauts, then it represents a tremendous danger to the spacecraft components, the human astronauts, and to itself. Advanced sensing is

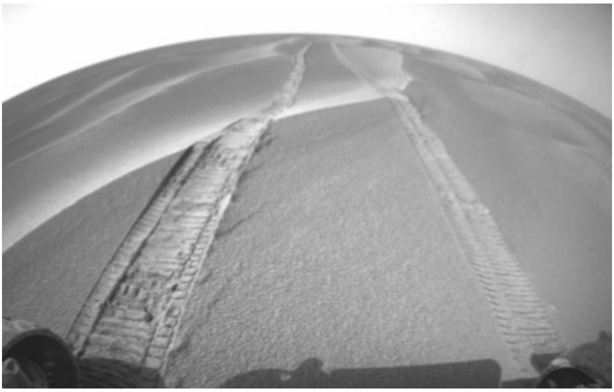


Fig. 3.14. Opportunity image of rover tracks leading into Purgatory Dune.

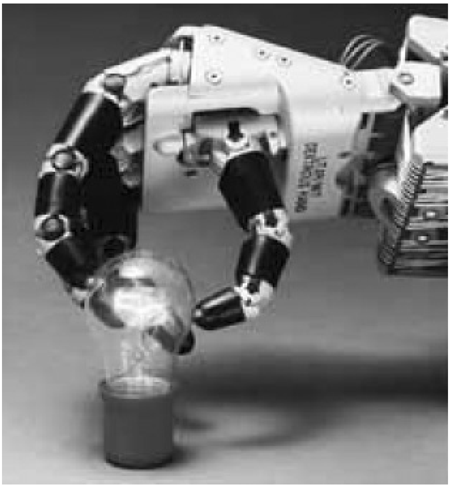


Fig. 3.15. SARCOS dexterous hand capable of force control.

needed to identify and keep track of which parts of the work volume are occupied and where workpieces are to be grasped. Whole-arm sensing of impending collisions may be required. A major advance in safety protocols is needed to allow humans to occupy the work volume of swift and strong robots — something that is not permitted in industry nowadays.

Time delay is a particular challenge for manipulation in space robotics. Industries that routinely use teleoperation, such as the nuclear industry, generally use "master–slave" teleoperators that mimic at the "slave" arm any motion of the "master" arm as maneuvered by the human. This approach only works well if the time-delay round trip between the master and the slave is a very small fraction of a second. When delays of a few seconds are encountered, human operators are very poor at managing the contact forces that the slave arm imparts on the workplace. For these cases, which include many or most that are of interest in space robotics, it is more appropriate for the human to command the slave arm by way of "supervisory control." In supervisory control, the contact forces are rapidly measured and controlled directly by the electronics at the slave arm, so that the time-delay back to the human operator does not result in overshoot or oscillation of the slave arm. The human gives commands for motion that can include contact with elements of the worksite, but those contact forces are managed within a pre-planned nominal range by the remote-site electronics independent of the motion of the master. Figure 3.16 shows an artist's conception of a submarine robot exploring the putative liquid water ocean thought to exist under the surface ice on Europa, a moon of Jupiter. The speed-of-light round trip for control of such a device would be at least hours, and practically it may only be possible to send commands to such a vehicle once every few days.

Figures 3.17–3.23 show a variety of planetary rovers developed in the United States. The rovers in Figs. 3.17–3.19 and 3.24 were developed at the Jet Propulsion Laboratory; the rovers in Figs. 3.20–3.23 were developed at

Fig. 3.16. Artist's concept of a submarine robot in the sub-ice liquid water ocean thought to exist on Europa, a moon of Jupiter.

Fig. 3.17. Artist's conception of Mars Exploration Rover.

Fig. 3.18. Image of Sojourner Rover as it explored Mermaid Dune on Mars in the summer of 1997.

Carnegie-Mellon University (with the rover in Fig. 3.20 jointly developed with Sandia Laboratories).

Figures 3.25–3.29 show a montage of space manipulators developed in North America (responsibility for the large manipulator arms used on the Space Shuttle and Space Station was assigned to Canada by mutual agreement between the governments of the United States and Canada).

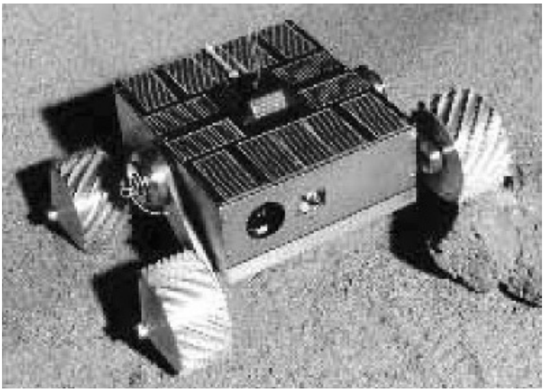


Fig. 3.19. 1.5 kg Nanorover developed by JPL for asteroid or Mars exploration.

Fig. 3.20. RATLER Rover developed jointly by Carnegie-Mellon University and Sandia Laboratory for use on the Moon.

Fig. 3.21. Hyperion robot developed by Carnegie-Mellon University used in arctic and other planetary analog sites.

Fig. 3.22. Dante-II Rover, which rappelled into the active caldera of Mt Spur in Alaska in 1994.

Fig. 3.23. Nomad Rover, developed by Carnegie-Mellon University, explored part of Antarctica in 1997 and 1998, and the Atacama desert in Chile in 1996–1997.

Fig. 3.24. Rocky-7 Rover, developed by JPL for long-range traverse in a Sojourner-sized vehicle.

One relatively straightforward use of robotics in space is free-flying inspection. Figure 3.30 shows the "AERCam Sprint" that was flown as part of a space shuttle mission in 1997. This spherical (14″ dia.) vehicle was remotely controlled from within the Space Shuttle cabin, and was

Fig. 3.25. Robonaut, developed by the Johnson Space Center, is used to study the use of anthropomorphic "astronaut equivalent" upper body sensing and manipulation as applied to space tasks.

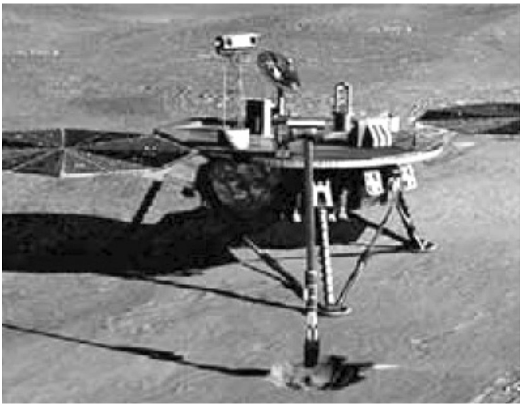


Fig. 3.26. Phoenix arm, built by the Alliance Spacesystems, Inc. for the Phoenix mission led by P. I. Peter Smith of the University of Arizona for use on the lander system developed by Lockheed-Martin of Denver.

able to perform inspection of the exterior of the Space Shuttle. Sadly, the vehicle has not been flown since, and in particular was not on-board during the final mission of the Shuttle Columbia, where in-flight inspection might have changed the outcome. Figure 3.31 shows the Mini-AERCam, which is a small (8″ dia.) successor to the AERCam-Sprint that has been funded

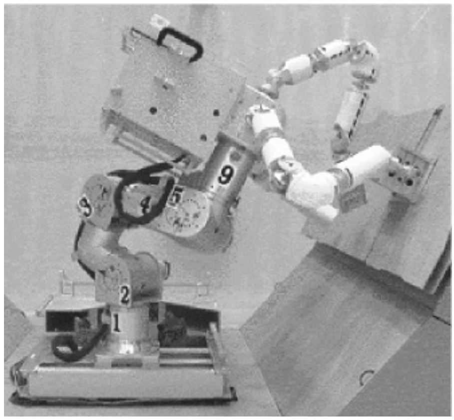


Fig. 3.27. Ranger Manipulator, developed by the University of Maryland, to demonstrate a wide variety of competent manipulation tasks in Earth orbit. Flight hardware was developed in the 1990s for both an expendable launch vehicle and the Space Shuttle, but presently there is no manifest for a flight experiment.

Fig. 3.28. Special-purpose dexterous end-effector, developed by McDonnell-Detweiler Robotics for the Canadian Space Agency.

subsequent to the Columbia disaster for routine operational use on future missions.

3.3. International Efforts in Space Robotics

Other nations have not been idle in developing space robotics. Many recognize that robotic systems offer extreme advantages over alternative

Fig. 3.29. Mars Exploration Rover robot arm, developed by Alliance Spacesystems, Inc., for JPL.

Fig. 3.30. AERCam-Sprint, developed by JSC, a free-flying inspection robot that was tested during a flight of the Space Shuttle in 1997.

approaches to certain space missions. Figures 3.32 and 3.33 show a series of images of the Japanese ETS-VII (the seventh of the Engineering Technology Satellites), which demonstrated in a flight in 1999 a number of advanced robotic capabilities in space. ETS-VII consisted of two satellites named "Chaser" and "Target." Each satellite was separated in space after launching, and a rendezvous docking experiment was conducted twice, where the Chaser satellite was automatically controlled and the Target was being remotely piloted. In addition, there were multiple space robot manipulation experiments, which included manipulation of small parts and propellant replenishment by using the robot arms installed on the Chaser.

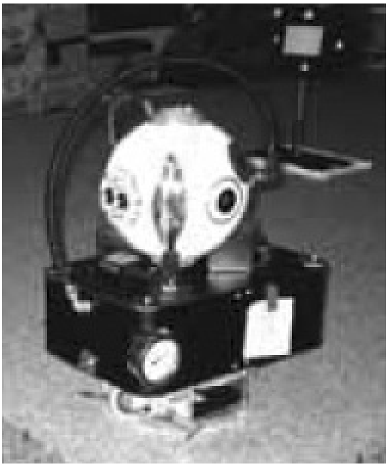


Fig. 3.31. Mini-AERCam, under development at Johnson Space Center (JSC) for operational use on future space missions.

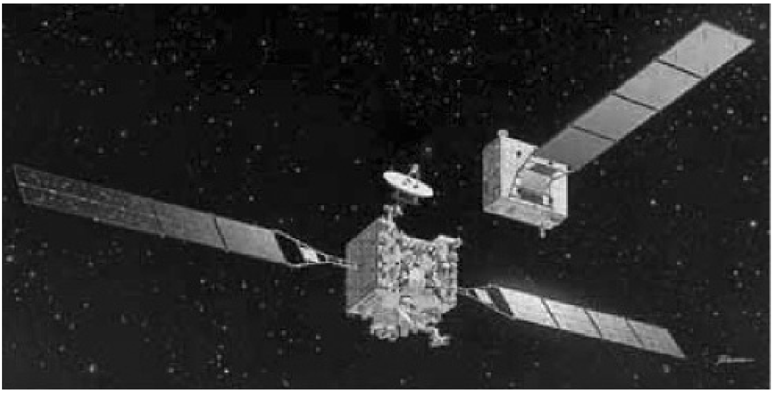


Fig. 3.32. Artist's conception of the ETS-VII rendezvous and docking experiment.

The Japanese have also developed advanced robotic elements for the Japanese Experiment Module (JEM) of the International Space Station. The Remote Manipulator System (RMS) consists of two robotic arms that support operations on the outside of JEM. The Main Arm can handle up to 7 metric tons (15,000 pounds) of hardware and the Small Fine Arm (SFA), when attached to the Main Arm, handles more delicate operations. Each arm has six joints that mimic the movements of a human arm. Astronauts operate the robot arms from a remote computer

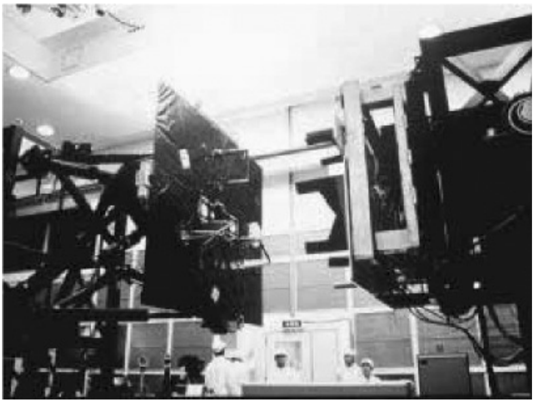


Fig. 3.33. Docking adapter testing for the ETS-VII robotics technology experiment.

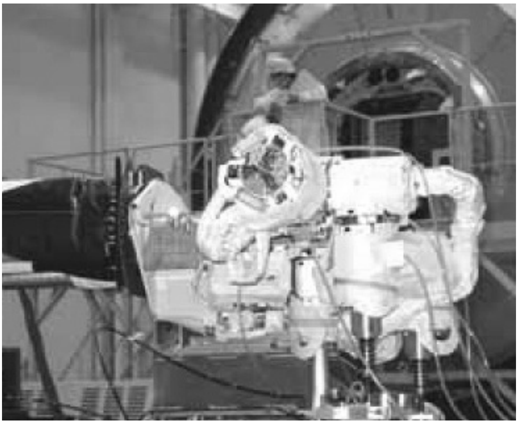


Fig. 3.34. Japanese Small Fine Arm developed for the Japanese Experiment Module awaiting launch to the International Space Stattion.

console inside the Pressurized Module and watch external images from a camera attached to the Main Arm on a television monitor at the RMS console. The arms are specifically used to exchange experiment payloads or hardware through a scientific airlock, support maintenance tasks of JEM, and handle orbital replacement units. The operations of a prototype SFA were evaluated as part of the Manipulator Flight Demonstration (MFD) experiment conducted during the STS-85 Space Shuttle mission in 1997. The Main Arm measures 9.9 m (32.5 ft) long, and the SFA measures 1.9 m (6.2 ft). Figure 3.34 shows the SFA, which is awaiting launch.

The Japanese MUSES-C asteroid sample return mission has several robotic elements. This mission (renamed after launch, in the Japanese tradition, to "Hayabusa," meaning "Falcon"). It successfully achieved rendezvous with the asteroid 25143 Itokowa, named after a Japanese rocketry pioneer. Hayabusa made only momentary contact with its target — descending to the surface of the asteroid, and immediately firing a small (5 gm) projectile into the surface at a speed of about 300 m/s, causing small fragments from the surface to be collected by a sample collection horn. This is a funnel which guides the fragments into a collection chamber. After less than a second on the surface, Hayabusa fired its rocket engines to lift off again. During the first descent to fire a pellet into the surface, a small surface hopper, called Minerva, was released. Technical difficulties caused MINERVA not to achieve contact with the asteroid, and the return to earth of the samples presumably acquired by Hayabusa was delayed. Minerva is shown in Fig. 3.35.

European researchers have also been active in space robotics. ROTEX was an experiment developed by the German Aerospace Center (DLR) near Munich that was flown in a cabinet on the SPACELAB module in the Space Shuttle in 1993 (Fig. 3.36). One of the most important successful experiments was the catching of a freely floating and tumbling cube. A key element of the system was the "predictive display," which allowed human operators on the ground to see what was projected to occur one speed-of-light-round-trip in the future based on the commands given to the manipulator and the laws of physics as applied to the motion of free objects. The system included a high-precision six-axis manipulator (robot arm)

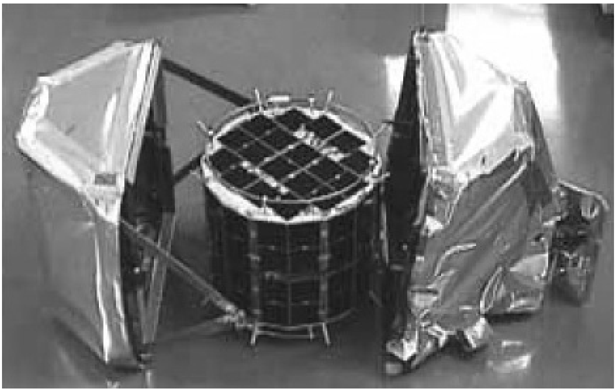


Fig. 3.35. Minerva hopping robot developed in Japan for asteroid mission MUSES-C.

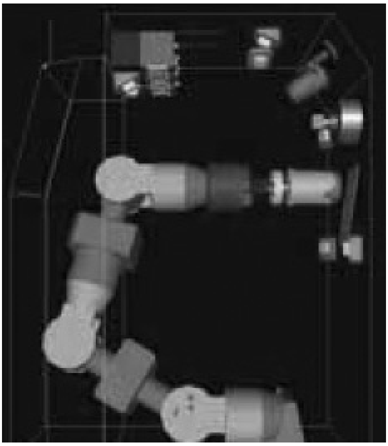


Fig. 3.36. Schematic of German Rotex experiment flown in 1993 with a manipulator and task elements inside a protective cabinet.

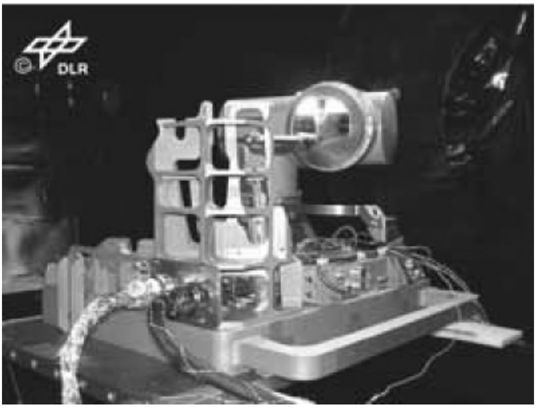


Fig. 3.37. ROKVISS experiment currently flying on International Space Station.

with grippers, tipped with distance, force, moment, and touch sensors that could be controlled (using stereoscopic vision) either from on-board shuttle or from ground operators at DLR. More recently, DLR has developed ROKVISS (Robot Komponent Verification on ISS). ROKVISS (Fig. 3.37) is a German technology experiment for testing the operation of the highly integrated, modular robotic components in microgravity. It is mounted on the exterior of the International Space Station, with a modular arm with a single finger used for force-control experiments. Stereocameras are used

Fig. 3.38. Advanced dexterous manipulator arm for space applications developed at DLR.

to permit remote visualization of the worksite, and a direct radio link with the command center is used when the ISS flies over Germany. The purpose of ROKVISS is to validate the space qualification of the newest lightweight robot joint technologies developed in DLR's lab, which are to form a basis for a new generation of ultralight, impedance-controllable, soft arms (Fig. 3.38), which, combined with DLR's newest articulated four-fingered hands (Fig. 3.39), are the essential components for the future "robonaut" systems. The main goals of the ROKVISS experiment are the demonstration and verification of lightweight robotics components, under realistic mission conditions, as well as the verification of direct telemanipulation to show the feasibility of applying telepresence methods for further satellite servicing tasks. It became operational in January of 2005. Figure 3.40 shows the Spacecraft Life Extension System (SLES), which will use a DLR capture mechanism to grapple, stabilize, and refuel commercial communication satellites.

Figure 3.41 shows the Beagle-2 Mars lander, which had a robot arm built by a collaboration of British industry and academia for use in sampling soil and rocks. Figure 3.42 shows a proposed Mars Rover that is conceived

Fig. 3.39. Dexterous four-fingered hand developed for space applications at DLR.

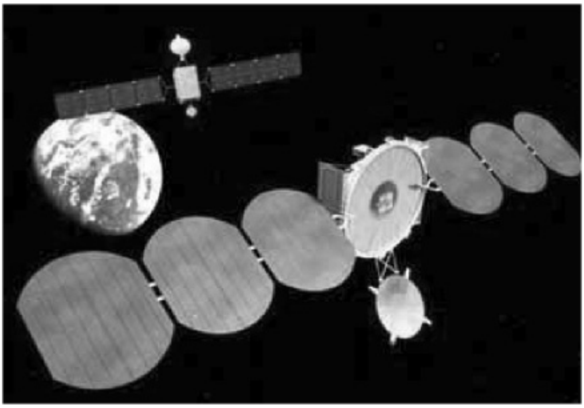


Fig. 3.40. Spacecraft Life Extension System (SLES), which will use a DLR capture mechanism to grapple, stabilize, and refuel commercial communication satellites.

for the ExoMars mission that the European Space Agency is planning to launch early in the next decade. French research centers at Toulouse (Centre National d'Etudes Spatiales (CNES) and Laboratoire d'Analyse et d'Architecture des Systèmes/Centre National de la Recherche Scientifique

Fig. 3.41. Beagle-2 Mars lander with robot arm developed in the United Kingdom.

Fig. 3.42. Artist's conception of ExoMars Rover planned by the European Space Agency.

(LAAS/CNRS)) have developed substantial expertise in rover autonomy in a series of research projects over the past 15 years. They have proposed a major role in developing the control algorithms for the ExoMars Rover.

3.4. The State of the Art in Space Robotics

The current state of the art in "flown" space robotics is defined by MER, the Canadian Shuttle and Station arms, the German DLR experiment

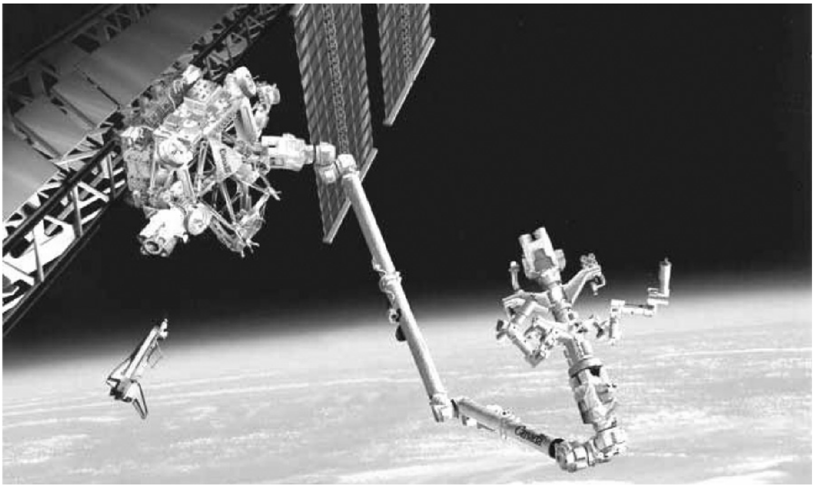


Fig. 3.43. Special Purpose Dexterous Manipulator on the end of the Space Station Remote Manipulator Dextre System, both developed for the Canadian Space Agency. The SSRMS is now in-flight, and the SPDM is awaiting launch.

Rotex (1993) and robot arm ROKVISS on the Station right now, and the Japanese experiment ETS-VII (1999). A number of systems are waiting to fly on the Space Station, such as the Canadian Special Purpose Dexterous Manipulator (SPDM or "Dextre," Fig. 3.43, was mounted on the Space Station in 2008) and the Japanese Main Arm and Small Fine Arm (Fig. 3.44). Investments in R&D for space robotics worldwide have been greatly reduced in the past decade as compared to the decade before that; the drop in the United States has been greater than in Japan or Germany. Programs such as the NASA Mars Technology Program (MTP) and Astrobiology Science and Technology for Exploring Planets (ASTEP), as well as the recent NASA Exploration Technology Development Program (ESDP) represent an exception to the generally low level of investment over the past decade. However, some or all of these programs are expected to be further scaled back as NASA seeks to make funds available to pursue the Vision for Space Exploration of the moon and Mars. Figure 3.45 shows an artist conception of a Robonaut-derived vehicle analogous to the mythical ancient Greek Centaurs, with the upper body of a human for sensing and manipulation, but with the lower body of a rover for mobility. Figure 3.46 shows a comparison between the first two autonomous planetary rovers flown, Sojourner (or actually the flight spare, Marie Curie) and Spirit.

In Asia, the Japanese have consolidated most space robotics work at NEC/Toshiba, who have several proposals submitted but no currently

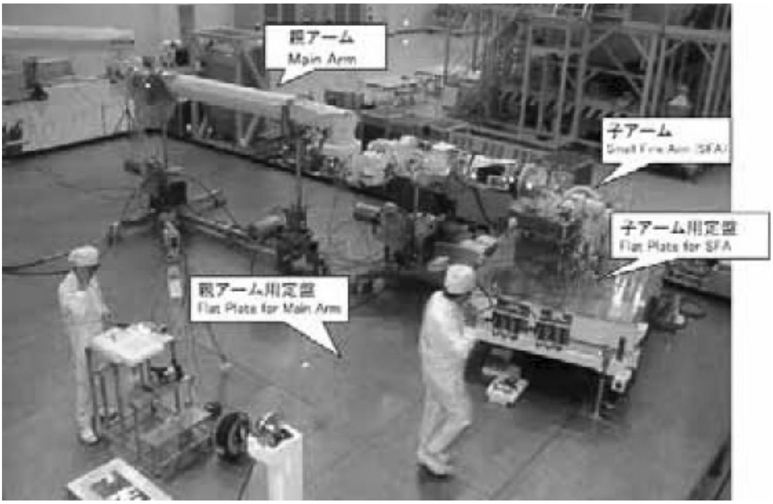


Fig. 3.44. Main Arm and Small Fine Arm undergoing air-bearing tests. Both were developed for the Japan Aerospace Exploration Agency (JAXA), and are awaiting launch to the International Space Station.

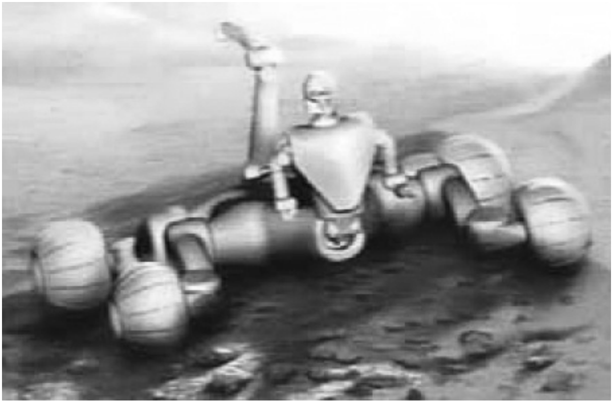


Fig. 3.45. Artist conception of a centaur-like vehicle with a robonaut upper body on a rover lower body for use in Mars operations.

funded space robotics follow-ons to the MFD, ETS-VII, or JEMRMS. The Japanese have developed several mission concepts that include lunar rovers. The South Koreans have essentially no work going on in space robotics. Both China and India are reported to be supporting a significant level of indigenous development of future lunar missions that may involve

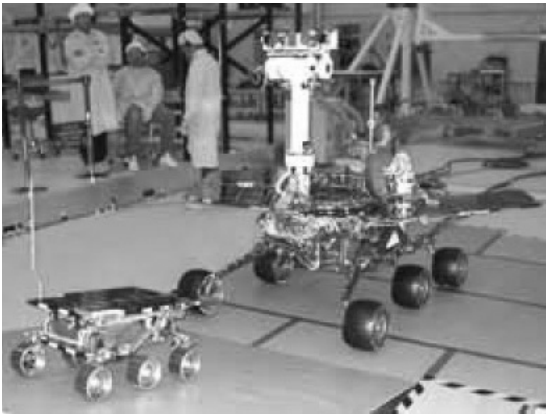


Fig. 3.46. Flight spare of original Sojourner Rover with Mars Exploration Rover "Spirit."

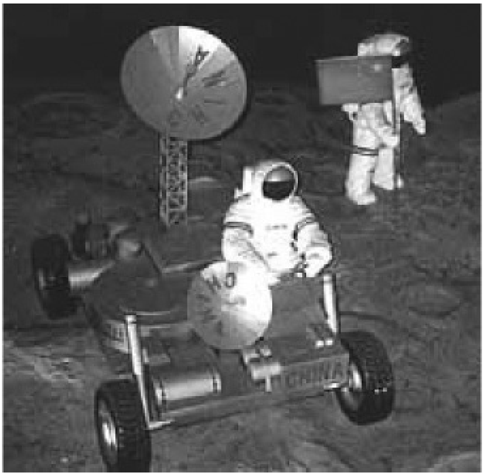


Fig. 3.47. Model at the Chinese Pavilion, Hannover Expo 2000 showing Chinese astronauts with lunar rover planting the People's Republic of China's flag on the lunar surface.

robotics. Figure 3.47 shows a model at the Chinese Pavilion at the Hannover Expo 2000 depicting Chinese astronauts with a lunar rover planting the flag of the People's Republic of China's on the lunar surface, while Fig. 3.48 shows a prototype of a lunar rover developed by the Japanese for the SELENE-II mission. In Europe, the Germans are planning a general-purpose satellite rendezvous, capture, re-boost, and stabilization system to

Fig. 3.48. Development model of a lunar rover for the Japanese mission SELENE-II.

Fig. 3.49. Artist's conception of a future European Space Agency astronaut examining the ExoMars Rover.

go after the market in commercial satellite life extension. In the United States, the Defense Advanced Research Projects Agency (DARPA) has a similar technology development called Spacecraft for the Unmanned Modification of Orbits (SUMO). The French are proposing a major role in a Mars Rover as part of the ESA ExoMars project. The French Space Agency

CNES and the research organization LAAS/CNRS have a significant capability, developed over many years, for rover hazard avoidance, roughly comparable to the US MER and planned Mars Science Laboratory (MSL) rovers. Neither the British nor the Italians have a defined program that is specific to Space Robotics, although there are relevant university efforts. Figure 3.49 shows an artist conception of a future ESA astronaut examining and retrieving an old ExoMars rover.

There are no clearly identified, funded or soon-to-be-funded missions for robotics except for the current manipulation systems for the Space Station, the planned US and European Mars rovers, and a possible Japanese lunar rover. There is no current plan by any nation to use robots for in-space assembly of a large structure, for example. The role of robotics in the NASA "vision" outlined in the speech by President Bush in January 2004 is not fully defined yet, but it may be substantial.

Future trends in Space Robotics are expected to lead to planetary rovers that can operate many days without commands, and can approach and analyze science targets from a substantial distance with only a single command, and robots that can assemble/construct, maintain, and service space hardware using very precise force control and dexterous hands, despite multi-second time delay.

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Chapter 4

HUMANOIDS

4.1. Background

Science fiction has led the field of robotics, like so many other disciplines, with visions of technology far beyond the contemporary state of the art. The term "robot" was coined by Czech author Čapek in his 1924 production of "Rossum's Universal Robots." The robots were played by human actors, and dealt with the issues of slavery and subjugation that were metaphors for concerns held by human workers of the day. These first robots were also the first humanoids, at least in theater.

Robots gained another foothold in science fiction with the works of Asimov, where the term "robotics" was first defined in 1941 as a discipline of study. And once again, the form and functions of the robots being studied and built (in fiction) were humanoid. Figure 4.1 shows the evolution of science fiction from the earliest works to modern media. In both cases, the robots did tasks designed for people, and they performed these tasks in environments with people present. Their functional skills were depicted as being so expert that they could be safely interspersed with people, doing the tasks with no accommodation in tools, terrain, or even technique.

This chapter describes the research activities that are currently being conducted in humanoid labs in Japan, Korea, the United States, and Europe. Humanoid robotics, beyond science fiction, began 30 years ago, with increased momentum in the last 10 years. In this chapter, we first discuss definitions for what makes a system humanoid, then document the state of the art in these defined characteristics. We end with a brief discussion of application domains, and the relative momentum found in the United States, Japan, Korea, and Europe.

Fig. 4.1. Čapek Paris Production, 1924; Asimov, Will Smith, *I Robot,* 2004.

4.2. Definitions of the Humanoid System

4.2.1. *Form and function*

Humanoids have been played by human actors in the movies, but are quickly being replaced by computer graphics. What remains a constant is that they work around humans safely (or intentionally not), doing tasks originally done by humans, in an urban environment and with tools designed for humans (Fig. 4.2).

As computer technologies free the media from the use of human actors, the forms of their fictional robots open up to include multiple limbs and the introduction of wheels. This trend may be instructive to the engineers designing real robots, and is being exploited, as will be shown later in

Fig. 4.2. Star Wars Episode II WA-7 Waitress robot, and Star Wars Episode III General Grievous.

this chapter. So the definition of the humanoid, while superficially in form, should be anchored by function. The human jobs of waitresses and generals are distinguished by their functions. Abilities to roll, or fight with multiple limbs, are enhancements that make these fictional robots perform with superhuman skill, but the jobs are nonetheless human. And yet a machine that does high-speed, repetitive tasks in a completely nonanthropomorphic manner, such as a printing press, is not considered humanoid.

So there is a tension in the definition of the humanoid robot, as we try to balance form and function. The following definition is proposed as a harmony of both:

Humanoids are machines that have the form or function of humans.

The easy cases of machines that have both human form and function are rare today. The speculation of science fiction indicates this will change.

4.2.2. *How are humanoids built?*

Modern humanoids have major subsystems that can best be defined as their lower and upper bodies. The lower bodies are legs, wheels, or tracks that provide locomotion for propelling the upper body through a workspace. The upper bodies are arms, hands, and heads, able to interact with the environment and perform work. The junction of these segments is a torso, which typically carries energy storage and computers for control (Fig. 4.3).

During the study team's review of labs active in humanoid research, many examples of each subsystem were found. Many humanoids had one of the above elements missing. Most labs were focused on a single subsystem, where their work was quite excellent. Eye–hand coordination and bipedal locomotion were the most common combinations of subsystems, where noncritical subsystems were omitted to allow the researchers to focus. There were few prototypes built with a full complement of upper and lower body subsystems, but these were excellent, expensive, and best known.

4.3. Current Challenges in Humanoids

4.3.1. *Design, packaging, and power*

There is a high cost of entry into the humanoid research domain. With few or no commercial products, the vast majority of research platforms were built in-house. The immature nature of these systems makes copying

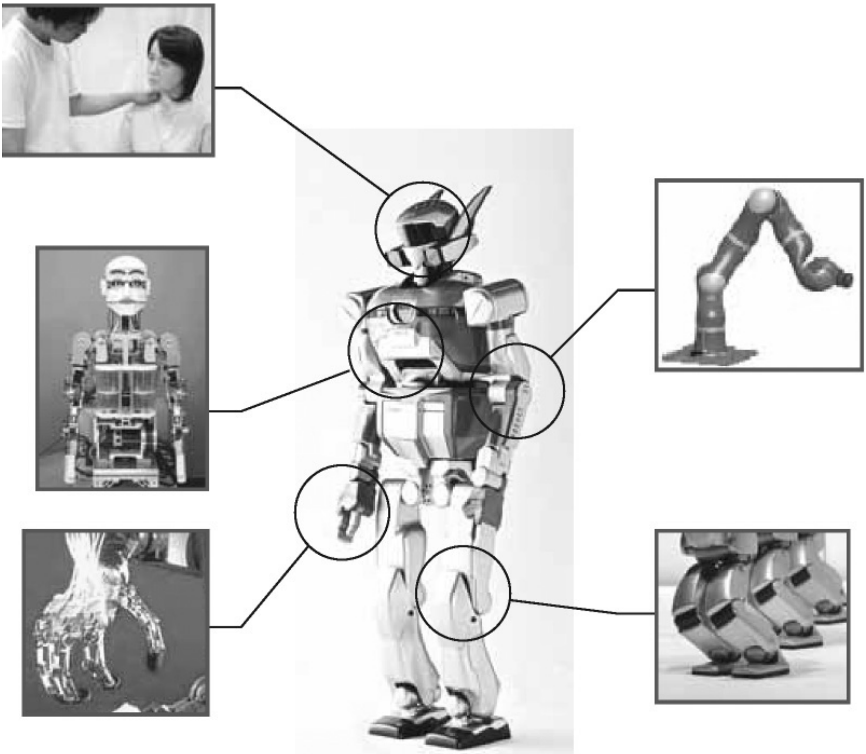

Fig. 4.3. Gross anatomy of the humanoid — heads, torsos, arms, hands, and legs.

them for use by other researchers risky, as these secondary adoption groups will not have the knowledge needed to maintain or evolve them. This will change as packaging and power challenges are overcome by design and the maturation of component technologies. This integrated design work is led by corporate teams, such as Honda, Toyota, and Sony, government/corporate teams such as National Institute of Advanced Industrial Science and Technology in Tsukuba (AIST), Korea Advanced Institute of Science and Technology (KAIST), National Aeronautics and Space Administration (NASA), and the German space agency Deutschen Zentrum für Luft- und Raumfahrt (DLR), and university-led teams with long traditions in mechatronics such as Waseda, Massachusetts Institute of Technology (MIT), and Technical University Munich (TUM) (Fig. 4.4).

Component technology advances have come from beyond the robotics discipline, but these have had a dramatic impact on humanoid design. The

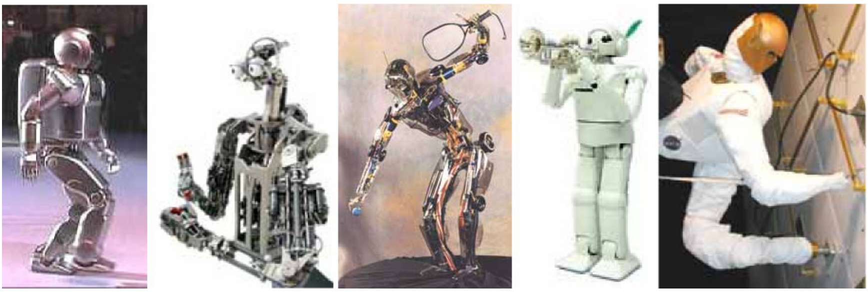

Fig. 4.4. Humanoids from Honda, MIT, Sarcos, Toyota, and NASA.

development of small, power-efficient computers have made much of the modern robot possible. Humanoids have needed more than computation. Arm and leg embodiment have required torque and power densities that were enabled by lightweight direct current (DC) motors and geared speed reducers. In particular, DC brushless motors and harmonic drives have provided the highest torque densities in electromechanical systems. These high-power limbs have been further made possible by the evolution of modern batteries, able to make these systems self-contained for brief periods of duty. In particular, lithium batteries have enabled robots to carry their own power supplies for locomotion and upper body work. New research continues in hydraulic systems (Sarcos) and low-pressure fluid power (Karlsruhe).

These advanced computers, drive trains, and batteries were not developed by roboticists, but were eagerly adopted. Modern laptops, cell phones, and automobiles have driven these component markets with their large consumer bases. The fact that corporations now producing humanoids include Honda, Toyota and Sony is not a coincidence.

4.3.2. *Bipedal walking*

The majority of the biped walking systems are humanoid in form, and use the zero moment point (ZMP) algorithm.[1,2] In this algorithm, the tipping point of the system is managed forward or backwards to walk (Fig. 4.5).

Many of the most famous humanoids have pioneered the implementation of the ZMP algorithm. The robots at AIST Tsukuba and AIST Waterfront have used wheeled gantries as a safe test bed for developing

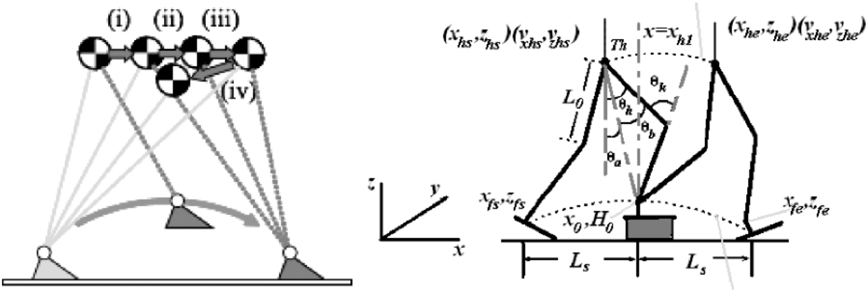

Fig. 4.5. ZMP mechanics.

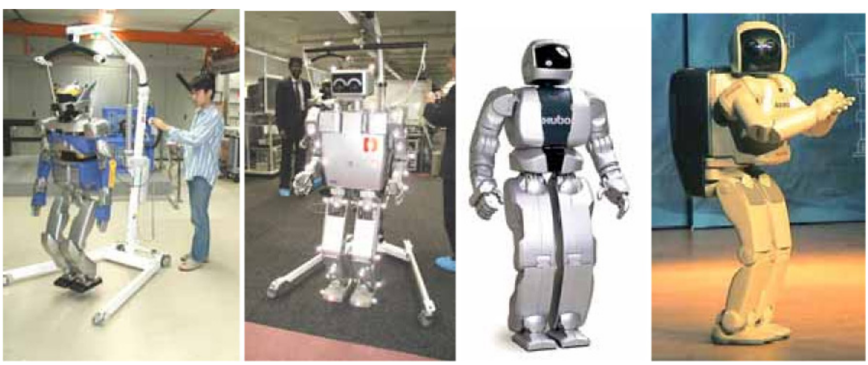

Fig. 4.6. ZMP walkers at AIST Tsukuba, AIST Waterfront, KAIST, and Honda.

and refining the ZMP walking systems. The Honda systems have many generations of success (Fig. 4.6).

A more dynamic form of walking has been postulated,[3,4] and is now being attempted in highly integrated humanoid systems at Waseda and TUM. These systems use the upper body, or additional degrees of freedom, to manage the vertical component of their center of gravity. This form of walking is observable from a distance, as the robot does not need to walk with a "crouched gait." As a result, the walking is becoming known as "straight leg walking." The Waseda design uses a lateral hip joint to "rock" the hips, keeping the torso center of gravity moving in a smooth and horizontal line. The TUM design uses substantial mass on the upper limbs to counter balance the lower body motion, as well as additional leg joints (Fig. 4.7).

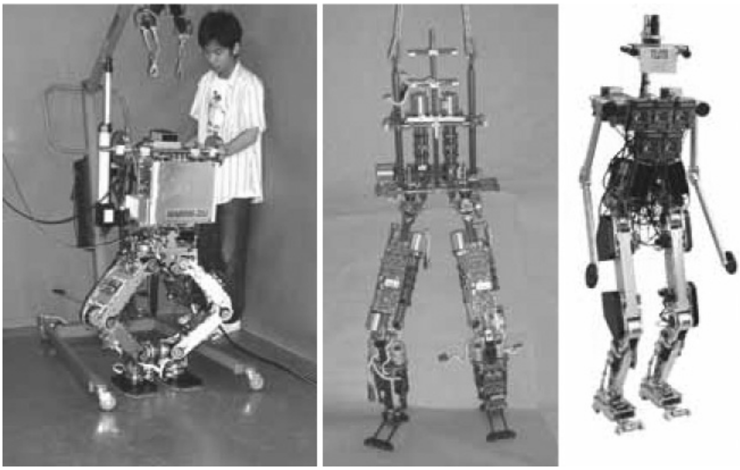

Fig. 4.7. Dynamic Walkers at Waseda, MIT, and TUM.

4.3.3. *Wheeled lower bodies*

Several labs are building new forms of lower bodies that use wheels for locomotion. These systems typically have small footprints, to allow their upper bodies to "overhang" the lower body and allow for interaction with the environment. Examples include statically stable wheeled bases, and dynamic balancing systems like a Segway. Three examples are shown in Fig. 4.8

Fig. 4.8. Dynamic balancing wheeled humanoids at NASA, Toyota, and MIT.

4.3.4. *Dexterous limbs*

The research in locomotion and navigation of mobile robots has outrun the research in dexterous manipulation. Twenty years ago, the intelligent robotics community was just forming, and there was little consensus on approaches or architectures for what we now call navigation of mobile robots. Today, this domain has greatly matured, with numerous architectures commercially available to upgrade a wheeled vehicle to a sophisticated thinking machine. But the class of interaction that such a machine can have with its environment is limited to perception, where physical contact is intentionally avoided. This technology is now being applied to the legged and wheeled systems previously described.

As complex as these locomotion functions are, the sophistication of their interaction with the environment pales in comparison to using a tool to modify the world. Understanding the world well enough to know that a change is needed and/or possible, and then forming a plan to use a known tool to implement that change is an infinitely open challenge. Emerging theories on the role of tool use and weapon-making in the evolution of human cognition bode poorly for any robotics team that intends to quickly automate a humanoid as a competent tool user.

The existing simultaneous localization and mapping (SLAM) techniques will be essential for this effort, but must be combined with symbolic, relational, associative, and generally qualitative representations of knowledge to complete the picture. A robot sees a box with rough texture on its top surface. A human looks at the same scene, and sees a workbench strewn with hand tools that bring back a lifetime of memories. Bringing the robot to the same perception level as the human tool user is the second most likely achievable step, making a humanoid equivalent to a human's apprentice. The first step is to have dexterous hands that have even crude manipulation abilities (Fig 4.9).

Having hands will be essential in the early advancement of this research, since the learning and association of knowledge with objects will be done in the robot's own terms, with the way a tool feels when grasped in sensorimotor space. Key advances in dexterous hands include tactile skins, finger tip load sensing, tendon drive trains, miniature gearing, embedded avionics, and very recent work in low-pressure fluid power systems (Fig. 4.10). The fundamental research in biologically inspired actuators will likely transform the nature of this domain in the next 10–15 years.

Hands must be well-sized and integrated with their arms for best effect. One of the challenges that has made entry into this research domain

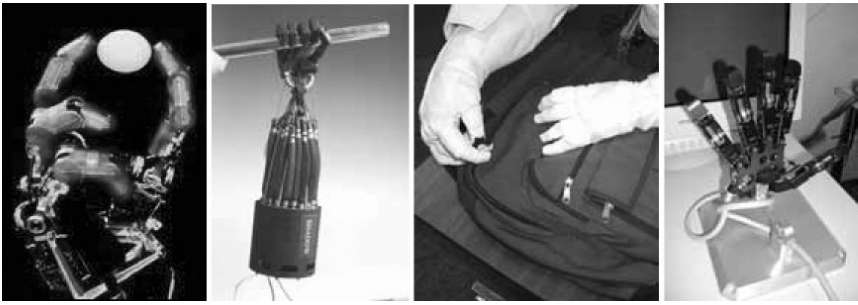

Fig. 4.9. Dexterous hands at DLR, Shadow, NASA, and Tsukuba.

Fig. 4.10. Dexterous arms at DLR, NASA, and UMASS.

difficult is the small number of arm options available to the researcher, and the corresponding high cost of such systems. There are few small, human-scale arms able to be integrated for mobile applications, and most of these have low strength. Most humanoid arms are low quality, have fewer than six degree-of-freedom (DOF)-positioning systems with backlash and little power that appear almost as cosmetic appendages. The AIST HRP2 system is one of the few bipedal humanoids that has strong arms, and the limbs can be used to help the robot get up from a prone position (Fig. 4.11).

The best arms in the field have integrated torque sensing, and terminal force–torque sensors that allow for smooth and fine force control. The arms have 7+ DOF, and are able to handle payloads in the order of 5 kg or higher. They have embedded avionics allowing for dense packaging and modular application.

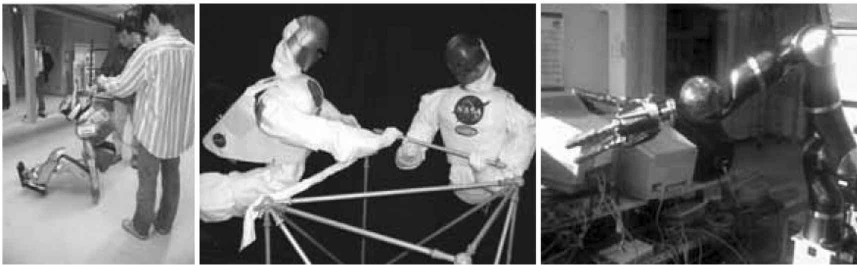

Fig. 4.11. Strong dexterous arms at AIST Tsukuba, NASA, and DLR.

4.3.5. *Mobile manipulation*

Mobile manipulation is achieved when combining a lower body able to position itself with ease, and a dexterous upper body able to perform value-added work. While this combination is not necessarily humanoid, people are ideal examples of mobile manipulators. Active balancing bases or legs have small footprints, allowing their upper limbs to get close to the environment, while maneuvering in tight urban environments. Dual and dexterous upper limbs offer primate-like workspace and grasping abilities that can work with the interfaces and objects in those same urban environments. This class of machine can redistribute force and position control duties from lower bodies to upper bodies, where differences in drive trains and sensors offer complementary capabilities. Pioneering work in this discipline was done at Stanford, and the work continues at the University of Massachusetts (UMASS), Carnegie-Mellon University (CMU), and the DLR (Fig. 4.12).

4.3.6. *Human–robot interaction*

Where humanoids are a subset of mobile manipulation, they are also an important part of the ongoing research in human–robot interaction (HRI). There are many aspects of HRI that have little to do with human function or form on the robot side of the interaction, but there are strong advantages to humanoid systems in human interaction. The large public response to humanoids has included a strong educational outreach program on the part of Honda, Sony, and national labs. The connection to science fiction may have a role in this phenomenon (Fig. 4.13).

But there is also a thrust in the science of interaction, where social and psychological factors are at play. Research at Osaka University and other sites is exploring the "Uncanny Valley" first postulated by Mori in

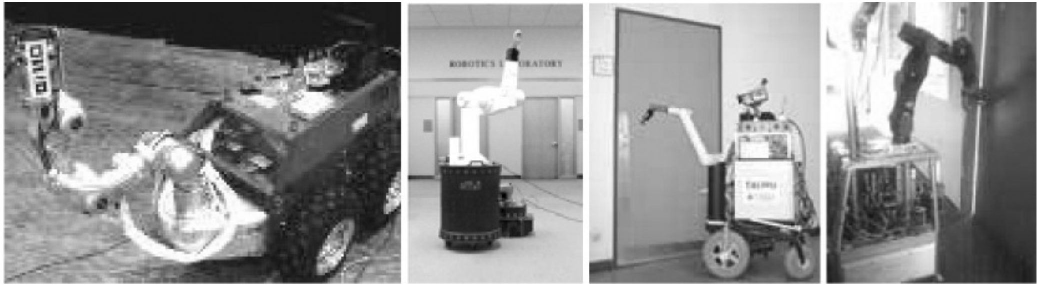

Fig. 4.12. Mobile manipulation at CMU, Stanford, RWTH Aachen, and the DLR.

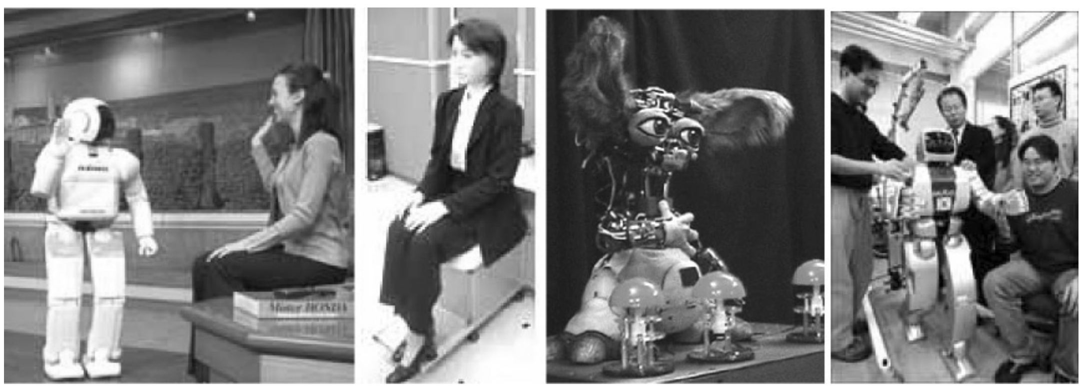

Fig. 4.13. Human–robot interaction at Honda, Osaka Univ., MIT, and KAIST.

Fig. 4.14. The Uncanny Valley, and robots at Osaka University.

1970, where the degree of human-like form and motion in human faces[5] are found to have a local minimum in reaction. There is a growing but still young body of research in this arena, with many active workshops in HRI, android science, and views on the Uncanny Valley in the past several years (Fig. 4.14).

This list shows that humanoid robotics has matured to an engineering discipline, where design issues of packaging, actuator technology, and power/energy considerations are paramount. Conversely, the fact that those few prototypes exist makes access to them problematic, leaving researchers without design and engineering skills disengaged. A maturing field with few commercial options is unusual.

4.4. Key Technologies

Key technologies for humanoid robotics include the following:

(a) Improved design and packaging of systems with new component technologies that are smaller, stronger, faster, and offer better resolution and accuracy.
(b) Dense and powerful energy storage for longer endurance, heavy lifting, and speed.
(c) Improved actuators that have higher power densities, including auxiliary subsystems such as power supplies, signal conditioning, drive trains, and cabling.
(d) Improved speed reduction and mechanisms for transferring power to the humanoid's extremities. Improved force control for whole body dynamics.
(e) Better tactile skins for sensing contact, touch, and proximity to objects in the environment.

(f) Advanced navigation that perceives and selects footfalls with 1-cm scale accuracy at high body speed. Vestibular systems for coordinating upper limbs and head-mounted sensors on dynamic bodies. Dexterous feet for dynamic running and jumping.
(g) Dexterous hands for tool use and handling of general objects.

4.5. Fundamental Research Challenges

A fully capable and embodied humanoid makes a strong research test bed. Such a system can serve to answer the following questions:

- What are the best leg, spine, and upper limb arrangements, in both mechanisms and sensors, to enable energy-efficient walking?
- How should robots represent knowledge about objects perceived, avoided, and handled in the environment?
- What are the algorithms for using upper body momentum management in driving lower body legs and wheeled balancers?
- How can a mobile manipulation robot place its body to facilitate inspection and manipulation in a complex workspace, where a small footprint and high reach requirements collide?
- How should vision/laser-based perception be combined with tactile/haptic perception to grasp objects?
- What roles do motion and appearance have in making people accept and work with robots?
- How can people interact with humanoids to form effective and safe teams?

4.6. Regions Visited by the Assessment Team

The study team visited Japan, Korea, Spain, France, Germany, Italy, Britain, Switzerland, and Sweden, in addition to the review of labs in the United States. The following map shows the distribution of humanoid systems found in research labs during the review (Fig. 4.15).

4.7. Observations, Applications, and Conclusions

4.7.1. *Quantitative observations*

Japan has the largest population of humanoid systems. The study team visited AIST Tsukuba, AIST Waterfront, Tsukuba University, Tokyo

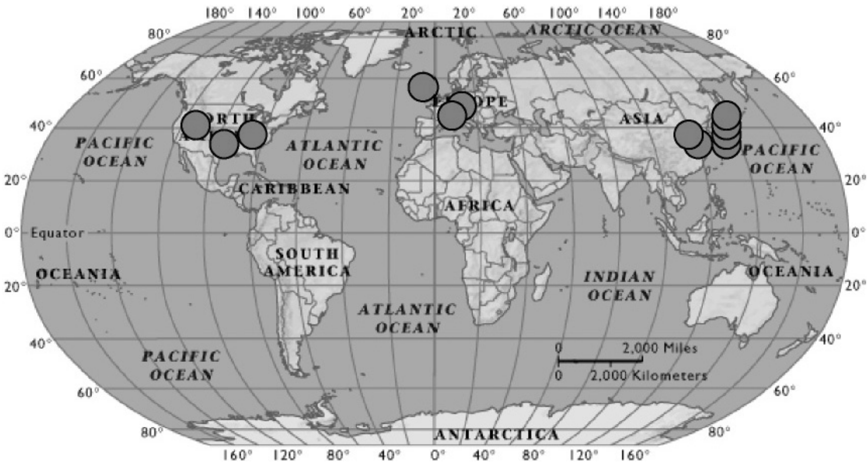

Fig. 4.15. Locations of humanoid systems reviewed.

University, Osaka University, Fujitsu, multiple labs at Waseda, Sony, and Advanced Telecommunications Research Institute (ATR). The field of humanoid robotics was founded in Japan with the work of Ichiro Kato and the Wabot project at Waseda University in 1970, and Waseda continues this tradition today with a strong program producing more humanoid graduate degrees than any other school (Fig. 4.16).

The study team was not invited to Honda or Toyota facilities. This was likely due to proprietary concerns. However, the impact of Honda's history is well understood in the community. The quiet development of the E-series humanoids, and then the public release of the P series in 1997, was a major turning point in humanoid history. The evolutionary approach was

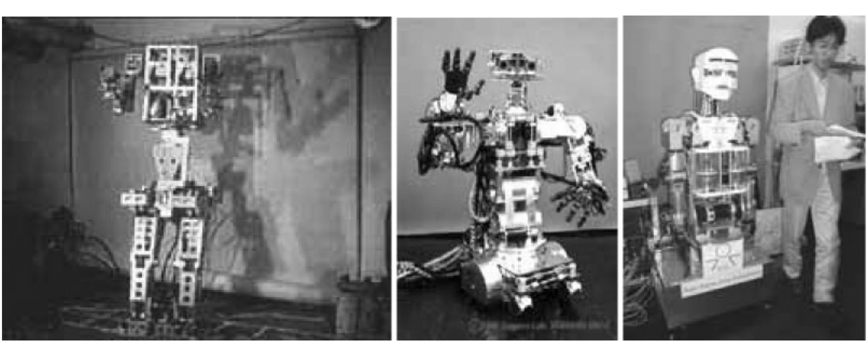

Fig. 4.16. Humanoid systems at Waseda, past and present.

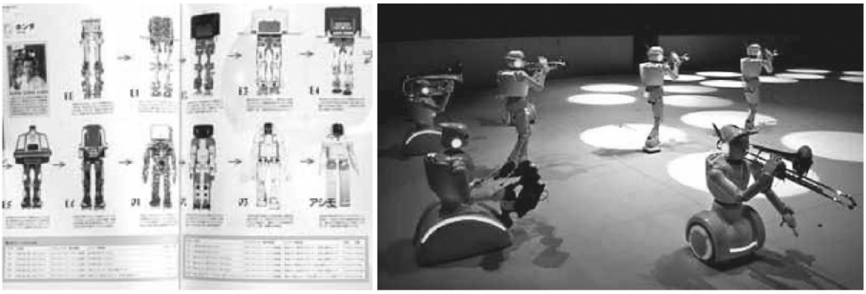

Fig. 4.17. Honda and Toyota humanoids.

remarkably organized and strategically guided. Work at Toyota at the time of this study indicated a similar interest and desire to build multiple forms of humanoids (Fig. 4.17).

The prototypes at AIST Waterfront and AIST Tsukuba are the class of the field (Fig. 4.18). These systems have taken a novel evolutionary path, developing the HRP-1 and HRP-2 systems with subgenerations that were legs only, then with arms, then reintegrated as the HRP final units. The study team saw HRP-2 unit #01 at AIST Tsukuba, and unit #12 at AIST Waterfront. Unit #12 was substantially upgraded, with new stereo vision in the head, and a new, waterproof hand on a dexterous wrist. Both systems were fully operational, and demonstrated excellent performance. The robots were built as a partnership between the Japanese government (Ministry of Economy, Trade and Industry (METI)) and industry (Kawada Industries), with university groups now using the robots as testbeds for research.

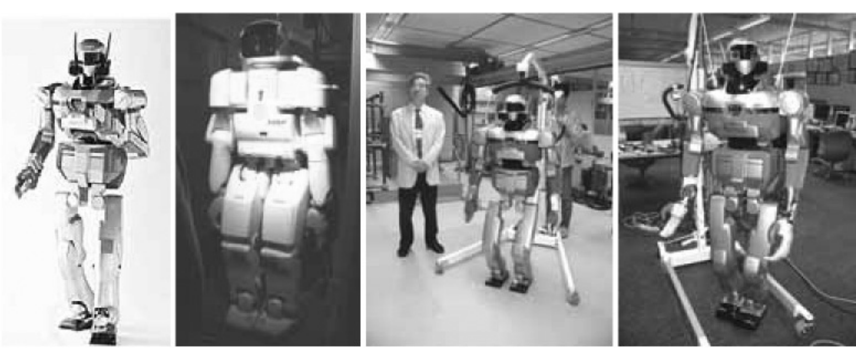

Fig. 4.18. AIST humanoids.

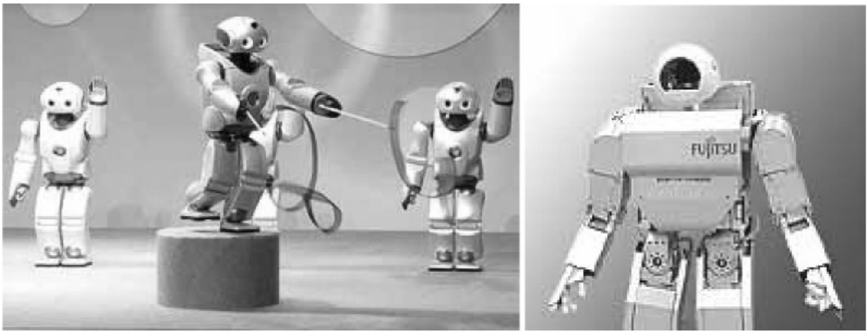

Fig. 4.19. Sony and Fujitsu humanoids.

Both Sony and Fujitsu were very gracious in hosting our study team, and presented business plans for their products (while Sony robots are no longer commercially available, they are included here because of their engineering and scientific innovations) (Fig. 4.19). Both have smaller scale humanoid products that appear commercially viable. Their work is well known, and follows the same evolutionary path as the larger humanoids developed at Waseda, AIST, and Honda. These systems have high strength to weight ratios, and are tolerant of falls. The Sony system has a well-developed visual perception, human interaction, and eye–hand coordination capabilities paired with a fast, power-efficient, and well-packaged torso and set of limbs. The Fujitsu system has a large limb range of motion, allowing it to get up from the floor, and stand on a single leg.

The study team was impressed by the Korean population of humanoid systems, many of which were in quiet development during our visit. These systems have since been released for public review. The designs at KAIST and Korean Institute of Science and Technology (KIST) were particularly far along at the time of the site visits in October 2004, and were shown to the public in 2005 (Fig. 4.20). These robots demonstrate that Korea is a power to be reckoned within humanoid research, and they show an acceleration of capability and skill. One important note on both systems is their attention to both legs and hands. Both robots have multi-fingered, multi-DOF end-effectors able to grasp and hold objects of modest scale. The humanoid system at the Pohang Science and Technology University (POSTECH) has not been made public, but represents a novel approach to leg mechanisms that is important, as many of these systems have made only minor changes to the Honda anatomy. This lower body was shown to the

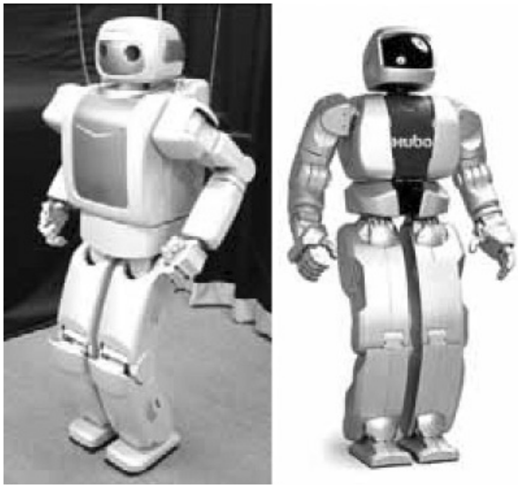

Fig. 4.20. KIST (NBH-1) and KAIST (KHR-3) humanoids.

study team, and is being developed by a team with a deep understanding of dynamics and control that has informed their design work.

4.7.2. *Qualitative observations*

Japan has the strongest program in the world, but Korea has the best first derivative, making major strides in the past 5 years. Both countries seem to have a healthy mix of government labs, corporations, and universities in teams. Asia is leading the world in biped locomotion, and business development of humanoids.

The United States leads in algorithm development for the control of limbs, but with few testbeds this theory is not being proven, and is being rediscovered in Asia where it is tested and refined. The use leads in upper body applications, with dexterous manipulation, grasping, and eye–hand coordination skills. The United States has the lowest first derivative, with few active programs, and will soon to be overtaken in these final areas of dominance.

Like the United States, the European work has been lacking a larger scale organization, plan, or strategy. Also like the United States, the European community has pockets of excellent work, such as the novel fluid-powered hands in Karlsruhe, the smooth walking at TUM, and the beautifully engineered dexterous limbs at DLR.

4.7.3. *Applications*

In every lab visited, the discussion turned to the question, "What is the killer app?" for humanoids. This slang phrase was used in all countries. In Japan, the work was motivated by support of the "Silver Society," a term used in several labs to describe the technology needs of an aging population. The humanoid form and function was proposed as ideal for this market, with Japan's cultural tendency to embrace robots and technology in general producing a "pull." Since our study tour, Waseda has demonstrated lifting a person from a bed, as would be needed in a nursing home.

In Korea, we were regularly welcomed with a description of the national programs for technology, where robotics was selected as one of the key technologies for advancing their national gross national product (GNP). This top–down strategy, and national goal, was unique in the world. Korean researchers were deeply interested in ubiquitous systems, and were looking at humanoids as a component of urban technology designed for service tasks.

A brief listing of applications being pursued by humanoid researchers includes:

- *Military & security* Search and rescue, mine/improvised explosive device (IED) handling, and direct weapons use.
- *Medical* Search and rescue, patient transfer, nursing, elder care, and friendship.
- *Home service* Cleaning, food preparation, shopping, inventory, and home security.
- *Space* Working safely with space-walking astronauts and caretakers between crews.
- *Dangerous jobs* Operating construction equipment, handling cargo, firefighting, and security.
- *Manufacturing* Small parts assembly, inventory control, delivery, and customer support.

4.8. Conclusions

Humanoids are now being developed in Asia, the United States, and Europe, though a clear business plan has yet to emerge. The early systems are expensive and brittle, being used as testbeds to develop walking, manipulation, and human-interaction capabilities. As these skills mature, and are coupled with better engineered machines, the potential is unlimited.

The only questions are: when will these future humanoids become viable, and who will make the first "Model T"-equivalent system.

The lack of a clear business plan will not limit interest and investment in humanoids for two reasons. First, there is an emotional and cultural drive toward building machines that look and work like humans. The Japanese eager embrace of robot technology is equaled only by the US interest in the dangers of humanoids depicted in our science fiction. The Korean focus on humanoids as a part of a highly wired and ubiquitous urban landscape is a third view, with building-integrated systems gradually yielding to mobile, human-like robots that can be upgraded more quickly than a home. Many of the current prototypes are viewed as "mascots," as symbols of the future and their developer's quest to lead. Wherever humanoids go, they will evoke strong emotions and opinions, from love to hate. But the drive to build them is strong, and not motivated by economics in the near term.

There is a second reason for the inevitability of humanoids. They encompass a large set of robotics domains. The archetypical humanoid, though not yet realized, will be able to locomote through most terrain, as humans do. They will be able to perform value added work, building with hands that take inspiration from human limbs, handling objects, and using tools with dexterity. They will slip into our society seamlessly, but over time as the technology matures, filling roles not well suited to humans. They will fit into our buildings, they will walk through our society, and they will manipulate the objects of modern life. Humanoids represent a massively complete system design, combining the research of cognition with navigation, perception, and manipulation. The completeness of this form yields a spectrum of functions that cannot be ignored. Most researchers would be able to use a humanoid platform today for their research, if one existed that they could afford.

The humanoid is where the robot began, in the imagination of the science fiction writers of the 20th century. Now it seems to be the engineers turn. The 21st century will see humanoids leave the pages of fiction and step, roll or run into our world.

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Chapter 5

INDUSTRIAL, PERSONAL, AND SERVICE ROBOTS

5.1. Introduction

Robots can be classified into different categories depending on their function and the market needs they are designed for. We identify two major classes of robots, *industrial robots* and *service robots.* The latter class of robots can be divided into *personal* service robots and *professional* service robots depending on their function and use.

According to the Robotic Industries Association, an *industrial robot* is an automatically controlled, reprogrammable, multipurpose manipulator, programmable in three or more axes which may be either fixed in place or mobile for use in industrial automation applications. The first industrial robot, manufactured by Unimate, was installed by General Motors in 1961. Thus, industrial robots have been around for over four decades.

According to the International Federation of Robotics, another professional organization, a *service robot* is a robot which operates partially or fully autonomously to provide services useful to the well-being of humans and equipment, excluding manufacturing operations.

Personal robots are service robots that educate, assist, or entertain at home. These include domestic robots that may perform daily chores, assistive robots (for people with disabilities), and robots that can serve as companions or pets for entertainment; examples are shown in Fig. 5.1.

Robots find applications in the so-called "4D tasks," tasks that are dangerous, dull, dirty, or dumb. An example of a task that may be too *dangerous* for humans to perform is the disposal of unexploded ordinance. Many industrial automation tasks like assembly tasks are repetitive and tasks like painting are *dirty.* Robots, sometimes, can easily perform these tasks. Human workers often do not like tasks that do not require intelligence or exercise any decision-making skills. Many of these *dumb tasks* like vacuum cleaning or loading packages onto pallets can be executed perfectly

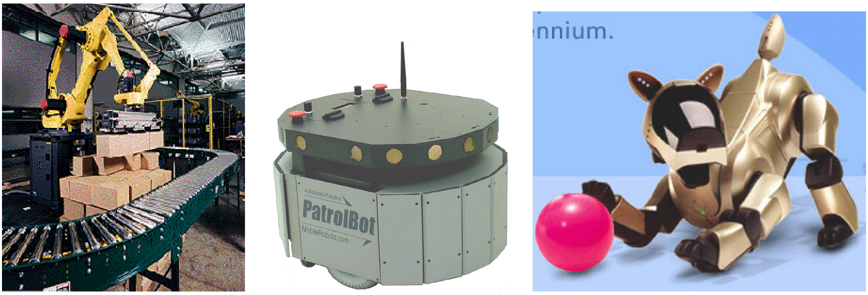

Fig. 5.1. Examples of robots. A Fanuc industrial robot (left), a service robot used for security made by Mobile Robotics (center), and a personal entertainment robot made by Sony (right).

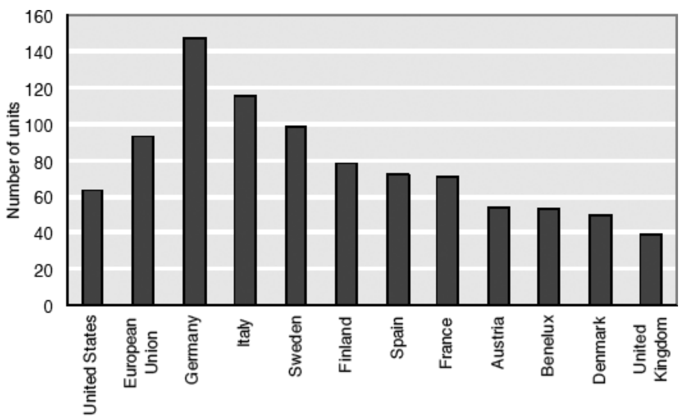

Fig. 5.2. Number of industrial robots for every 10,000 human workers in the US and Europe.
Source: World Robotics 2004, United Nations Economic Commission for Europe (UNECE), 20 October 2004.

by robots with a degree of precision and reliability that humans may lack. As our population ages and the number of wage earners becomes a smaller fraction of our population, it is clear that robots have to fill the void in society. Industrial, and to a greater extent, service robots have the potential to fill this void in the coming years. The ratio of robot to human workers in the manufacturing industry in the US and Europe is seen in Fig. 5.2.

A second reason for the deployment of industrial robots is the trend toward small product volumes and an increase in product variety. As the volume of products being produced decreases, hard automation becomes a more expensive proposition and robotics is the only alternative to manual production.

5.2. Market Analysis and Trends

In 2004, industrial robots accounted for a $4 billion market with a growth rate of around 4%. Most of the current applications are either in material handling or in welding. Spot welding and painting operations in the automotive industry are almost exclusively performed by robots (Fig. 5.3).

The quality of industrial robots is improving, and the ratio of price to performance is falling. As Fig. 5.4 shows, while prices have fallen over

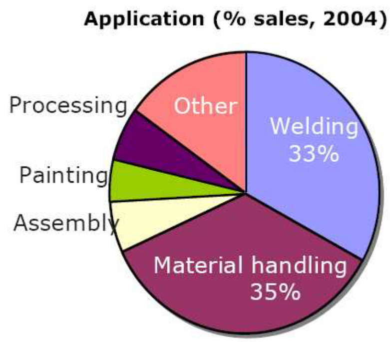

Fig. 5.3. Industrial Robot Sales (2004).
Source: World Robotics 2004, United Nations Economic Commission for Europe (UNECE), 20 October 2004.

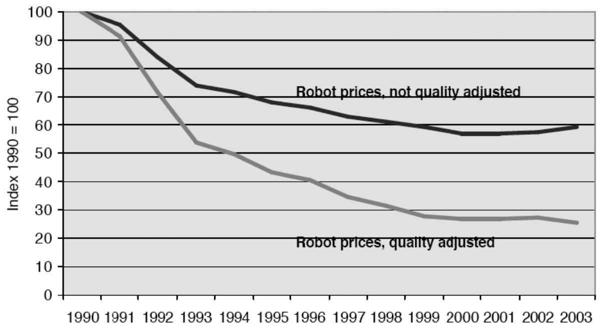

Fig. 5.4. Trends in robot price and performance.
Source: World Robotics 2004, United Nations Economic Commission for Europe (UNECE), 20 October 2004.

Table 5.1. Service robots industry: Number of units in operation in 2005 and their estimated value.

Category	No. units	Value ($ million)
Field (agriculture, forestry, mining)	885	117
Cleaning/maintenance	3370	68
Inspection	185	21
Construction, demolition	3030	195
Medical robotics	2440	352
Security, defense	1010	76
Underwater	4785	1467
Laboratory	3060	37
Others	2295	110
	21060	2443

Source: World Robotics 2004, United Nations Economic Commission for Europe (UNECE), 20 October 2004.

40% over the last 15 years, the accuracy and payload rating of robots have almost doubled in the same period.

According to the UNECE, there are over 20,000 professional service robots in use today, valued at an estimated $2.4 billion (see Table 5.1). If personal entertainment robots and domestic robots like vacuum cleaners are included, this number would be well over $3.5 billion. The UNECE estimates that the annual sales of service robots (both professional and personal) in 2005 will be around $5 billion.

5.3. State of the Art in Theory and Practice

Today industrial robots present a mature technology. They are capable of lifting hundreds of pounds of payload and positioning them with accuracy of a fraction of a millimeter. Sophisticated control algorithms are used to perform positioning tasks exceptionally well in structured environments.

Fanuc, the leading manufacturer of industrial robots, has an impressive array of industrial robot products ranging from CNC machines with 1 nm Cartesian resolution and 10^{-5} degrees angular resolution to robots with 450 kg payloads and 0.5 mm repeatability. Some of their robots include such features as collision detection, compliance control, and payload inertia/weight identification. The control software supports networking and continuous coordinated control of two arms. Force feedback is sometimes used for assembly tasks. Vision-guided fixturing and grasping are becoming commonplace as structured-lighting systems mature. Robots use vision to estimate the locations of parts to determine the exact trajectory and type of operation. However, the cost of the end-effector tooling still remains a large fraction of the total cost of the workcell. Typically, the end-effector cost is often around 25% of the cost of the industrial robot. Further, the cost of the robot is usually only around 40% of the cost of the entire workcell.

The nature of robotic workcells has changed since the early days of robotics. Instead of having a single robot synchronized with material handling equipment like conveyors, robots now work together in a co-operative fashion eliminating mechanized transfer devices. Human workers can be seen in closer proximity to robots and human–robot cooperation is closer to becoming a reality.

However, industrial robots still do not have the sensing, control, and decision-making capabilities that are required to operate in unstructured, 3D environments. Cost-effective, reliable force sensing for assembly still remains a challenge. Finally, we still lack the fundamental theory and algorithms for manipulation in unstructured environments and industrial robots currently lack dexterity in their end effectors and hands.

The service robotics industry has leveraged recent advances in mobility and perception and algorithmic advances that enable robots to localize in a two-dimensional map of the world, and map an unknown two-dimensional environment. Vacuum cleaning robots use very simple algorithms to map sensory inputs to control commands and cover a two-dimensional area while avoiding obstacles. Security robots are able to use sensory information to infer their position in a two-dimensional world and send back images of the environment to a remotely located human operator. Robots are able to provide logistics support in office and industrial environments by transporting materials (packages, medicines, or supplies) or by leading visitors through hallways. Remotely controlled and monitored robots are also able to enter hazardous or unpleasant environments. Examples include underwater remotely operated vehicles, pipe cleaning and inspection robots, and bomb disposal robots (see Fig. 5.5).

The challenges in service and personal robotics include all the challenges of industrial robotics. Dexterous manipulation and integration of force and vision sensing in support of manipulation are critical to the growth of this industry. In addition, mobility is a key challenge for service robotics. The current generation of robots is only able to operate in two-dimensional, even, indoor environments. Because service robots must be mobile, there are difficulties in designing robots that are capable of carrying their own power source. Further, operation in domestic environments imposes constraints on

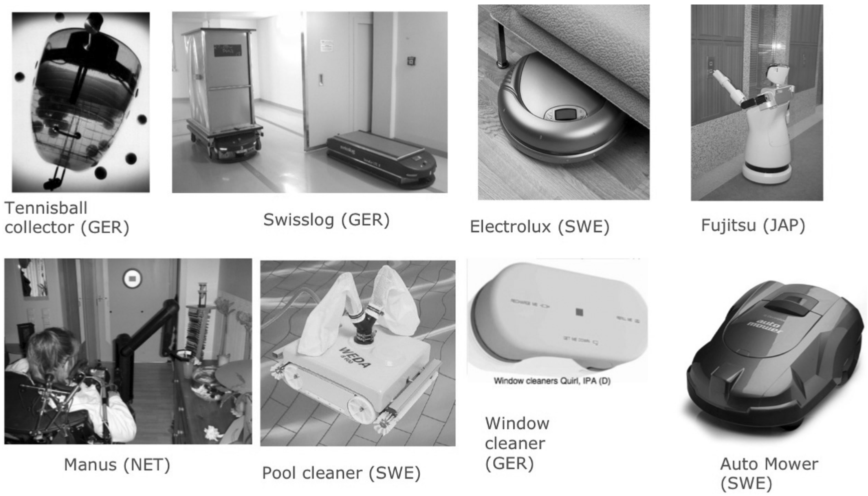

Fig. 5.5. Examples of Service robots.
Source: H. I. Christensen, EURON — the European Robotics Network. *IEEE Robotics Autom. Mag.* **12**(2) (2005) 10–13.

packaging. Finally, service robots, especially personal robots, will operate close to human users. Safety is extremely important. Since interaction with human users is very important in service robotics, it is clear that the industry needs to overcome significant challenges in human–robot interfaces.

5.4. International Assessment

5.4.1. *United States*

Most of the industrial robotics industry is based in Japan and Europe, despite the fact that the first industrial robots were manufactured in the United States. At one time, General Motors, Cincinnati Milacron, Westinghouse, and General Electric made robots. In 2005, only Adept, a San Jose-based company, was manufacturing industrial robots in the United States.

However, there are a number of small companies developing service robots in the United States. iRobot, Barrett Technology, and Mobile Robotics, companies in New England, are pioneering new technologies. Several million *Roomba* vacuum cleaners (made by iRobot) have been sold.

Fig. 5.6. The ABB pick-and-place robot capable of performing two pick-and-place operations per second.

iCreate, a new robot based on the *Roomba* platform, allows developers to create new behaviors for personal and service robotics.

5.4.2. *Europe*

The two big manufacturers of industrial robots in Europe are ABB and Kuka. Over 50% of ABB is focused on automation products, and industrial robots are a big part of their manufacturing automation with an annual revenue of $1.5 billon (Fig. 5.6.). ABB spends 5% of their revenues in R&D, with research centers all over the world. As in the automotive and other businesses, European companies outsource the manufacture of components (motors, sensors) unlike Japanese companies that emphasize vertical integration.

As in the United States, service robots are made by small companies, which include spin-offs launched from university research programs.

5.4.3. *Japan and Korea*

Fanuc is the leading manufacturer of industrial robots with products ranging from CNC machines with 1 nm Cartesian resolution and 10^{-5} degrees angular resolution to robots with 450 kg payloads and 0.5 mm repeatability. Fanuc has 17% of the industrial robotics market in Japan, 16% in Europe, and 20% in North America. After Fanuc come Kawasaki and Yaskawa. Fanuc is also the leading manufacturer of CNC machines with Siemens as its closest competitor.

Fig. 5.7. Personal robots from the Japanese industry.

Unlike the United States and Europe, the service robotics industry includes big companies like Toyota, Fujitsu, and Honda (Fig. 5.7). At the time of the writing of this chapter (2005), Sony had a big presence in this industry. While Sony robots are no longer manufactured, their technology has had a strong influence on entertainment robots worldwide. The service robotics industry is largely driven by the perceived need for entertainment robots and domestic companions and assistants.

5.4.4. *Australia*

Australia is a leader in field robotics. The University of Sydney's Australian Center for Field Robotics has developed many commercial robots for cargo handling and mining and operates a number of demonstration vehicles. They have also pioneered the use of novel sensors like millimeter-wave

Fig. 5.8. Autonomous straddle carriers in operation at the Port of Brisbane (left) and an autonomous mining haul truck (right).

radar for field applications and new algorithms for state estimation and localization. See Figure 5.8.

5.5. International Comparisons

5.5.1. *Relative strengths*

Even though industrial robots are mostly made in Europe and Japan, they have found acceptance in industry all around the world. Figure 5.9 shows that a large majority of industrial robots (around 40%) are operating in Japan, but this number was around 60% in 1990. It is clear from Fig. 5.10 that the demand for industrial robots is widespread, with Asia leading the other regions. In Fig. 5.11, it is clear that the increase in Japanese demand is comparable to the increase in Europe and North America. Above average growth rate is seen in South Korea and Taiwan (ROC).

In contrast to industrial robotics, the service robotics industry is more uniformly divided across the world. There are many small service robotics companies in the United States, iRobot Corporation, Mobile Robotics, and Evolution Robotics to name a few. Similarly, in Europe, commercial products include rehabilitation robots on wheelchairs, tennisball collectors, pool cleaners, window cleaners, and lawn mowers. The Japanese and Korean robotics industries have developed many personal robots, some for

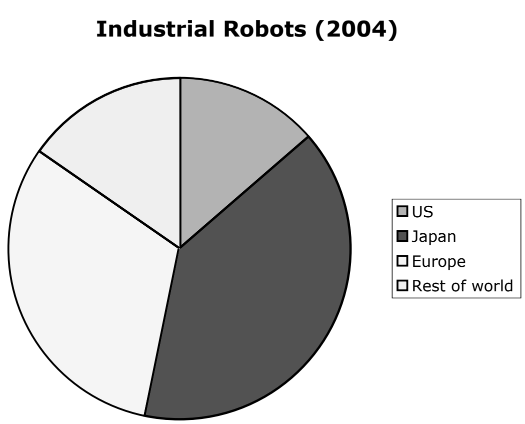

Fig. 5.9. Industrial robots installed world wide.
Source: World Robotics 2004, United Nations Economic Commission for Europe (UNECE), 20 October 2004.

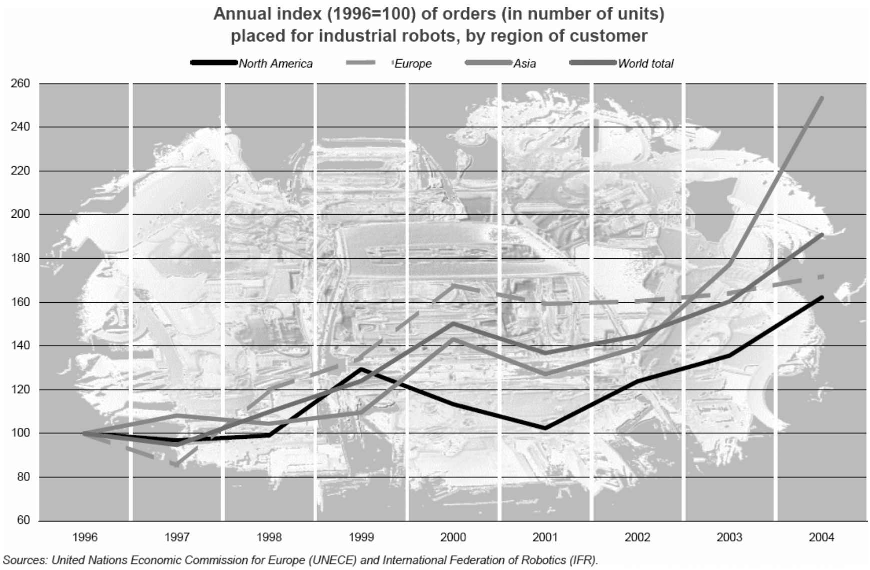

Fig. 5.10. Annual index of orders for industrial robots by region.
Source: World Robotics 2004, United Nations Economic Commission for Europe (UNECE), 20 October 2004.

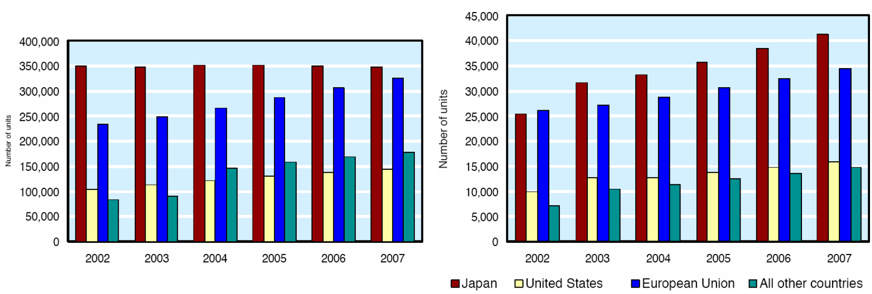

Fig. 5.11. Number of installed industrial robots (left) and number of robots installed annually (right).
Source: World Robotics 2004, United Nations Economic Commission for Europe (UNECE), 20 October 2004.

entertainment and others for domestic assistance. There is a noticeable difference in the emphasis on humanoid robots in Japan and Korea, directly related to their interests in domestic companions, while the United States lags behind in this area with only a handful of humanoid projects and virtually no commercial products.

5.5.2. *Qualitative observations*

The most striking difference in research and development programs in robotics across the continents can be seen in the level of coordination and collaboration between government, academia, and industry. There is a concerted effort to understand the big picture, and to develop and implement a national agenda in both Japan and Korea. In Japan, the national strategy for creating new industries includes robotics as one of the seven areas of emphasis. In Korea, robotics has been listed as one of the 10 next generation growth engines. The Humanoid Project in Japan was an example of a national project involving many industrial, government, and academic research laboratories. Similarly, in Europe there are many EU projects across the continent that bring together synergistic efforts and expertise in industry and academia with the goal of developing robotics industry.[1] The European Robotics Platform (EUROP) is a major new research initiative in Europe driven by a joint academia/industry initiative. It was recently approved by the European commission for funding from 2007–2013 at the level of $100 million (http://www.cas.kth.se/europ/EUROP). There are no such projects in the United States, and there is no national strategy for developing robotics in the United States.

Second, it is also clear that Japan, Korea, and European countries have professional associations and national networks. The Japan Robot Association and the EURON, European Union Robotics Network (www.euron.org), are examples of national networks. There are no robotics organizations or networks in the United States, perhaps because of the lack of a significant industry representation, which will be discussed next.

The third observation is that the big companies in robotics are presently in Japan, Sweden, and Italy. Robotics companies have a bigger presence in Europe and Asia. This includes small companies and start-ups. Although the United States is known for its entrepreneurial culture, there appear to be more start-ups and spin-offs from research labs in the Europe than that in the United States.

Finally, it is worth remarking on the technical strengths and emphasis in the different continents. While the US-led research and development efforts have emphasized wheeled mobility, perception, and autonomy in navigation, the efforts elsewhere have addressed legged mobility, and perception and autonomy in support of other tasks such as manipulation tasks. Human–robot interaction is an area of importance that needs a lot of attention. The United States seems to have the lead in this area. The fundamental driver for robotics in the United States comes from military programs and Department of Defense interests. In Europe, Japan, and Korea, these drivers are social and economic factors. Robotics is viewed to be an important industry, while Asians have identified an important role for robots in an aging society.

5.6. Future Challenges

There are many unsolved problems and fundamental challenges for robotics. At a very high level, challenges for industrial and service robotics can be categorized in the following areas.

- *Manipulation and physical interaction with the real world.* We need concerted modeling and control efforts together with the development of good hardware to make arms and hands that can perform anything but the simplest of pick and place operations that are prevalent in industry.
- *Perception for unstructured environments.* Most industrial robots have fairly primitive sensing, and perception is limited to 2D structured environments. A robot's ability to perceive 3D environments and take actions currently is limited to very simple tasks.
- *Safety for operation near humans.* Personal robots will have to operate in the vicinity of humans. Even in industry, there are many applications now where robots and humans augment each others' skills. While industrial robotics has had a history of cordoning off robots and not allowing humans to enter robotic work areas, this culture is changing. This means robots will need to be made safe. This in turn leads to both hardware and software challenges.
- *Human–Robot interaction.* Robotics applications call for humans operating in proximity to robots and with robots as assistants to humans. The relevant understanding of human–machine interaction mostly comes from studies of human–computer interaction. Clearly, robots that perform physical work and operate in a 3D world are more than computers and there is a definite need to develop this field further.
- *Networks of robots, sensors, and users.* Most current applications see a robot operating with a human user or with a collection of sensors in a very structured environment in a predetermined manner. With the emergence of networked, embedded systems and the increased presence of networks in homes and in factories, robots will need to work with

other robots, learn from different types of sensors, and interact with different human users depending on their immediate environment. This is particularly true for mobile robotic systems whose environments are constantly changing.

Finally, it is important to note that these challenges call for a concerted effort to develop a physical infrastructure (hardware) as well as a basic scientific research agenda. Most high caliber robotics research programs have a strong experimental program, and progress has been hampered by the lack of affordable instrumentation in all these areas, but particularly in the area of dexterous manipulation.

References

1. H. I. Christensen, EURON — The European Robotics Network. *IEEE Robotics Autom. Mag.* **12**(2) (2005) 10–13.
2. K. J. Kyriakopoulos and H. I. Christensen, European robotic projects. *IEEE Robotics Autom. Mag.* **12**(2) (2005) 4.
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Chapter 6

ROBOTICS FOR BIOLOGICAL AND MEDICAL APPLICATIONS

6.1. Background

This chapter describes research activities currently conducted in the world that are related to robotics for biological and medical applications. Robotics for medical applications started 15 years ago while for biological applications it is rather new (about 5 years old). In this chapter, we first discuss why we need robots and automation in biology and medicine. Then we present robotic tools, devices and systems, key technologies, and fundamental research challenges that are relevant to the two applications. Research activities conducted and visited by the assessment team in the United States, Japan, Korea, and Europe are introduced.

6.2. Why Robots and Automation in Biology and Medicine

6.2.1. *Biological applications*

The primary purpose of robotics in biology is to achieve high throughput in experiments related to research and development of life science. Those experiments involve the delivery and dispensation of biological samples/solutions in large numbers, each with very small volumes. Typical applications include high-throughput systems for large-scale DNA sequencing, single nucleotide polymorphism (SNP) analysis, haplotype mapping, compound screening for drug development, and biosolution mixing and dispensing for membrane protein crystallization. Without robots and automation, biosamples/solutions must be handled by human hands, which is not only tedious, but also very slow. Various robotic systems have been developed in laboratories that are either specially developed for a particular application (Fig. 6.1) or for integration of commercially available robots, general purpose tools, and sensors.

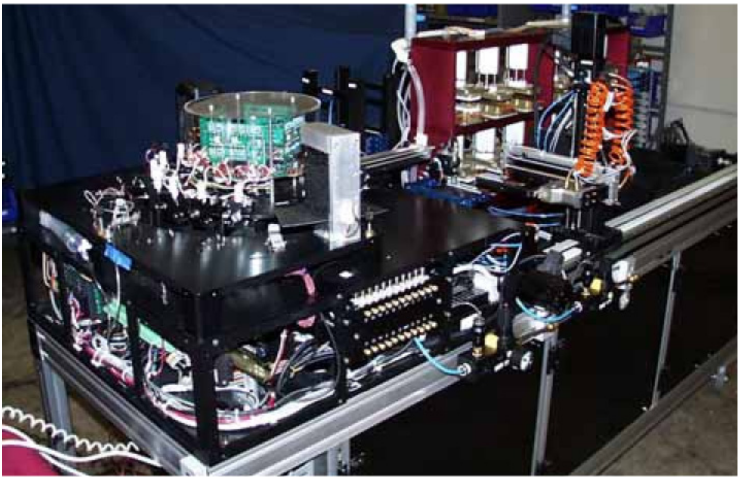

Fig. 6.1. High-throughput systems for DNA sequencing (University of Washington) (Ref. 3).

The second purpose of robotics for biological applications is for effective handling and exploration of molecular and cell biology. This type of application includes immobilization of individual cells, cell manipulation, and cell injection for pronuclei DNA insertion. Special tools fabricated using different technologies have to be developed, such as lasers for microsensing and manipulating, electroactive polymer for cell manipulation, and microneedles for cell penetration.

Another interesting area of application is robotics-inspired algorithms for molecular and cellular biology. This includes the work for predicting protein folding, and for structural biology.[1]

6.2.2. *Medical applications*

Research on robotics for medical applications started 15 years ago and is very active today. The purpose is threefold. First it is for robotic surgery. Robotic surgery can accomplish what doctors cannot, because of precision and repeatability of robotic systems. Besides, robots are able to operate in a contained space inside the human body. All these make robots especially suitable for noninvasive or minimally invasive surgery and for better outcomes of surgery. Today, robots have been demonstrated or routinely used for heart, brain, spinal cord, throat, and knee surgeries at many

Fig. 6.2. Doctors perform knee surgery using a robotic system (Ref. 4).

hospitals in the United States.[2] Figure 6.2 shows doctors performing knee surgery using a robotic system. Since robotic surgery improves consistency and quality, it is becoming more and more popular.

The second use of robotics in medicine is diagnosis. Robotic diagnosis reduces invasiveness to the human body and improves the accuracy and scope of the diagnosis. One example is the robotic capsular endoscope that has been developed for noninvasive diagnosis of gastrointestinal tract by Polo Sant'Anna Valdera of the Sant'Anna School of Advanced Studies in Italy (Fig. 6.3).

The third use of robotics is for providing artificial components to recover physical functions of human beings such as robotic prosthetic legs, arms, and hands. For example, at the Technical University of Berlin there is work on powered leg orthoses using electromyographic signals for control and on prosthetic hands. The latter is basically an exoskeleton for a nonfunctional hand. Prosthetic hands are also being developed at the University of Tsukuba in Japan. In addition, rehabilitation robotics can help patients recover physical functions more effectively after injury by replacing or supplementing the work of physical therapists. Robotic devices and systems can also help elderly people move around; this includes intelligent wheelchairs, walking-assistance machines, and limb-empowering robotic devices. For example, a new type of powered walker

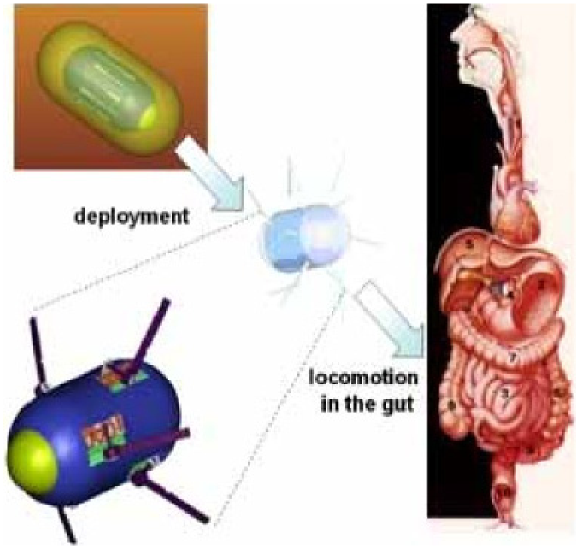

Fig. 6.3. Robotic capsular endoscope for examination of gastrointestinal tract (Polo Sant'Anna Valdera of the Sant'Anna School of Advanced Studies, 2005).

was developed at Waseda University. It is capable of sensing pressure from both the left and right arms (see Fig. 6.6).

6.2.3. *Robotic tools, devices, and systems*

Robotics for biological and medical applications uses many tools, devices, and systems of both general-purpose and specially designed types. The former includes robot manipulators for picking and placing, and microactuators for dispensing biosamples/solutions such as the one shown in Fig. 6.4. Another example is the system developed by the Novartis Research Foundation's Genomics Institute, which includes standard industrial manipulators for high-throughput screening of compounds up to 1 million samples per day.[3] In robotic surgery, commercially available robots are often a part of an integrated system.

Special-purpose devices and systems come in many varieties depending on the purpose of applications. For example, special systems are developed for high-throughput preparation of bio-solutions such as the one developed by the University of Washington, shown in Fig. 6.1. Special-purpose sensors have even more types including visual, force, and neurosensing. Biosensors

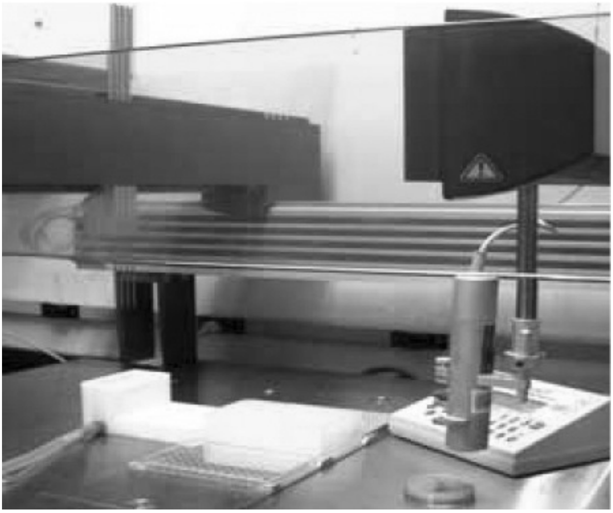

Fig. 6.4. Off-the-shelf robot is a part of a biosolution dispensing system (Ohio State University).

often are very small and so microelectromechanical systems (MEMS) technology is used to fabricate such elements as the microforce sensor from the University of Minnesota and ETH-Zürich, shown in Fig. 6.5. Special tools using nontraditional principles are also developed to handle biosolutions or to manipulate cells. For example, Nagoya University in Japan used local photo-polymerization on a chip to immobilize individual cells.

Besides tools and devices, software and algorithms are also an important part of robotics for biological and medical applications. In robotic surgery, for example, effective algorithms for modeling and analysis of human body components are important topics of research. The purpose is to develop patient-specific models for performing precise surgery.

6.2.4. *Key technologies*

Key technologies for robotics in biological and medical applications include the following:

(a) MEMS technologies that can fabricate tools and devices suitable for microsensing, microactuation, and micromanipulation, of biosamples/solutions and bio-objects such as cells. These technologies use either IC-fabricating methods or micromachining methods.

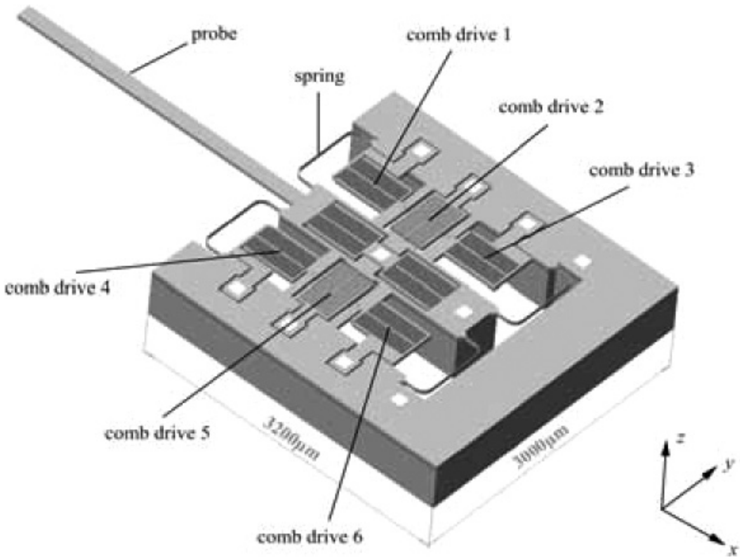

Fig. 6.5. Microforce sensor using integrated circuit (IC) fabrication technology, University of Minnesota (Ref. 5).

(b) Special robotic systems that can perform surgery precisely and at low cost. The challenge is to program motion of robots efficiently based on patient-specific modeling and analysis.
(c) Modeling and analysis algorithms that are precise and fast for individual patients.
(d) Reliable and efficient system integration of off-the-shelf components and devices for specific biological and medical operations.
(e) Engineering modeling of biological systems. The purpose is to develop mathematical models for explaining the behavior and structure of biological systems as engineers do for artificial physical systems. This has been proved extremely challenging because of the complexity of the biological systems.
(f) Solid understanding of life science. To develop an effective robotic or automation system for biological and medical applications, it is necessary for engineers to have a deep understanding of life science.

From the above, one can see that robotics for biological and medical applications covers a wide scope of technologies from conventional robots and sensors to microsensors and actuators, from tools and devices to algorithms. For molecular-level study of biological systems, nanodevices and actuation are key technologies as well.

6.2.5. *Fundamental research challenges*

There are a number of fundamental research challenges in robotics for biological and medical applications that can be summarized as follows. First and foremost, technologies for biological and medical applications are not mature, especially for biology.[6] There is still a lack of effective tooling and sensing technologies to deal with both massive and tiny bio-objects and biosamples/solutions. In particular, the following issues in biological research are still not resolved:

- Automated cell handling and operations (probing and sensing) are extremely challenging because of the tiny size of the cells.
- Automated protein characterization and functional analysis are extremely difficult because finding protein structure is slow and costly.
- Automated protein crystallography, including protein crystallization, crystal harvesting, and X-ray detection, is still not possible because protein crystals are so small that they are difficult to be detected using vision sensors, and there are no effective tools for picking and placing.
- Automated DNA sequencing is still slow and expensive.
- Automated DNA and protein chip production and analysis are still expensive and slow, although technologies have been improved constantly.

For medical applications, Russell Taylor of the Johns Hopkins University summarized core challenges in three areas: modeling and analysis, interface technologies, and systems, which are described below.[4]

- For modeling and analysis, the emphasis is on developing computationally effective methods for patient-specific modeling and analysis.
- For interface technology, the emphasis is on fundamentally extending the sensory, motor, and human-adaptation abilities of computer-based systems in an unusually demanding and constrained environment.
- For systems, the emphasis is on developing architectures, building blocks, and analysis techniques that facilitate rapid development and

validation of versatile computer integrated surgery (CIS) systems and processes with predicable performance.

In general, robotics for biological and medical applications is still new, and relevant technologies are immature, especially for biological applications. Consequently, methods of robotics and automation are often *ad hoc*, and systems developed for a particular application are evolutional, not revolutionary.[7] For medical applications, robotic methods are more systematic, but not necessarily a matter of science yet. Furthermore, engineers of robotics and automation have limited knowledge of life science. As a result, engineers have difficulty in developing effective tools, devices, and systems in an efficient way for both biological and medical applications. Collaboration between engineering and biology is still rare, although that between engineering and medicine has a longer history.

6.3. Regions Visited by the Assessment Team

The assessment team visited two regions in addition to the workshop held in the United States, which reported research results by US researchers. The countries in the two regions are Japan, Korea, and a number of European countries.

6.3.1. *United States*

The US workshop was attended by US researchers of academia, research laboratories, and industries. Three presentations related to robotics for biological and medical applications were:

(a) Deirdre R. Meldrum (University of Washington) and Lydia E. Kavraki (Rice University) on the topic of robotics and robotics-inspired algorithms for molecular and cellular biology: diagnostics, genomics, proteomics.
(b) Brad Nelson (University of Minnesota and ETH-Zürich) and Yuan F. Zheng (Ohio State University) on the topic of status of robotics in the United States: Bio/Pharmaceutical.
(c) Russell Taylor (Johns Hopkins University) on the topic of medical robotics and computer-integrated surgery.

It should be noted that the number of US organizations involved in robotics for biological and medical applications mentioned by the three presentations is more than 30. Some of the research activities performed by these organizations have been described earlier in this chapter. In biological applications, for example, the United States is particularly strong in developing robotic systems for high-throughput handling of biosamples in life science, such as gene-sequencing and protein crystallization. In medical applications, the National Science Foundation has funded Johns Hopkins University for the Engineering Research Center for Computer-Integrated Surgical Systems and Technology, which has a focus on robotics in medical applications, especially robotic surgery.

In terms of commercial applications, the United States has a very successful system called *Da Vinci* which is designed to assist surgeons with complicated medical operations. The system has been purchased by many hospitals in the United States (in the world as well) for robotic knee replacements and prostate and heart surgeries.

6.3.2. *Japan and Korea*

In Japan, the assessment team visited Nagoya University, Waseda University, and ATR Computational Neuroscience Laboratories; in Korea KIST (Korea Institute of Science and Technology) and Seoul National University, among others. The organizations mentioned here performed research on robotics for biological and medical applications. Nagoya University studies noncontact cell manipulations using lasers, and intravascular surgery based on 3D-reconstructed cerebral arterial model using CT images and an *in vitro* model of human aorta.

Waseda University is well known for its research on legged locomotion. In recent years, Waseda has also been active in the research on robotic surgery and walking-assistance devices for elderly people (Fig. 6.6).

ATR studies brain function using a special computational approach called "understanding the brain by creating one." In Korea, Seoul National University studies MEMS and nanotechnologies for bio-applications, and KIST studies advanced techniques for cell handling.

6.3.3. *Europe*

Research on robotics for biological and medical applications has been active in Europe for a long time. There are many institutions involved, of which the assessment team could visit only a few in the limited time period. The team visited the group at the ETH Swiss Federal Institute of

Fig. 6.6. The walking-assistance device by Waseda University.

Technology, which is led by Dr Brad Nelson, who is also associated with the University of Minnesota. Dr Nelson's group studies MEMS technologies for tools for cell manipulation and operation. The University of Zurich's Artificial Intelligence Laboratory studies the evolution of artificial cells whose purpose is to mimic biological growth. At the University of Genova in Italy, scientists study haptic control mechanisms of human arms, and control mechanisms of human eyes. At the Technical University of Munich, Dr Alois Knoll leads a research group that develops surgical robots. Researchers there use haptic approaches based on force feedback and touch sensing for surgery and skill transfer. The advantage is to scale robot motions to nonhuman-sized situations to improve accessibility and range of distance, dexterity and speed for applications such as minimally invasive heart surgery.

Polo Sant'Anna Valdera of the Sant'Anna School of Advanced Studies in Italy is one of the largest groups, which performs research on robotics for biological and medical applications. The group consists of eight laboratories and centers: (a) ARTS Lab (Advanced Robotics Technology and Systems Laboratory), (b) BIO Labs (Biological Laboratories), (c) CRIM (Center for Applied Research in Micro and Nano Engineering), (d) PERCRO (Perceptual Robotic Laboratory), (e) RETIS (Real-Time Systems Laboratory), (f) EZ-Lab Research Center which focuses on technologies and support services related to longevity, (g) IN.SAT (Business and Territorial Systems Innovation Laboratory), and (h) Humanoid Robotics Research Center. Of the eight laboratories, ARTS and CRIM are involved in the research of robotics for biological and medical applications.

The ARTS laboratory focuses on basic research of robotics, mechatronics, and bioengineering. Research projects in progress explore biomorphic and anthropomorphic solutions for robotic devices in general, and biomechanics, neuro-robotics, and rehabilitation and assistive devices in particular. One such project investigates implantable microdevices which can detect neuron signals from human arms to directly control robotic devices (Fig. 6.7).

The CRIM laboratory focuses on the design and development of micro- and nanodevices, but its strategy is to avoid the silicon processing method popularly used for fabricating IC devices, which includes many chemical processes such as lithography, itching, and diffusion. Instead, CRIM cuts materials, plastic, metal, or silicon directly, using precision machines. For that purpose, CRIM is facilitated with a set of machining equipments such as a Kern HSPC micro-computerized numerical control (CNC) machine, an electrical discharge machine, a plastic injection molding machine, and

Fig. 6.7. Human arm implantable microprobes.

a microerosion system. The robotic capsular endoscope mentioned earlier (Fig. 6.3) was developed by the laboratory using the technologies just mentioned.

Another large group visited by the assessment team is led by Dr Tim C. Lüth who is associated with the Medical School Charite of Humboldt University and Fraunhofer Institute for Production and Design (IPK) in Berlin, Germany. The team observed that Dr Lüth's involvement in both sides was deep and had yielded great results. The team saw excellent facilities for conducting research on medical robots, which included a wide mix of small machine shops and integration areas, mixed with facilities for clinical trials, teaching hospital theaters, and full-time surgical suites. This vertical integration of research, founded at IPK, does not match with that in the United States (see Fig. 6.8).

Dr Lüth leads a group called Berlin Center for Mechatronical Medical Devices, which focuses on three areas of surgical robots, namely navigation, robotic, and navigation control. Navigation is to develop mechanisms for leading the tip of a medical instrument to precise positions and orientations with respect to a patient's tissue structure; Robotic is to develop devices for carrying the tip to the desired positions and orientations; and Navigation Control is to actively constrain the instruments' power during operations. The group has studied extensively the navigation mechanisms for various types of operations including neurosurgery, knee replacement, dental implantology, radiation therapy, radiology, etc. Multiple generations of navigation systems have been developed in-house. The latest generation has reduced the required interocular baseline to a small distance ($\sim 0.4\,\mathrm{m}$). This is mounted on a small roller mount that takes up only a small amount

Fig. 6.8. Medical robot facilities at the Berlin Center for Mechatronical Medical Devices (Charite and IPK).

of floor space. Many types of surgeries have been performed by these navigation systems, which are by no means less than what we have seen in the United States.

6.4. Quantitative and Qualitative Observations

6.4.1. *Quantitative observations*

In terms of quantity, the United States is leading the world in both the number of organizations and the types of applications for both biological and medical applications. As mentioned earlier, in the United States, there are at least 30 research organizations performing research on robotics for biological applications. The United States is leading the world in the following areas: DNA sequencing, cell manipulation, protein crystallography, DNA and protein chip production and analysis, computational biology, and bioinformatics.

For medical applications, there is a National Science Foundation Engineering Research Center (NSF/ERC) at the Johns Hopkins University, named the NSF/ERC Computer Integrated Surgical Systems and Technology. The center has over $5 million of support per year, not counting numerous small research groups in the United States. Many university hospitals study and perform robotic surgeries on hearts, brains, knees, prostates, spinal cords, etc., (often sponsored by the National Institutes of Health) including Johns Hopkins University, University of Southern California, CMU, Ohio State University, University of California at Berkeley, University of Illinois at Chicago, and many others. Many nonuniversity hospitals routinely use robotic devices for minimally invasive surgery.

There is no doubt that the United States is leading the world in the research of robotics for biological and medical applications. However, other countries are catching up; the assessment team saw many organizations in Japan, Korea, and Europe actively participating in the research, and more of the others are joining, such as the Chinese University of Hong Kong (Dr Wen J. Li's group, which will be mentioned later).

6.4.2. *Qualitative observations*

Research on robotics and automation for biological and medical applications is still young. However, many quality results have been generated by the scientists in the United States and all over the world. The maturity of new robotics technologies vary from laboratory demonstrations to reliable applications. It is fair to say that quality of research in the United States is as good as in any other country in the world. For biological applications, the United States is clearly leading the world in the areas of DNA sequencing, protein crystallography, drug discovery, and cell operation. Other countries are also producing promising results, such as the best paper award of the IEEE 2003 International Conference on Robotics and Automation, which was won by Dr Wen J. Li of the Chinese University of Hong Kong for his outstanding work on electroactive polymer cell manipulation.

In spite of great progress, there are still obstacles and challenges. First, approaches are still *ad hoc*, i.e. no systematic theory governs the area as mentioned earlier. Secondly, progress in this area heavily relies on the development of MEMS and nanotechnologies, which unfortunately have proven to be slow. Finally, collaboration between engineers and biologists is still new and challenging. For medical applications, the United States is most active for robotic surgeries. The United States is also leading the world in the development of robotic tools and systems for medical applications.

The leading position of the United States in both quantity and quality is not a surprise since the country invests the most in the two areas. As other countries are now putting in more resources, the US government has to maintain the level of investment or invest even more to keep the leading position.

6.5. Conclusions

Research on robotics for biological and medical applications is still young. Scientists in the United States are more active in identifying and developing new applications of robotics for the two applications. Many significant results have been achieved, and some have been commercialized to become useful devices and systems such as the *Da Vinci* surgical system.[2] In the United States, the number of institutions involved in the research of robotics for both the applications is significantly higher than that in any other country, while the quality of research is equally good.

On the other hand, approaches for robotics for biological and medical applications, especially for the former, are evolutionary, not revolutionary. Still there are many opportunities for collaboration between engineers and biologists, and between engineers and doctors. It is believed that any new breakthrough in biology and in medicine may need revolutionary tools, perhaps in robotics, to take place. Although the United States is still leading the world in the two applications, more and more countries are participating and making impressive progress. After all, the field has potential to bring great economic impact.

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Chapter 7

NETWORKED ROBOTS

7.1. Introduction

Networked robots refer to multiple robots operating together in coordination or cooperatively[a] with sensors, embedded computers, and human users. Cooperation entails more than one entity working toward a common goal while coordination implies a relationship between entities that ensures efficiency or harmony. Communication between entities is fundamental to both cooperation and coordination and hence the central role of the network. Embedded computers and sensors are now ubiquitous in homes and factories, and increasingly wireless *ad hoc* networks or plug-and-play wired networks are becoming commonplace. Robots are functioning in environments performing tasks that require them to coordinate with other robots, cooperate with humans, and act on information derived from multiple sensors. In many cases, these human users, robots, and sensors are not collocated and the coordination and communication happen through a network.

Networked robots allow multiple robots and auxiliary entities to perform *tasks that are well beyond the abilities of a single robot.* Figure 7.1 shows many prototype concepts derived from academic laboratories and industry. In all these examples, independent robot or robotic modules can cooperate to perform tasks that a single robot (or module) cannot perform. Robots can automatically couple to perform locomotion tasks (also see Fig. 7.2) and manipulation tasks that either a single robot cannot perform, or would require a special-purpose larger robot to perform. They can also coordinate to perform search and reconnaissance tasks exploiting the efficiency that is inherent in parallelism. They can also perform independent

[a] "Working cooperatively" according to the Oxford English Dictionary mutual assistance in working toward a common goal: *every member has clearly defined tasks in a cooperative enterprise.*

(a) (b) (c) (d)

Fig. 7.1. (a) Small modules can automatically connect and communicate information to perform locomotion tasks (MIT). (b) Robot arms on mobile bases can cooperate to perform household chores (Stanford). (c) Swarms of robots can be used to explore an unknown environment (U. Tennessee). (d) Industrial robots can cooperate in welding operations (Fanuc).

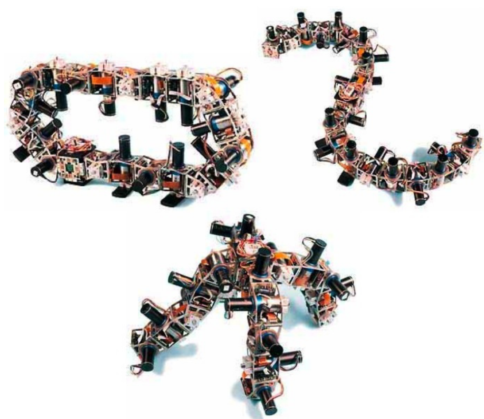

Fig. 7.2. Robotic modules (PARC/University of Pennsylvania can be reconfigured to "morph" into different locomotion systems including a wheel-like rolling system (top left), a snake-like undulatory locomotion system (top right), and a four-legged walking system (bottom).

tasks that need to be coordinated (for example, fixturing and welding) in the manufacturing industry.

Networked robots also result in *improved efficiency*. Tasks like searching or mapping, in principle, are performed faster with an increase in the number of robots. A speed up in manufacturing operations can be achieved by deploying multiple robots performing operations in parallel but in a coordinated fashion.

Perhaps the biggest advantage of using the network to connect robots is the ability to connect and *harness physically removed assets*. Mobile robots can react to information sensed by other mobile robots in the next room. Industrial robots can adapt their end-effectors to new parts being manufactured up-stream in the assembly line. Human users can use machines that are remotely located via the network.

The ability to network robots also enables fault-tolerance in design. If robots can in fact dynamically reconfigure themselves using the network, they are more tolerant to robot failures. This is seen in the internet where multiple gateways, routers, and computers provide for a fault-tolerant system (although the internet is not robust in other ways). Similarly, robots that can "plug" and "play" can be swapped in and out, automatically, to provide for a robust operating environment.

Finally, networked robots have the potential to provide great synergy by bringing together components with complementary benefits and making the whole greater than the sum of the parts (Fig. 7.3).

Applications for networked robots abound. The US military routinely deploys unmanned vehicles that are reprogrammed remotely based on intelligence gathered by other unmanned vehicles, sometimes automatically. The deployment of satellites in space, often by astronauts in a shuttle with the shuttle robot arm requires the coordination of complex instrumentation onboard the space shuttle, human operators on a ground station, the shuttle arm, and a human user on the shuttle. Home appliances now contain sensors and are becoming networked. As domestic and personal robots become more

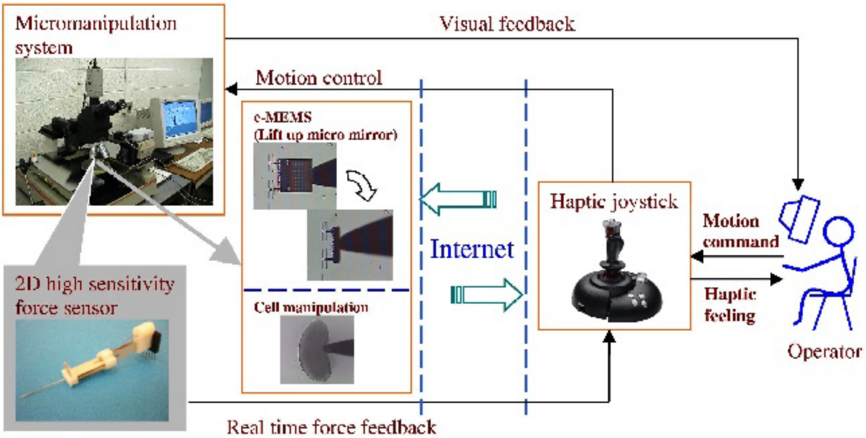

Fig. 7.3. A human user communicating with remotely located expensive robots that can manipulate objects on the micro or nanoscale (Michigan State University). These robots can have multiple users without requiring collocation of the robots with the users.

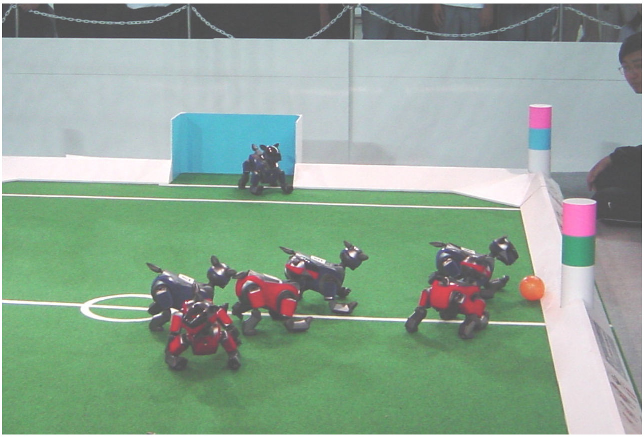

Fig. 7.4. Sony entertainment robots communicate and coordinate with each other in a game of soccer. The annual Robocup competition features teams from all over the World.

commonplace, it is natural to see these robots working with sensors and appliances in the house while cooperating with one or more human users (Fig. 7.4).

7.2. Significance and Potential

The Network Robot Forum established in Japan in 2003 estimates the Networked Robot industry to be over $20B by 2013, approximately five times the industrial robot market for manufacturing applications.[1] This growth is broad-based across many industries.

Sensor networks have been projected to grow dramatically in terms of commercialization and market value. Robot networks are analogous to sensor networks except that they allow sensors to have mobility and allow the geographical distribution of the sensors to be adapted based on the information acquired.

Networks allow health care professionals to interact with their patients, other professionals, expensive diagnostic instruments, and in the future surgical robots. Telemedicine is expected to provide a major growth impetus for remote networked robotic devices that will take the place of today's stand-alone medical devices.

The manufacturing industry is finding it easier to reconfigure existing infrastructure by networking new robots and sensors with existing robots

Fig. 7.5. Human operators can interact with a network of semi-autonomous or autonomous mining and construction vehicles.

via wireless networks. There is a noticeable trend toward robots interacting with each other and cooperating with humans (Fig. 7.5).

There are already many commercial products, notably in Japan, where robots can be programmed via and communicate with cellular phones. For example, the MARON robot developed by Fujitsu lets a human user dial up her robot and instruct it to conduct simple tasks including sending pictures back to the user via her cellular phone.

Nature provides the proof-of-concept of what is possible. There are numerous examples of simple animals executing simple behaviors but communication with and sensing nearest neighbors enable complex emergent behaviors that are fundamental to navigation, foraging, hunting, constructing nests, survival, and eventually growth. Biology has shown how simple decentralized behaviors in unidentified individuals (for example, insects and birds exhibiting swarming behaviors) can exhibit a wide array of seemingly intelligent group behaviors. Similarly networked robots can potentially communicate and cooperate with each other, and even though individual robots may not be sophisticated, it is possible for networked robots to provide a range of intelligent behaviors that are beyond the scope of individual robots.

7.3. State of the Art in Theory and Practice

There are already many impressive successful demonstrations of networked robots.

In the manufacturing industry, work cells comprise multiple robots, numerous sensors and controllers, automated guided vehicles, and one or two human operators working in a supervisory role. However, in most of these cells, the networked robots operate in a structured environment with very little variation in configuration and/or operating conditions. There is a growing emphasis on networked robots in applications of field robotics, for example, in the mining industry. Like the manufacturing industry, operating conditions are often unpleasant and the tasks are repetitive. However, these applications are less structured and human operators play a more important role (Fig. 7.6).

The US military has a big Future Combat Systems initiative to develop network-centric approaches to deploy autonomous vehicles. While networked robots are already in operation, current approaches are limited to human users commanding a single vehicle or sensor system. However, it takes many human operators (between 2–10 depending on the complexity of the system) to deploy complex systems like unmanned aerial vehicles. A Predator UAV is operated from a tactical control station, which may be on an aircraft carrier, with a basic crew of 3–10 operators. The eventual goal is to enable a single human user to deploy networks of unmanned aerial, ground, surface, and underwater vehicles.

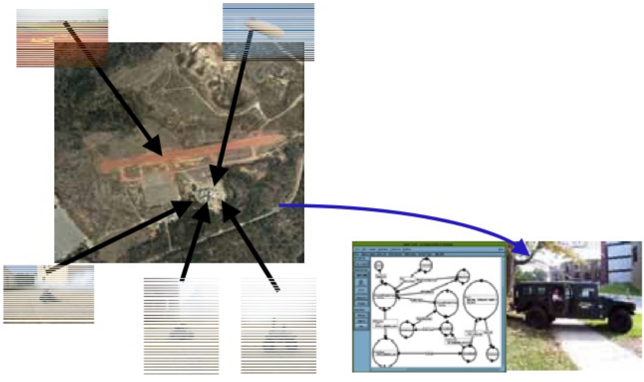

Fig. 7.6. A single operator commanding a network of aerial and ground vehicles from a command and control vehicle in an urban environment for scouting and reconnaissance in a recent demonstration by the University of Pennsylvania, Georgia Tech. and University of Southern California (Ref. 5).

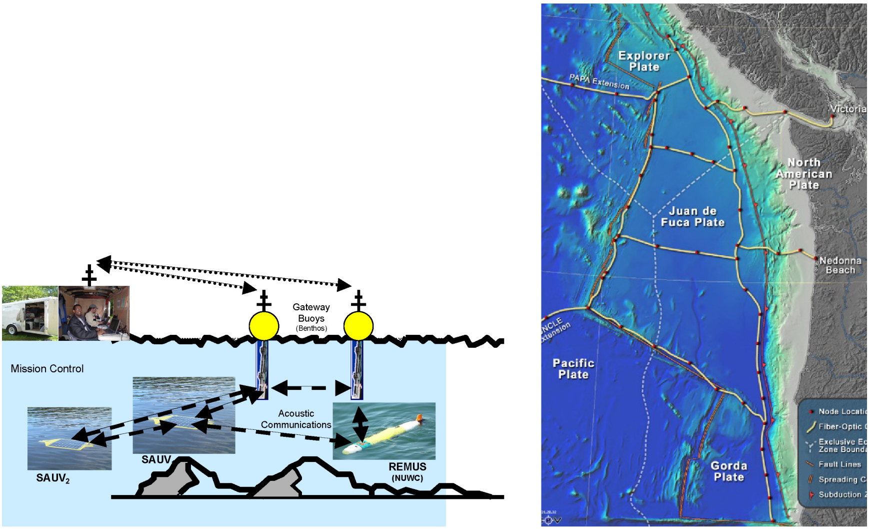

Fig. 7.7. A network of buoys and underwater vehicles[6] used for measuring oxygen content, salinity, and chlorophyll on the Hudson Bay (top) and the Neptune project (right) off the west coast of North America.

Mobile sensor networks are finding use of environmental studies and research projects in which robots are used to deploy sensors and measure environmental conditions. There are examples of measurements of salinity gradients in oceans, temperature and humidity variations in forests, and chemical composition of air and water in different ecologies (Fig. 7.7). The main benefit is to speed up the collection of data and increase the efficiency. Mobile platforms allow the same sensor to collect data from multiple locations while communication allows the coordinated control and aggregation of information (Fig. 7.8).

The European Union has several EU-wide coordinated projects on collective intelligence or swarm intelligence.[2,3] The *I-Swarm* project in Karlsruhe and the *swarm-bot* project in EPFL are examples of swarm intelligence (Figs. 7.9 and 7.10).

The Laboratory for Analysis and Architecture of Systems (LAAS) has a strong group in robotics and artificial intelligence. This group has had a long history of basic and applied research in multi-robot systems. The most recent focus of this group is the COMET project, which integrates multiple unmanned vehicles for applications like terrain mapping and fire-fighting (Fig. 7.11).

Fig. 7.8. The Software for Distributed Robotics project demonstrated the ability to deploy 70 robots to detect intruders in an unknown building (University of Tennessee, University of Southern California, and SAIC) (Ref. 4).

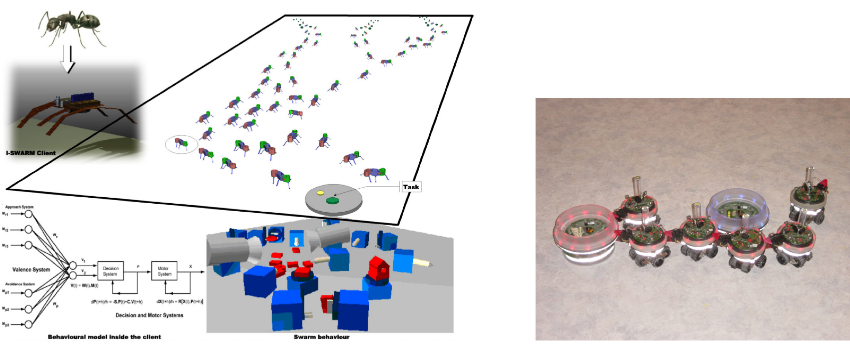

Fig. 7.9. The EU project on Swarm Intelligence: the I-Swarm project in Karlsruhe (left) and the *swarm-bot* project in EPFL with multiple robots forming physical connections for manipulation and locomotion (right).

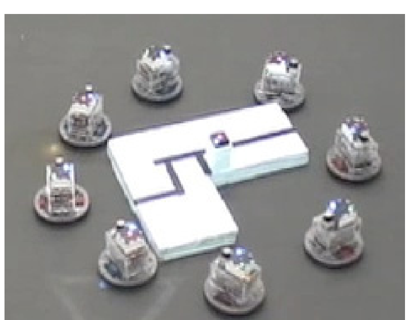

Fig. 7.10. A swarm of robots cooperatively manipulate an object using algorithms that are based on unidentified robots using only local information, with minimal communication, robust to the number of robots in the team (University of Pennsylvania).

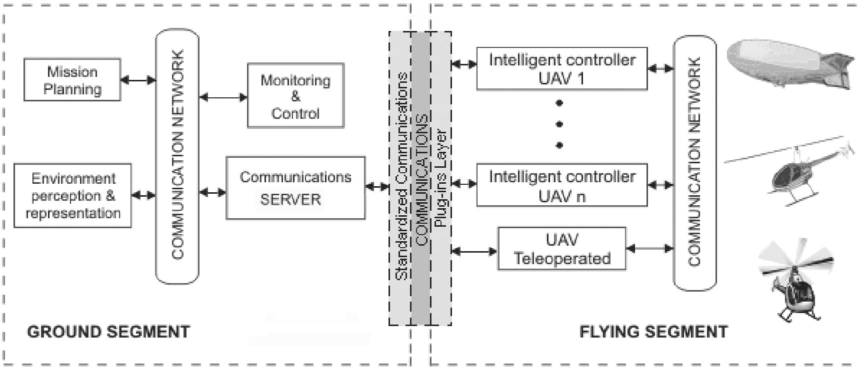

Fig. 7.11. The COMETS project at INRIA seeks the implementation of a distributed control system for cooperative detection and monitoring using heterogeneous UAVs with applications to fire fighting, emergency response, traffic monitoring, and terrain mapping.

7.4. Scientific and Technical Challenges

While there are many successful embodiments of networked robots with applications to manufacturing industry, defense industry, space exploration, domestic assistance, and civilian infrastructure, there are significant challenges that have to be overcome.

First, the problem of coordinating multiple autonomous units and making them cooperate creates problems at the intersection of communication, control, and perception. Who should talk to whom and what information should be conveyed? How does each unit move in order to accomplish the task? How should the team members acquire information? How should the team aggregate information? These are all basic questions that need basic advances in control theory, perception, and networking.

Second, because humans are part of the network (as in the case of the Internet), we have to devise an effective way for multiple humans to be embedded in the network and command/control/monitor the network without worrying about the specificity of individual robots in the network.

Third, today's networks tend to be static and responsive or reactive. They are static in the sense that sensors, computers, or machines are networked together in a fixed topology. They are responsive or reactive in the sense they respond to specific instructions provided by human users. Increasingly robot networks are being dynamic. When a robot moves, its neighbors change and its relationship to the environment changes. As a consequence, the information it acquires and the actions it executes must change. Not only is the network topology dynamic, but also the robot's behavior changes as the topology changes. It is very difficult to predict the performance of such dynamic robot networks. And yet, it is this analysis problem designers of robot networks must solve before deploying the robot network.

7.5. International Comparisons

Japan has many national R&D programs related to this area. The 5-year Ubiquitous Networking Project established in 2003 has paved the way for a 5-year Network Robots Project in 2004. The Network Robot Forum was established in 2003 and now has more than 100 prominent members from industry, academia, and government.

There are many mature efforts in Japan and Europe to develop better sensors and robot hardware to facilitate the development of robot networks. The United States too has more impressive embodiments and imaginative applications of networked robots. Japan has a bigger investment in network robots and has done a better job of creating national agendas that will impact the development of networked robots for service applications and eventually for domestic assistance and companionship.

7.6. Future Challenges

There are many scientific challenges to realize the vision for networked robots. The main overarching challenges are summarized here.

Technical challenges to scalability: We do not have a methodology for creating selforganizing robot networks that are robust to labeling (or numbering), with completely decentralized controllers and estimators, and with provable emergent response. This requires basic research at the intersection of control, perception, and communication.

Performing physical tasks in the real world: Most of our present applications are emphasizing going from static sensor networks to mobile sensor networks and, as such, are able to acquire and process information. We are a long way from creating robust robot networks that can perform physical tasks in the real world.

Human interaction for network-centric control and monitoring: Advances over the past decade have provided human users the ability to interact with hundreds and thousands of computers on the Internet. It is necessary to develop similar network-centric approaches to interface, both for control and for monitoring.

Finally, a major challenge is to create robot networks that are proactive and anticipate our needs and commands rather than reacting (with delays) to human commands.

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AUTHORS' BIOGRAPHIES

George Bekey (Panel Chair)

Dr Bekey is an Emeritus Professor of computer science at the University of Southern California. His research interests include autonomous robotic systems, multi-robot cooperation, and human–robot interaction. He received his PhD in engineering from University of California, Los Angeles (UCLA). Following employment at Beckman Instruments and TRW Systems he joined as a faculty at USC in 1962. He served as the Chairman of the Electrical Engineering Systems Department from 1978 to 1982, as Chairman of the Computer Science Department from 1984 to 1989, and as an Associate Dean for research at the USC School of Engineering from 1996 to 1999, in addition to founding the Biomedical Engineering Department and the Robotics Research Laboratory. He has published over 200 papers and several books in robotics, biomedical engineering, computer simulation, control systems, and human–machine systems. Dr Bekey is a member of the National Academy of Engineering, a fellow of the Institute of Electrical and Electronics Engineers (IEEE) and the American Association for Artificial Intelligence (AAAI). He was the Editor-in-Chief for the journal *Autonomous Robots* from its founding in 1993 to 2007, and the founding editor of the *IEEE Transactions on Robotics and Automation.* During 1996 and 1997 he served as the president of the IEEE Robotics and Automation Society.

His latest book, *Autonomous Robots: From Biological Inspiration to Implementation and Control,* was published by MIT Press in May 2005.

George Bekey officially retired from USC in 2003, but continues to be active on a part-time basis at the University, as well as in consulting and service on the advisory boards of several high-technology companies. He is also affiliated with a medical devices startup company in San Luis Obispo and a robotics company in Los Angeles. Since September 2005, he is also an adjunct professor of engineering at California Polytechnic State University in San Luis Obispo, California.

Robert Ambrose

Dr Ambrose serves as the chief of the Robotics Systems Technology Branch within the Automation, Robotics and Simulation Division at NASA's Johnson Space Center (JSC). His branch is tasked with developing a new robot technology for NASA's Space Operations and Exploration Mission Directorates.

Robert Ambrose received his BS (1986) and MS (1987) in mechanical engineering from Washington University, and his PhD (1991) from the University of Texas. During his postdoctoral period at the University of Texas, he was a coinvestigator on a NASA grant studying remote operations of robots, and furthered his work on robot design methodologies. In 1992, he joined NASA's Johnson Space Center working for MITRE and then Metrica, Inc., on contracts assisting in the design of new robotic systems. In 1995, he led the development of space-worthy joint drive components for the Dexterous Robot System. In 1997, he served as the principal investigator on a project that designed and built robots for service in the plant growth chamber of JSC's BioPlex, a Mars habitat mockup. In 1998, he served as the manipulator subsystem lead for Robonaut, and in 1999, he was selected to lead the Robonaut Team. In 2000, he was hired by NASA, and continued to lead the Robonaut Team through the integration of the first robot, then a second prototype with multiple lower body options. In 2004, he served as the acting chief of the Robotics Systems Technology Branch, and in 2005, he was selected as the permanent chief, leading personnel working on Robonaut and other JSC projects. In these and other assignments he has built robotic systems for space, microelectronics, nuclear, and agricultural applications, including manipulators, force feedback joysticks, gantries, walking machines, and wheeled robots.

Dr Ambrose currently serves as the principal investigator on two research projects for the NASA Exploration Directorate, titled

"Telepresence for Remote Supervision of Robots," and "Flight Demonstration of a Dexterous Robot with EVA Crew." He also serves as a coinvestigator on three additional projects with Jet Propulsion Laboratory (JPL), Ames, and Langley personnel. He is a member of the review board for the Mars Rover Technology Program at JPL, and has served on numerous NASA grant review boards. He has chaired two accident investigations at JSC, recommending changes in facility designs to improve safety. He is on the editorial board of *Industrial Robot*, *The International Journal of Humanoid Robotics*, and *The Journal of Field Robotics*. He has authored more than 60 papers on topics in robot design, space environmental modeling, actuator development, kinematics, kinetics, biomechanics, interactive design software, and nonlinear optimization.

Vijay Kumar

Dr Kumar received his MSc and PhD in mechanical engineering from The Ohio State University in 1985 and 1987, respectively. He has been a faculty in the Mechanical Engineering and Applied Mechanics Department with a secondary appointment in the Computer and Information Science Department at the University of Pennsylvania since 1987. He is currently the UPS Foundation Professor and the Chairman of the Mechanical Engineering and Applied Mechanics Department.

Dr Kumar served as the Deputy Dean of the School of Engineering and Applied Science from 2000 to 2004. He directed the General Robotics, Automation, Sensing and Perception (GRASP) Laboratory, a multidisciplinary robotics and perception laboratory, from 1998 to 2004. He is a cofounder of Bio Software Systems, a start-up company in Camden commercializing novel software tools for the analysis of regulatory networks.

Dr Kumar's research interests lie in the area of robotics and networked multiagent systems. He is a fellow of the American Society of Mechanical Engineers, a fellow member of the Institute of Electrical and Electronic Engineers (IEEE), and a member of the Robotics International, Society of Manufacturing Engineers. He has served on the editorial board of the *IEEE Transactions on Robotics and Automation*, editorial board of the *Journal* *of Franklin Institute* and the American Society of Mechanical Engineers (ASME) *Journal of Mechanical Design*. He is the recipient of the 1991 National Science Foundation Presidential Young Investigator award, the Lindback Award for Distinguished Teaching, the 1997 Freudenstein Award for significant accomplishments in mechanisms and robotics, and the 2004 IEEE International Conference on Robotics and Automation Kawamori best paper award.

Dave Lavery

Dave Lavery is the Program Executive for Solar System Exploration at NASA headquarters, where he is the Telerobotics Technology Program Manager. He is responsible for the early development of space science and exploration missions, including projects to Mars, comets, asteroids, and the outer planets. He was a field party member of the Dante I and Dante II projects, which developed robots to explore volcanoes in the Antarctic and Alaska. His research program developed the Sojourner planetary rover, which landed on Mars on 4 July 1997 as a part of the Mars Pathfinder mission. The program is also developing the AERcam and Ranger STX robotics that may one day be used to repair and maintain satellites in low Earth orbit.

Arthur Sanderson

Dr Sanderson received his BS degree from Brown University, Providence, RI, in 1968, and MS degree and PhD from Carnegie Mellon University, Pittsburgh, in 1970 and 1972, respectively. Dr Sanderson held faculty positions at the Carnegie Mellon University from 1973 to 1987, where he was a codirector of the Robotics Institute, the largest university-based robotics research center in the United States. In that role, he provided guidance for programs in industrial robotics, mobile robotics with applications to space, defense, and hazardous environments, medical robotics, and fundamental research in intelligent systems. He pioneered his research on real-time visual servo control systems for robotics applications, and introduced sensor-based control architectures in a number of different domains.

He has held visiting positions at Delft University of Technology, Universidad Iberoamericana, Mexico City, Mexico, and Philips Laboratories, Briarcliff Manor, NY. In 1987, he joined Rensselaer Polytechnic Institute as a Professor and served as the department head of the Electrical, Computer and Systems Engineering Department from 1987 to 1994. He was a codirector of the Center for Advanced Technology in Automation and Robotics, and a coprincipal investigator of the Center for Intelligent Robotic Systems for Space Exploration, and developed real-time hierarchical architectures for space flight applications. He developed the "Tetrabot" system of modular distributed robotics that provides flexible reconfiguration of robotics capability for different applications.

Dr Sanderson has authored more than 250 publications and proceedings in the areas of biomedical signal processing, robotics and automation systems, sensor-based control, computer vision, and applications of knowledge-based systems. He has published the following books: *Intelligent Task Planning using Fuzzy Petri Nets*, World Scientific Publishers, 1996, with T. Cao; *Tetrabot: A Modular Approach to Reconfigurable Parallel Robotics*, Kluwer Academic Press, 1998, with G. Hamlin; and *Multisensor Fusion: A Minimal Representation Framework*, World Scientific Publishers, 1999, with R. Joshi. The book *Network-based Distributed Planning Using Coevolutionary Algorithms,* coauthored with R. Subbu, World Scientific Publishers, is currently in press.

In January 2000, Dr Sanderson was appointed as the Vice President for research of Rensselaer Polytechnic Institute. In this role, he is responsible for coordination of all research programs on the campus. He has a leadership role in the development of strategic priorities for research at Rensselaer, and has oversight of interdisciplinary research centers in nanotechnology, microelectronics, scientific computation, automation technology, terahertz research, and pervasive computing and networking. In April 2003, New York State established the Rivers and Estuaries Center on the Hudson with strong involvement of Rensselaer, and Dr Sanderson is currently working with the Center on the application of distributed systems, sensors and sensor networks, and robotics to environmental sensing and monitoring.

Brain Wilcox

Brian Wilcox is the principal investigator of the Rough and Steep Terrain Lunar Surface Mobility Project, which is developing a robot for use in the upcoming NASA Vision for Space Exploration of the moon and Mars outlined by President Bush in January of 2004.

Brian was the supervisor of the Robotic Vehicles Group at JPL for more than 20 years, leading the development of numerous robotic vehicles, and has also been the manager of the JPL Solar System Exploration Mobility Technology program. Under his leadership, the Robotic Vehicles group was responsible for the electronics, software, and mission operations for the Sojourner Rover that explored a small part of Mars in 1997, and he was personally responsible for Sojourner's hazard avoidance sensors and cameras and autonomous navigation algorithms.

He is a member of the Committee on Autonomous Vehicles in Support of Naval Operations under the auspices of the National Academies, is a member and past chair (2000–2004) of the Space Automation and Robotics Technical Committee of the American Institute of Aeronautics and Astronautics, is a recipient of the NASA Exceptional Engineering Achievement Medal, and has seven US patents. He received his BS degree in physics and his BA degree in mathematics from the University of California at Santa Barbara, and his MS degree in electrical engineering from the University of Southern California.

Junku Yuh

Dr Junku Yuh is the Fifth President of Korea Aerospace University in Korea. He spent most of his past 26 years in the United States and Japan with extensive experience in science, engineering, and technology programs and policy matters as a researcher and as a US Federal Government officer. Dr Yuh served as the Head (Director) of the National Science Foundation (NSF) Tokyo Regional Office. Dr Yuh also served as the Program Director of the Robotics and Computer Vision programs in NSF's Directorate for Computer and Information Sciences and Engineering in Washington, DC. Prior to coming to NSF, Dr Yuh was a Professor of Mechanical Engineering and Information & Computer Science at the University of Hawaii (UH) for 16 years, where he also served as the Director of the Autonomous Systems Laboratory.

Dr Yuh is an elected IEEE Fellow and received several prestigious awards, including a Lifetime Achievement Award from World Automation Congress (2004), an NSF Presidential Young Investigator Award from former US President George Bush (1991), a Boeing Faculty Award (1991), a UH Fujio Matsuda Fellow award (1991), and an ASEE DOW Outstanding Young Faculty Award (1989). His technical specialty field is robotics, especially underwater robotics. He has published more than 120 technical articles and edited/coedited 10 books in the area of robotics.

Dr Yuh currently serves as the Editor-in-Chief for the *International Journal of Intelligent Service Robotics* (Springer); as an Associate Editor for the *International Journal of Engineering Design and Automation* and the *International Journal of Intelligent Automation & Soft Computing*; and on the Editorial Board of the *Journal of Autonomous Robots and the International Journal of Intelligent Automation & Soft Computing.* He also served as an Associate Editor for *IEEE Transaction on Robotics and Automation.* He has been an active member of technical societies in the robotics field: served as the Program Chair of the 2003 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS); a Program Cochair of the 2006 and 2001 IEEE International Conference on Robotics and Automation. He founded and chairs the technical committee on Underwater Robotics of the IEEE Robotics and Automation Society.

Dr Yuh received his BS degree in Mechanics and Design from Seoul National University in Korea in 1981, and his MS degree and PhD in Mechanical Engineering from Oregon State University in 1982 and 1986, respectively.

Yuan Zheng

Professor Yuan F Zheng received his MS degree and PhD in electrical engineering from The Ohio State University, Columbus, Ohio, in 1980 and 1984, respectively. His undergraduate studies took place at Tsinghua University, Beijing, China from 1970 to 1974.

From 1984 to 1989, he was with the Department of Electrical and Computer Engineering at Clemson University, Clemson, South Carolina. Since August 1989, he has been with The Ohio State University, where he is currently a Winbigler professor of electrical and computer engineering. Professor Zheng served as the chairman of the department from 1994 to 2004. Between 2004 and 2005, Professor Zheng was on leave at the Shanghai Jiao Tong University (SJTU) in Shanghai, China where he continues to have an adjunct appointment.

Professor Zheng was the Vice President for technical affairs of the IEEE Robotics and Automation Society from 1996 to 1999. He was an Associate Editor of the *IEEE Transactions on Robotics and Automation* between 1995 and 1997. He was the Program Chair of the 1999 IEEE International Conference on Robotics and Automation, held in Detroit, Michigan, on 10–15 May 1999. Professor Zheng received the Presidential Young Investigator Award from President Ronald Reagan in 1986.

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