WTEC Panel Report on

INTERNATIONAL ASSESSMENT OF RESEARCH AND DEVELOPMENT IN ROBOTICS

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WTEC PANEL ON ROBOTICS

Sponsored by the National Science Foundation, the National Aeronautics and Space Administration, and the National Institute of Biomedical Imaging and Bioengineering of the United States Government

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The WTEC staff helps select topics, recruits expert panelists, arranges study visits to foreign laboratories, organizes workshop presentations, and finally, edits and disseminates the final reports.

WTEC Panel on

INTERNATIONAL ASSESSMENT OF RESEARCH AND DEVELOPMENT IN ROBOTICS

FINAL REPORT

January 2006

George Bekey (Panel Chair)
Robert Ambrose
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Art Sanderson
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This document was sponsored by the National Science Foundation (NSF) and other agencies of the U.S. government under an award from the NSF (ENG-0423742) granted to the World Technology Evaluation Center, Inc. The government has certain rights in this material. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the United States government, the authors' parent institutions, nor WTEC, Inc.

ABSTRACT

The purpose of this study was to assess the state of robotics worldwide and to compare the R&D programs in this field between the U.S. and other countries. The comparison was to be based on the criteria of quality, scope, funding and potential for commercialization. The panel found 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 U.S. There are numerous start-up companies in robotics, both in the U.S. and abroad. Venture capital appears to be available. The U.S. 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, particularly in such areas as cargo handling and mining, as well as in the theory and application of localization and navigation. In contrast with the U.S., Korea and Japan have national strategic initiatives in robotics; the European Community has EC-wide programs. In the U.S., DARPA programs are highly applied and short-term oriented, while its support for basic research in robotics has been drastically reduced in the past year. The U.S. 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. The U.S. is in danger of losing its leading position in other aspects of robotics as well.

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FOREWORD

> We have come to know that our ability to survive and grow as a nation to a very large degree depends upon our scientific progress. Moreover, it is not enough simply to keep abreast of the rest of the world in scientific matters. We must maintain our leadership.[1]

President Harry Truman spoke those words in 1950, in the aftermath of World War II and in the midst of the Cold War. Indeed, the scientific and engineering leadership of the United States and its allies in the twentieth century played key roles in the successful outcomes of both World War II and the Cold War, sparing the world the twin horrors of fascism and totalitarian communism, and fueling the economic prosperity that followed. Today, as the United States and its allies once again find themselves at war, President Truman's words ring as true as they did a half-century ago. The goal set out in the Truman Administration of maintaining leadership in science has remained the policy of the U.S. Government to this day: Dr. John Marburger, the Director of the Office of Science and Technology (OSTP) in the Executive Office of the President made remarks to that effect during his confirmation hearings in October 2001.[2]

The United States needs metrics for measuring its success in meeting this goal of maintaining leadership in science and technology. That is one of the reasons that the National Science Foundation (NSF) and many other agencies of the U.S. Government have supported the World Technology Evaluation Center (WTEC) and its predecessor programs for the past 20 years. While other programs have attempted to measure the international competitiveness of U.S. research by comparing funding amounts, publication statistics, or patent activity, WTEC has been the most significant public domain effort in the U.S. Government to use peer review to evaluate the status of U.S. efforts in comparison to those abroad. Since 1983, WTEC has conducted over 50 such assessments in a wide variety of fields, from advanced computing, to nanoscience and technology, to biotechnology.

The results have been extremely useful to NSF and other agencies in evaluating ongoing research programs, and in setting objectives for the future. WTEC studies also have been important in establishing new lines of communication and identifying opportunities for cooperation between U.S. researchers and their colleagues abroad, thus helping to accelerate the progress of science and technology generally within the international community. WTEC is an excellent example of cooperation and coordination among the many agencies of the U.S. Government that are involved in funding research and development: almost every WTEC study has been supported by a coalition of agencies with interests related to the particular subject at hand.

As President Truman said over 50 years ago, our very survival depends upon continued leadership in science and technology. WTEC plays a key role in determining whether the United States is meeting that challenge, and in promoting that leadership.

Michael Reischman
Deputy Assistant Director for Engineering
National Science Foundation

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[1] Remarks by the President on May 10, 1950, on the occasion of the signing of the law that created the National Science Foundation. *Public Papers of the Presidents* 120: p. 338.

[2] http://www.ostp.gov/html/01_1012.html.

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EXECUTIVE SUMMARY

George Bekey

EXECUTIVE SUMMARY

- 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 U.S.
- There are numerous start-up companies in robotics, both in the U.S. and abroad. Venture capital appears to be available.
- The U.S. 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, particularly in such areas as cargo handling and mining, as well as in the theory and application of localization and navigation.
- In contrast with the U.S., Korea and Japan have national strategic initiatives in robotics; the European community has EC-wide programs. In the U.S., DARPA programs are highly applied and short-term oriented, while its support for basic research in robotics has been drastically reduced in the past year.
- The U.S. 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. We are in danger of losing our leading position in other aspects of robotics as well.
- Some examples of funding disparities:
  - In Korea, robotics has been selected as one of 10 areas of technology as “engines for economic growth”; the total funding for robotics is about $80 million per year. By contrast, NSF funding for robotics is under $10 million per year; funding from other agencies is small. DARPA support is restricted to military robotics.
  - In Europe, a new program called “Advanced Robotics” is about to be funded at about $100 million for three years.

A summary of the areas of major strength in various aspects of robotics in the U.S., Asia, and Europe is given in Table 1 below. 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 E.1
Robotics comparison chart

AREA		DEGREE OR LEVEL OF ACTIVITY			
		U.S.	JAPAN	KOREA	EUROPE
INPUT	Basic, university-based research (Individuals, groups, centers)	*****	***	***	***
	Applied, industry-based research (corporate, national labs)	**	*****	****	****
	National or multi-national research initiatives or programs	**	*****	*****	****
	University-industry-government partnerships; entrepreneurship	**	*****	*****	****
OUTPUT	Robotic vehicles: military and civilian	****	**	**	**
	Space robotics	***	**	NA	***
	Humanoids	**	*****	****	**
	Industrial robotics: manufacturing	**	*****	**	****
	Service robotics: non-manufacturing	***	***	****	***
	Personal robotics: home	**	*****	****	**
	Biological and biomedical applications	****	**	**	****

NA = Not applicable

OBJECTIVES OF THE STUDY

The purpose of this study was to assess the state of robotics worldwide and to compare the R&D programs in this field between the U.S. and other countries. The comparison was to be based on the criteria of quality, scope, funding and potential for commercialization. In order to obtain a baseline for comparisons, the study was to begin with an assessment of the status of robotics in the U.S.

In order to restrict the study to the level of available funding, the survey was restricted to current efforts in Japan, South Korea, and Western Europe. Clearly, significant work is going on in many other countries, but it was not possible to include them all in this survey. Australia was included by a “virtual site visit,” where selected laboratories were requested to answer a series of questions and to provide pictures of the major robotic systems they have developed. Nevertheless, the work in the countries studied provides an excellent overview of work outside of the United States.

An additional objective of the study was to encourage international cooperation in robotics research between the U.S. and other countries. Currently, exchanges of ideas occur primarily at international conferences, but there are few active research collaborations between the U.S. and other countries. By its very nature, there are significant collaborations between member states of the European community.

This report is a presentation of the findings of this study to our sponsors, other U.S. government agencies, Congress and the wider technical community from industry and academia.

CHAPTER 1

INTRODUCTION

George Bekey

HISTORY AND METHODOLOGY

The major milestones in the project have been the following:

July 2003

G. Bekey was invited by J. Yuh (NSF) and Y. T. Chien (WTEC) to form a team of researchers for a study of the status of robotics R&D in the U.S. and abroad.

January 2004

NASA Headquarters (D. Lavery) joins as a major supporter of the project.

February 2004

Study Team is formed. Members meet at NSF to plan a "U.S. Workshop" as a baseline for the international study.

July 2004

"Status of Robotics R&D in the U.S." Workshop is held at NSF. Approximately 100 participants present "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
- Multi-robot systems
- Humanoid robots

and applications in such fields as:

- Entertainment
- Education
- Medicine and rehabilitation
- Military
- Space
- Underwater

The proceedings of this workshop have been published and are available from WTEC at http://www.wtec.org/robotics/us_workshop/welcome.htm.

October 2004

Team travels to Japan and Korea, visiting 29 sites.

April 2005

Team travels to Europe, visiting 21 laboratories in six countries.

September 2005

Results of study are presented at a public workshop. Draft report is completed.

December 2005

Virtual site visits are conducted with two laboratories in Australia.

January 2006

Final report is completed.

THE STUDY TEAM

The 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 included:

- 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

All administrative arrangements for the team's meetings and travel were handled by WTEC under a grant from NSF, with additional funding from NASA and the National Institute for Biomedical Imaging and Bioengineering (NIBIB) of the NIH.

SITES VISITED DURING THE STUDY

The team visited laboratories in Asia (Japan and Korea) and Europe (Germany, England, France, Italy, Sweden and Switzerland). While there is significant work in robotics in other countries (such as Australia, Belgium, China, Russia, Spain and others) the itinerary was constrained by time and budget. Based on extensive discussions among team members, consultation with sponsors, and email discussions with colleagues throughout the world, the visits were restricted to the specific countries listed above. The complete list of all sites visited is given in Table 1.1. In addition, “virtual site visits” were conducted with two leading laboratories in Australia. The directors of these laboratories submitted replies to questions from the team and provided pictures of the robots they developed. Site visit reports from all the listed laboratories are available in Appendices B and C of the final report. The virtual site visit reports from Australia are in Appendix D.

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
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

Table 1.1
Sites visited in Asia and Europe

Site	Panelists	Date
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
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

Most visits were completed in half a day. Even so, in order to visit 20 laboratories in Japan in one week it was necessary to split the team into two smaller groups. 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:

From NASA:

- David Lavery, NASA Headquarters
- Minoo Dastoor, NASA Headquarters

From NSF:

- Junku Yuh (Director, Robotics and Computer Vision Program)

From WTEC:

- Y.T. Chien
- Hassan Ali
- Masanobu Miyahara

QUESTIONS FOR HOSTS

In order to focus the discussions in the various laboratories, the host engineers and scientists were provided with a set of questions in advance of the visits. While the discussion did not necessarily follow the specific questions, 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? With labs in other countries?
6. What other major research groups *in your country* are working in your area of research?
7. What other major research groups *outside of your country* are working in your area of research?
8. How do you assess robotics research in the U.S. as compared to your country? In your field of robotics, do you think your country is leading the U.S.?

OVERVIEW OF THE REPORT

This report is organized into six chapters, each concerned with a major area of robotics. 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 U.S., Korea, Japan and the European countries visited
- Provides a qualitative comparison between R&D activities in these regions

The specific topics and their authors are:

- Chapter 2: Robotic vehicles by Arthur Sanderson, George Bekey and Brian Wilcox

- Chapter 3: Space robotics by Brian Wilcox, Robert Ambrose and Vijay Kumar
- Chapter 4: Humanoid robots by Robert Ambrose, Yuan Zheng and Brian Wilcox
- Chapter 5: Industrial, service and personal robots by Vijay Kumar, George Bekey and Yuan Zheng
- Chapter 6: Robotics in biology and medicine by Yuan Zheng, George Bekey and Art Sanderson
- Chapter 7: Networked robots by Vijay Kumar, George Bekey and Art Sanderson

Appendix A has short biographies of the panelists. Appendices B and C have the site reports for Asia and Europe, respectively. Appendix D contains the virtual site visit reports for Australia, and Appendix E is a glossary.

CHAPTER 2

ROBOTIC VEHICLES

Arthur Sanderson, George Bekey, Brian Wilcox

INTRODUCTION

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, that is, "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," or 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.

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 one 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 Figure 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.

Figure 2.1. NASA Mars Rover (NASA Jet Propulsion Laboratory (JPL)).

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 hundred meters or more, but pressure, light, 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 of up to 3,000 meters in depth and is capable of carrying a wide variety of instrumentation for physical, chemical, and biological sensing and monitoring. In United States research, 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.

Figure 2.2. IFREMER ASTER autonomous underwater vehicle.

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.

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.

(a)

(b)

Figure 2.3. Agricultural robotic vehicle (Int Harv, U.S.) (a). Mining haul truck (ACFR, Australia) (b).

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.

Figure 2.4. IBOT advanced wheel chair (DEKA, U.S.).

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 aides increasingly capable and practical for everyday use. An example of a wheelchair that utilizes emerging robotic technologies for guidance and balance is shown in Figure 2.4. More details on medical robotics and robotic aids to the handicapped will be described in Chapter 6.

Other examples of such personal aides 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 Figure 2.5, is a major topic of this international comparative study. More detailed examples of personal and entertainment robotic vehicles will be described in Chapter 5, and of humanoid robots in Chapter 4.

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

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. In order to achieve these various modes of propulsion, a large number of different technological solutions have been proposed and investigated. 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:

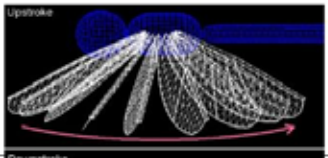
   Engineering solutions are borrowed from the evolution of technologies that have been developed over many centuries for transportation. Robotic ground vehicles are developed with wheels and treads, much like automobiles. Robotic air vehicles are developed with propellers, or jet engines, and stationary 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 have 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.

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 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 a physical and behavioral manner.

Table 2.1
Types of robotic mobility systems

	Engineering Design	Biomimetic Design
AIR		
GROUND		
WATER		

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 pre-programmed motions (e.g. missiles and torpedoes). However, only with the development of microelectronics and embedded computation has it 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:

Mechanisms and Mobility

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

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 “quasi-static” 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 current research topics.

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 micro fuel 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 six to eight hours of continuous underwater operation.

Figure 2.6. Solar-powered AUV (Autonomous Undersea Systems Institute (AUSI), FSL, Rensselaer Polytechnic Institute (RPI), U.S.).

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

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 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 Figure 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 ten meters away with no likely collisions”), and a first simple motion control (e.g. “move the wheel motors at one revolution per minute”).

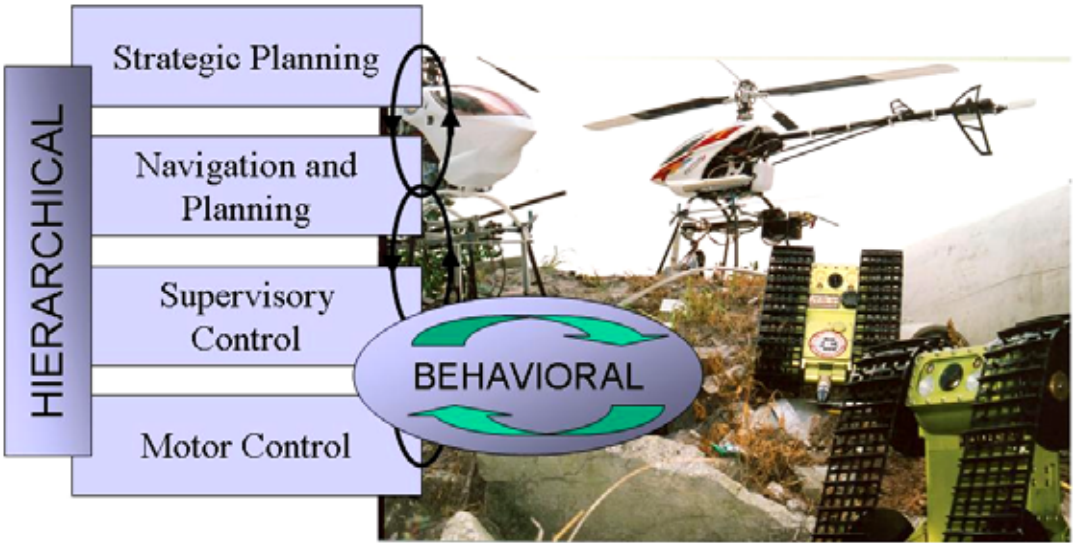


Figure 2.7. Integration of hierarchical and behavior control architectures in a search-and-rescue domain (Center for Robot-Assisted Search and Rescue (CRASAR), University of South Flordia (USF), U.S.).

Behavioral Control Structures

The behavior 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 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 behavior architectures continue to be 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. The integration of such embedded software systems is a major key to the success and longevity of vehicle prototypes and products. In addition, advances in communications technologies provide information links for command and control and have a strong role in multivehicle and distributed architectures.

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 monitor the environment and are used 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 microelectromechanical systems technologies for specific sensors in air and water. Detection of nitrogen compounds in air, and detection of dissolved oxygen in water, support valuable environmental applications.

b. Sensors are essential to the fundamental 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 ten 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 U.S., Europe, and Australia, have derived algorithms that enable a vehicle to efficient 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 able 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 tremendous 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 Figure 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 define fundamental principles that underlie the consistent interpretation of such complex activities, and support the development of reliable implementations.

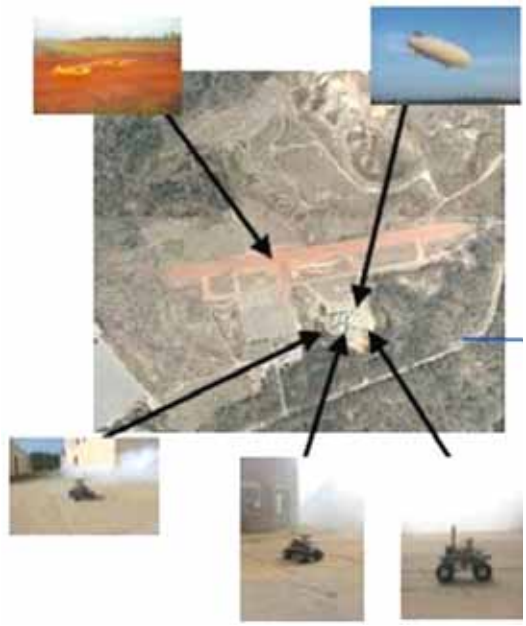


Figure 2.8. Integration of sensor and navigation in a military application (U. Penn, U.S.).

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 of types of vehicles, approaches to design, and the applications of interest have varied among these different international communities. This section summarizes these observations.

Research on Robotic Vehicles – United States

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

Military and Defense Systems

U.S. investment in robotic vehicle research has strongly emphasized the development of ground, air, and underwater vehicles with military applications. As shown in Figure 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, that is, a human controller works interactively to move the vehicle and position 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 U.S. is generally acknowledged as the world leader in military applications of robotic vehicle technologies.

Figure 2.9. Examples of military and defense robotic vehicles.

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 Chapter 3. 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 U.S. NASA effort has been the only successful demonstration of interplanetary vehicle space technology and is clearly recognized as the world leader in this domain.

Field Robotics

Robotic vehicles developed for both military and space applications are intended for use in rough terrain, that is, without roads or cleared areas. In this context, the experience of off-road robotic vehicles in the U.S. 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, U.S. industrial companies active in these areas have invested in prototype developments for these applications. Figure 2.3 is an example of these prototype vehicles.

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,' U.S. 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 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.

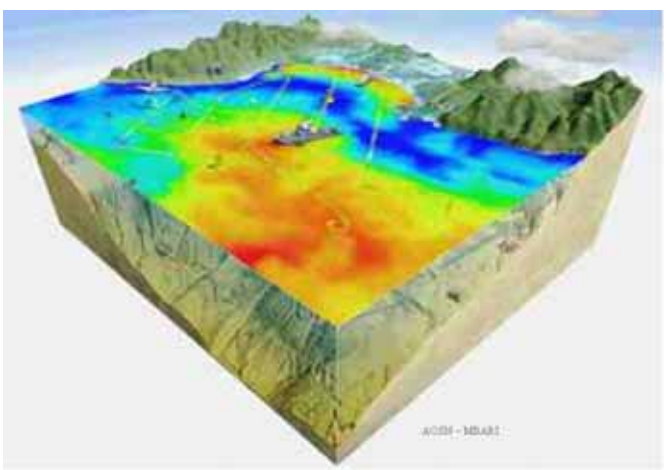


Figure 2.10. Advanced Oceanographic Sensor Network (MBARI, U.S.).

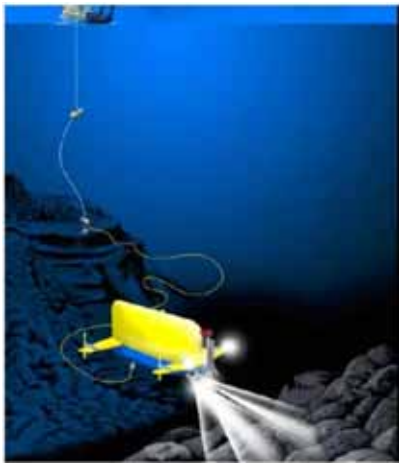


Figure 2.11. HROV (Hybrid ROV) project (Johns Hopkins University (JHU) and Woods Hole (WHOL), U.S.).

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, deepsea biological phenomena, and migration and changes 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 U.S. 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 to 11,000 meters depth as shown in Figure 2.11.

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 disasters, like 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 Figure 2.12.

Figure 2.12. Search-and-rescue robotics (CRASAR, USF, U.S.).

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

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 areas of opportunity. Examples of household robotic vehicles include vacuum cleaners, as shown in Figure 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 Chapter 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.

Figure 2.13. Personal and service robots (Hanool, S. Korea).

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

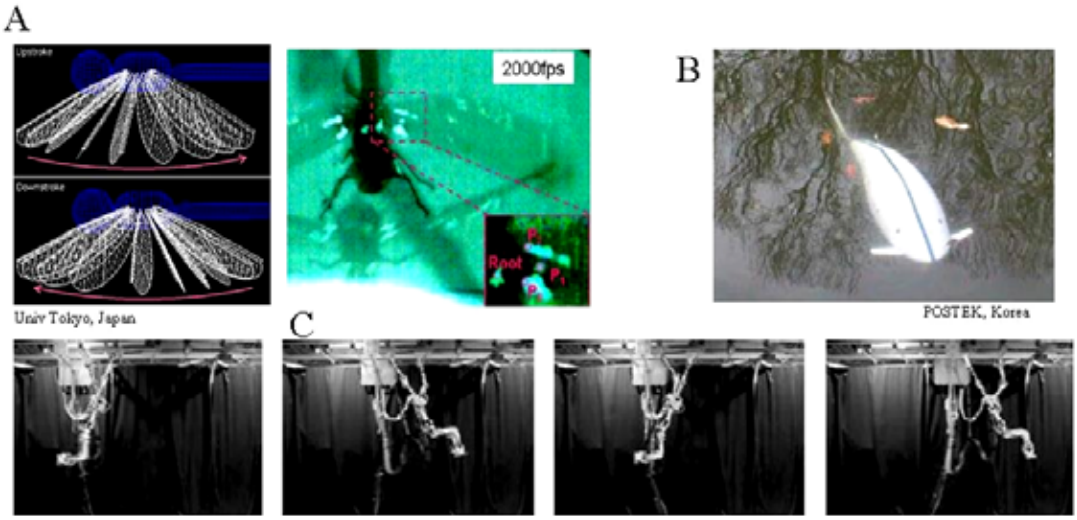


Figure 2.14. Projects in biomimetic robot design. A. Insect flight studies (Uno, U. Tokyo, Japan), B. Robotic fish (Pohang University of Science & Technology (POSTECH), S. Korea), C. Brachiation robot (U. Nagoya, Japan).

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

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 deepsea vehicles for ocean science and exploration of ocean resources. Figure 2.15 shows the URASHIMA vehicle, which is ten meters long and will be powered by fuel cell technology.

Figure 2.15. URASHIMA AUV (JAMSTEC, Japan).

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 a 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.

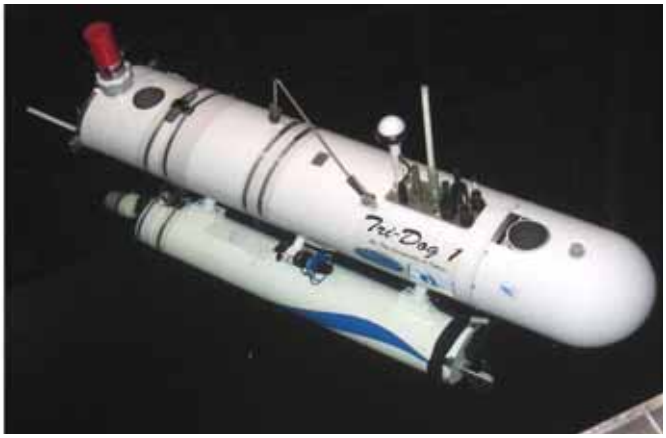


Figure 2.16. Tri-Dog AUV with sensor guidance (U. Tokyo, Japan).

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.

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, U.K., and the University of Karlsruhe, Germany, on computational architectures and communications in support of algorithms for navigation and mapping. These programs have 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 Figure 2.17. European laboratories have been among the leaders in international research in these fundamental areas.

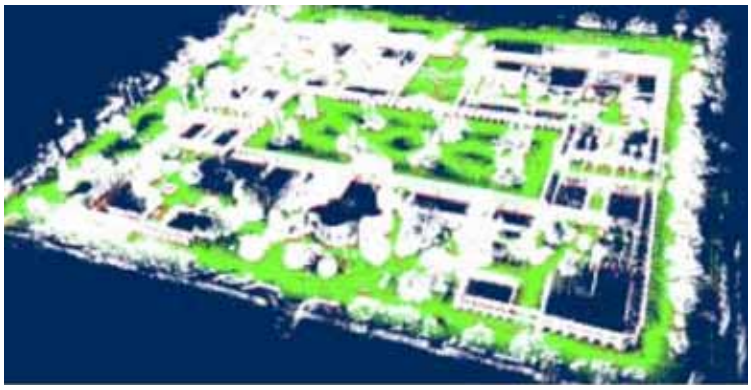


Figure 2.17. Sensor-based mapping and localization using SLAM algorithms (U. Oxford, U.K.).

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.

Figure 2.18. CYBERCar Prototype (INRIA, France).

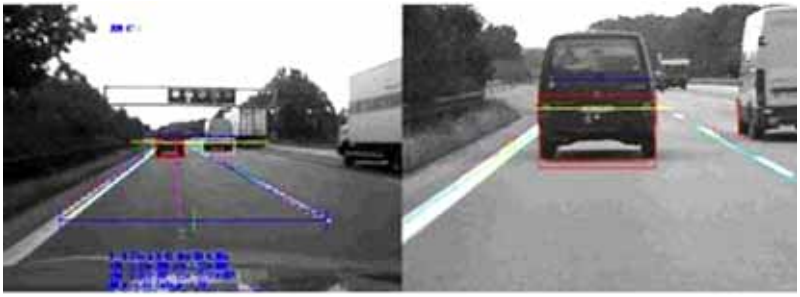


Figure 2.19. Autonomous road following and vehicle following at high speed (U. Braunschweig, Germany).

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

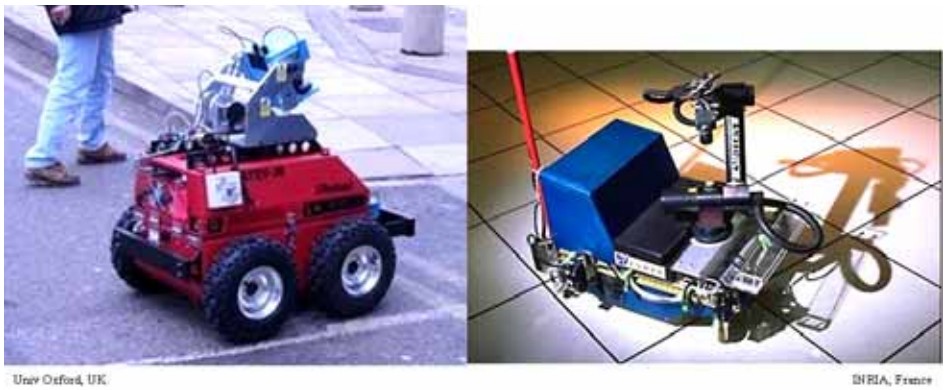


Figure 2.20. Prototype vehicles used in urban and indoor settings.

Undersea Robotics

European programs have been very active in undersea robotics research. Programs at the Heriot-Watt University in Edinburgh, U.K., Southampton University in the U.K., 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.

Figure 2.21. Undersea robotic vehicles.

COMPARITIVE REVIEW OF PROGRAMS

Based on the visits described in this report 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 6.2. In order to further analyze these activities a review of papers published in the Proceedings of the 2005 IEEE International Conference on Robotics and Automation was conducted and the distribution of papers in the areas of robotic vehicles was compiled. These results are consistent overall with the priority list shown in Table 2.2.

Table 2.2
International research priorities in robotic vehicles

Region	Research Priorities
United States	Outdoor Vehicular Mobility: Ground, Air, Undersea Navigation and Mapping in Complex Outdoor Environments *Key Applications:* Defense, Space
Japan and South Korea	Indoor Mobility using Humanoid Locomotion Novel Mechanisms of Locomotion *Key Applications:* Service, Entertainment, Commercial Applications
Europe	Mobility in Urban and Built Environments Sensor-based Navigation with Maps *Key Applications:* Infrastructure Support and Transportation

A further analysis of these areas of research resulted in the chart of comparative analysis of research activities in the area of robotic vehicles shown in Table 2.3.

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

- U.S. 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.
- U.S. 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

Table 2.3
Comparative analysis of international programs in robotic vehicles

Area	U.S.	Japan/Korea	Europe
Basic			
Mobility	**	****	***
Power	**	***	***
Architecture	****	**	****
Navigation	***	**	***
Applications			
Entertainment	*	****	**
Field	***	**	***
Military	****	*	**
Personal/Service	**	****	***
Space	****	*	**
Transportation	**	***	****
Undersea	****	***	****

REFERENCES

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

Arkin, R. C. 1998. *Behavior-Based Robotics*. Cambridge, MA: MIT Press.

Bekey, G. A. 2005. *Autonomous Robots: From Biological Inspiration to Implementation and Control.* Cambridge, MA: MIT Press.

Braunl, T. 2001. *Embedded Robotics: Mobile Robot Design and Applications with Embedded Systems.* New York: Springer-Verlag.

Choset, H., K. Lynch, S. Hutchinson, G. Kantor, W. Burgard, L. Kavraki, S. Thrun. 2005. *Principles of Robot Motion: Theory, Algorithms, and Implementations.* Cambridge, MA: MIT Press.

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Murphy, R. 2000. *An Introduction to AI Robotics.* Cambridge, MA: MIT Press.

Siegwart, R. and I. R. Nourbakhsh. 2004. *Introduction to Autonomous Mobile Robots.* Cambridge, MA: MIT Press.

Thrun, S., W. Burgard and D. Fox. 2005. *Probabilistic Robotics.* Cambridge, MA: MIT Press.

CHAPTER 3

SPACE ROBOTICS

Brian Wilcox, Robert Ambrose, Vijay Kumar

WHAT IS SPACE ROBOTICS?

Space robotics is the development of 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 from either a "local" control console (e.g. with essentially zero speed-of-light delay, as in the case of the Space Shuttle robot arm (Figure 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 (Figure 3.2) controlled from 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).

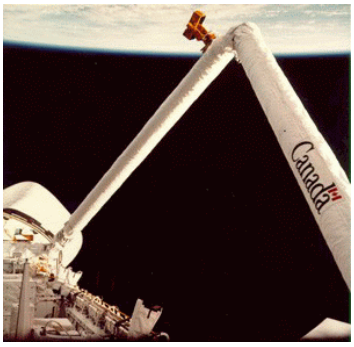

Figure 3.1. Space Shuttle robot arm developed by Canadian Space Agency.

Figure 3.2. Mars Exploration Rover.

Figure 3.3. Artist's conception of Robot Blimp on Titan.

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, 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 place when it stops operating, since the cost of return-to-Earth is (literally) astronomical (and that cost would be better spent in return of scientific samples in almost every case). Missions to distant targets such as Titan (a moon of Saturn thought to have liquid methane lakes or rivers) presently require a substantial fraction of a human lifetime during the transit from Earth to the destination. Access to space is expensive (currently about $10,000 for every kilogram lofted into Low Earth Orbit (LEO)), implying that, for certain jobs, robots that are smaller than a human and require much less infrastructure (e.g. life support) makes them very attractive for broad classes of missions.

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

ISSUES IN SPACE ROBOTICS

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 risk, **Manipulation**—using arms and hands 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.

Shown in Figure 3.5 is 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. The "supervisory control" provided by human operators is at a higher level, allowing the vehicle to stay productive even though humans only give 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 of the expected range will cause the vehicle to "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 Figure 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 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.

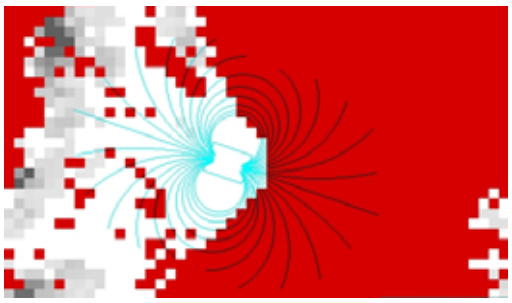

Figure 3.5. MER path planner evaluates arcs through sensed terrain (gray levels indicate traversability; red, unknown terrain).

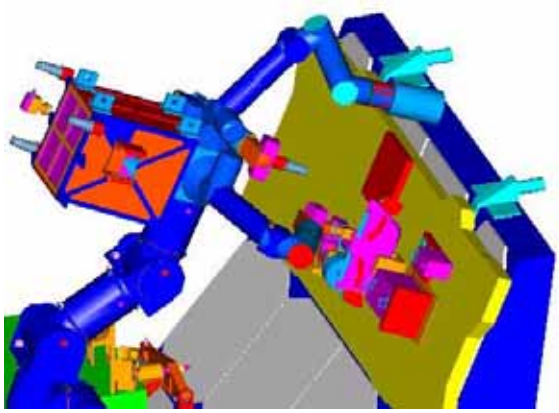

Figure 3.6. Ranger (U. MD) robot was developed to demonstrate advanced robotics in the space shuttle payload bay.

All space robots share a need to operate in extreme environments. Generally this includes increased levels of ionizing radiation, requiring non-commercial 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 at a minimum systems that are cooled not by air or convection, but by conduction. 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 cost.

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 over 80,000 images and 1.5 million spectra since arriving on Mars in January 2004 (Bowen, 2005). 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.

Figure 3.7. Robot arm on Mars Exploration Rover.

Robonaut (Figure 3.8) is an "astronaut-equivalent" robot being developed at the Johnson Space Center. The central premise of robonaut is that a robot that is about the same size, strength, and dexterity as a suited astronaut 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.

Figure 3.8. Robonaut performing dexterous grasp.

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

Figure 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 stereo correlation, a process where images taken from stereoscopic cameras are matched together to calculate 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 an important decision. 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 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 Figure 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%. While stereo vision 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 loadbearing strength of the soil. Shown in Figure 3.13 is "Purgatory Dune," a soft soil formation on Mars where the rover Opportunity got stuck for five weeks in the spring of 2005. Shown in Figure 3.14 are the tracks leading into 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 require specialized sensors.

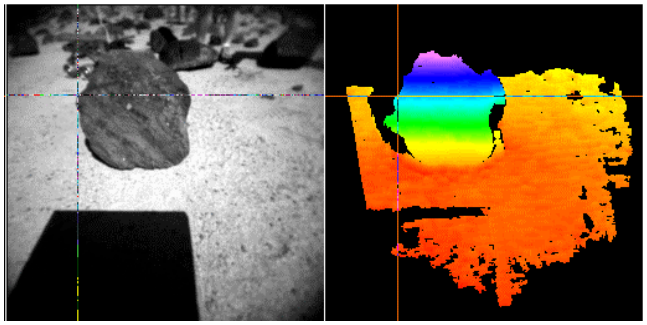

Figure 3.11. Stereo correlation example.

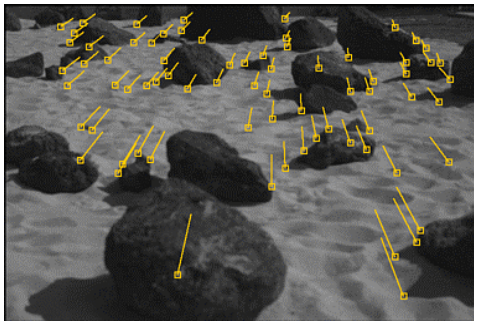

Figure 3.12. Visual odometry example.

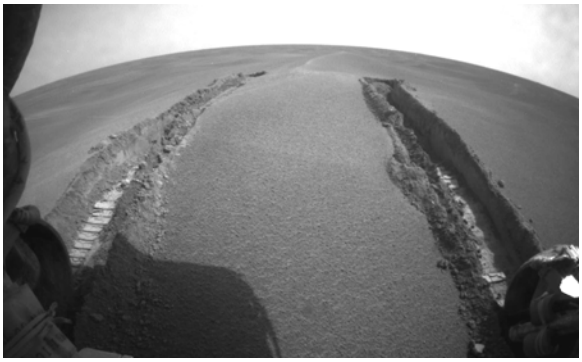

Figure 3.13. Opportunity rover image of Purgatory Dune.

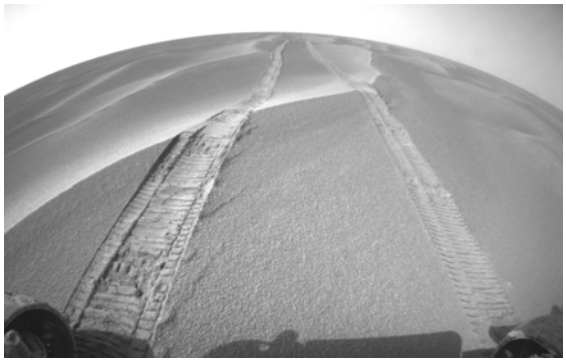

Figure 3.14. Opportunity image of rover tracks leading into Purgatory Dune.

Another area of fundamental research for space robotics relates to manipulation. 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 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 now permitted in industry.

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 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 doesn't result in overshoot or oscillation of the slave arm. The human gives commands for motions that can include contact with elements of the worksite, but those contact forces are managed within a preplanned 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.

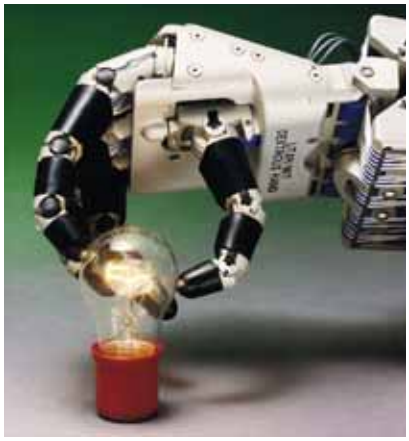

Figure 3.15. SARCOS dexterous hand capable of force control.

Figure 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.

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

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

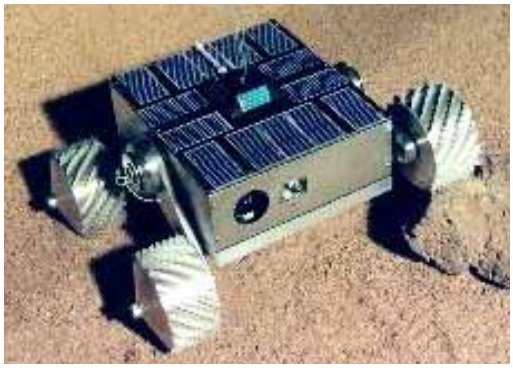

Figure 3.19. 1.5 kg Nanorover developed by JPL for asteroid or Mars exploration.

Figures 3.17–23 show a variety of planetary rovers developed in the U.S. The rovers in Figures 3.17–19 and 3.24 were developed at the Jet Propulsion Laboratory; the rovers in Figures 3.20–23 were developed at Carnegie-Mellon University (with the rover in Figure 3.20 jointly developed with Sandia Laboratories).

Figures 3.25–29 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 given to Canada by mutual agreement in the 1980s).

Figure 3.20. RATLER rover developed jointly by Carnegie-Mellon University and Sandia Laboratory for use on the moon.

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

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

Figure 3.23. Nomad rover, developed by Carnegie-Mellon University, explored part of Antarctica in 1997 and 1998, and the Atacama desert in Chile in 1996–7.

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

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

Figure 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.

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 approaches to certain space missions. Figures 3.32–33 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.

Figure 3.26. Phoenix arm, developed by the Jet Propulsion Laboratory 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.

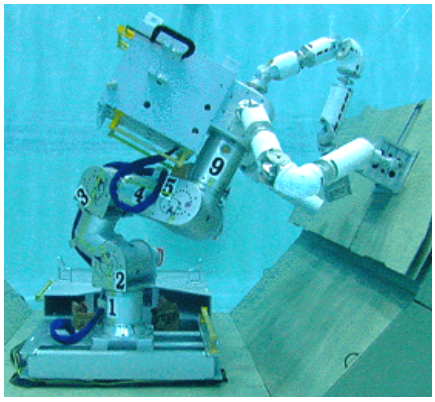

Figure 3.27. Ranger Manipulator, developed by the University of Maryland, to demonstrate a wide variety of competent manipulation tasks in Earth orbit. Flight hardware was developed in the 1990s for both an expendable launch vehicle and the Space Shuttle, but at present there is no manifest for a flight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

The Japanese have also developed advanced robotic elements for the Japanese Experiment Module (JEM) of the International Space Station. The Remote Manipulator System, or 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 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 meters (32.5 feet) long, and the SFA measures 1.9 meters (6.2 feet). Figure 3.34 shows the SFA, which is awaiting launch.

Figure 3.28. Special-purpose dexterous end-effector, developed by McDonall-Detwiler Robotics for the Canadian Space Agency.

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

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

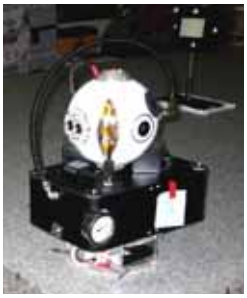

Figure 3.31. Mini-AERCam, under development at Johnson Space Center (JSC) for operational use on future space missions.

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”) approached in late 2005 the asteroid 25143 Itokowa, named after a Japanese rocketry pioneer. Hayabusa made only momentary contact with its target. It descended to the surface of the asteroid, and immediately fired a small (5 gram) 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 to be eased slowly onto the asteroid's surface, but the timing was not right and the Minerva was lost. For one to two days it was supposed to slowly leap about the asteroid taking surface temperature measurements and high-resolution images with each of its three miniature cameras. Minerva is shown in Figure 3.35.

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

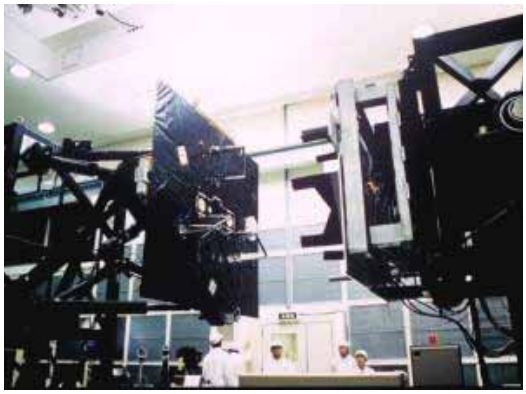

Figure 3.33. Docking adapter testing for the ETS-VII robotics technology experiment.

Figure 3.34. Japanese Small Fine Arm developed for the Japanese Experiment Module, awaiting launch to the International Space Station.

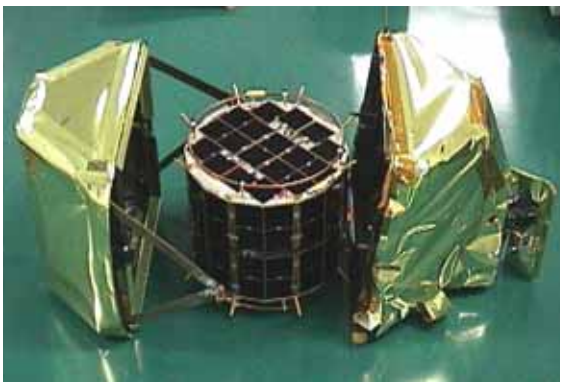

Figure 3.35. Minerva hopping robot developed in Japan for asteroid mission MUSES-C.

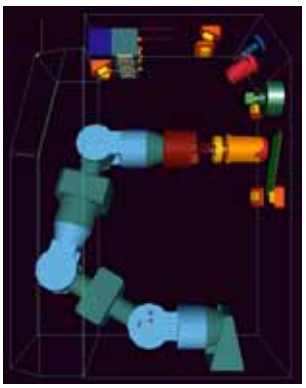

Figure 3.36. Schematic of German Rotex experiment flown in 1993 with a manipulator and task elements inside a protective cabinet.

European researchers have also been active in space robotics. ROTEX is 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 (Figure 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 applied to the motion of free objects. The system included a high-precision six-axis manipulator (robot arm) with grippers, tipped with distance, force, moment, and touch sensors that could be controlled (using stereoscopic vision) either from onboard the shuttle or from ground operators at DLR. More recently, DLR has developed ROKVISS (RObot

Komponent Verification on ISS). ROKVISS (Figure 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. Stereo cameras are used 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 ultra-light, impedance controllable and soft arms (Figure 3.39), which, combined with DLR's newest articulated four-fingered hands (Figure 3.40), are the essential components for future "robonaut" systems. The main goals of the ROKVISS experiment are the demonstration and verification of light-weight 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 3.38 shows the Spacecraft Life Extension System (SLES), which will use a DLR capture mechanism to grapple, stabilize, and refuel commercial communications satellites.

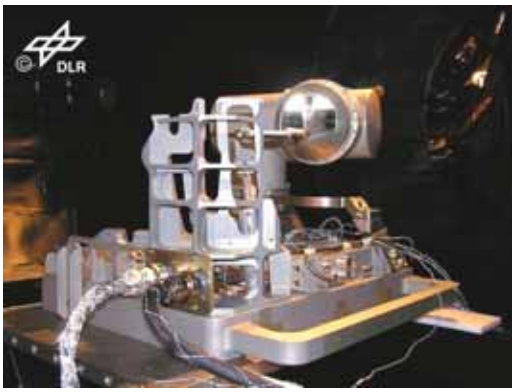

Figure 3.37. ROKVISS experiment currently flying on International Space Station.

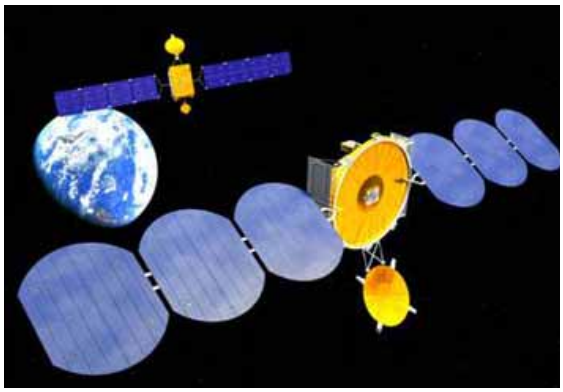

Figure 3.38. Spacecraft Life Extension System (SLES), which will use a DLR capture mechanism to grapple, stabilize, and refuel commercial communications satellites.

Figure 3.39. Advanced dexterous manipulator arm for space applications developed at DLR.

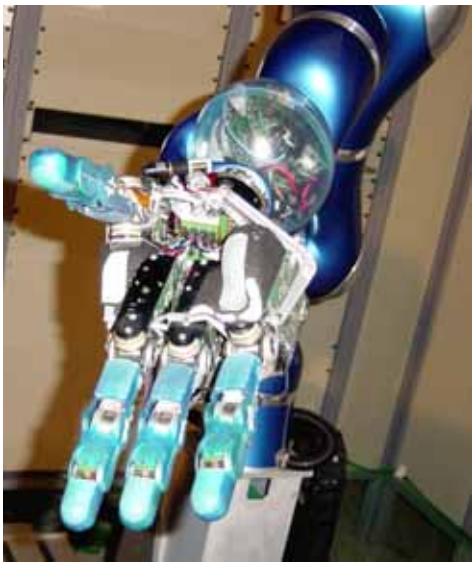

Figure 3.40. Dexterous four-fingered hand developed for space applications at DLR.

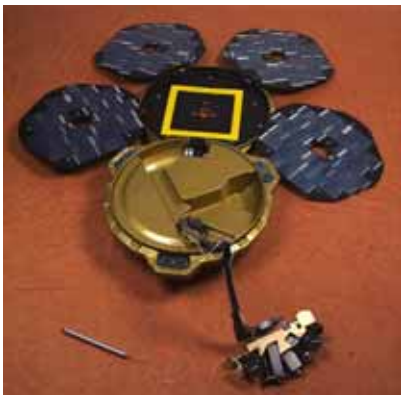

Figure 3.41. Beagle-2 Mars lander with robot arm developed in the U.K.

Figure 3.42. Artist's conception of ExoMars rover planned by the European Space Agency.

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 for the ExoMars mission that the European Space Agency is considering for launch at about the end of this 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 (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.

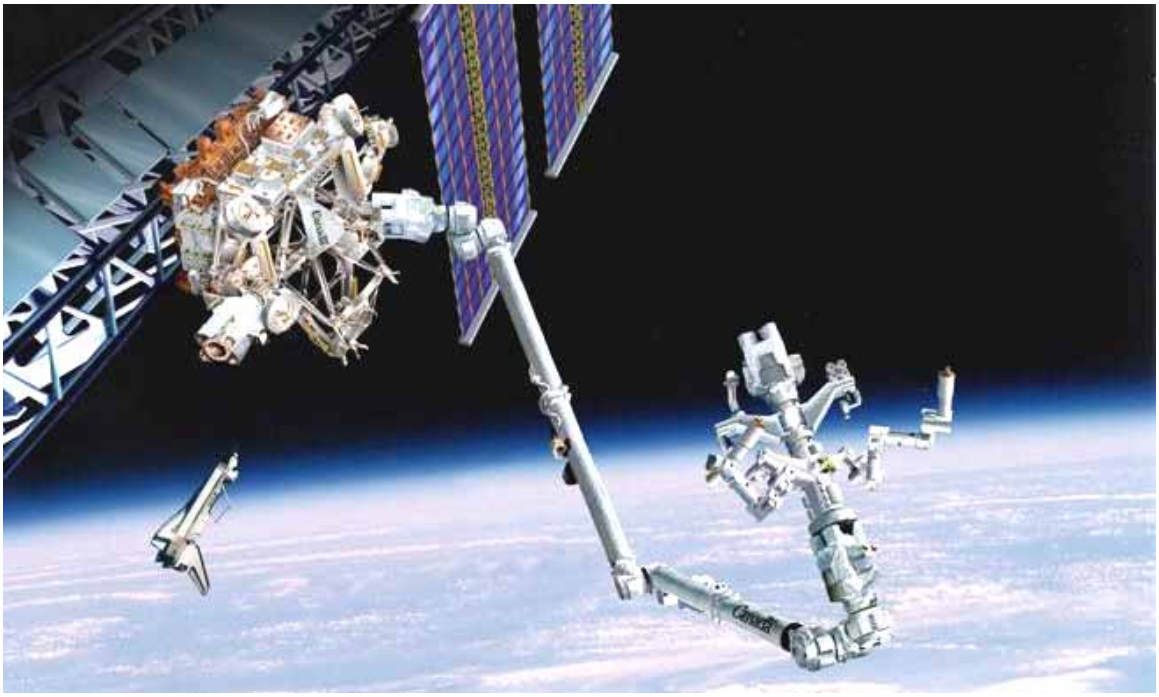

Figure 3.43. Special Purpose Dexterous Manipulator on the end of the Space Station Remote Manipulator System, both developed for the Canadian Space Agency. The SSRMS is now in-flight, and the SPDM is awaiting launch.

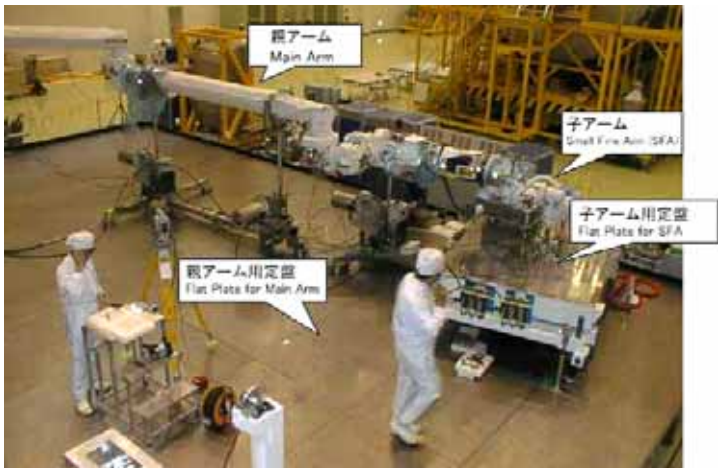

Figure 3.44. Main arm and Small Fine Arm undergoing air-bearing tests. Both were developed for the Japan Aerospace Exploration Agency (JAXA), and are awaiting launch to the International Space Station.

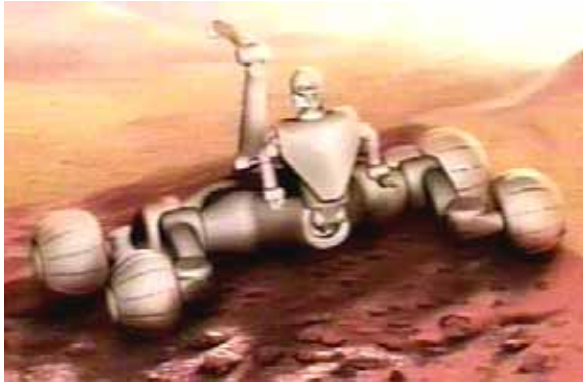

Figure 3.45. Artist conception of a centaur-like vehicle with a robonaut upper body on a rover lower body for use in Mars operations.

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

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 Rotex (1993) and the experimental 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, Figure 3.43) and the Japanese Main Arm and Small Fine Arm (SFA, Figure 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 U.S. 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 Systems Research and Technology (ESRT) programs 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 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.

Figure 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.

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

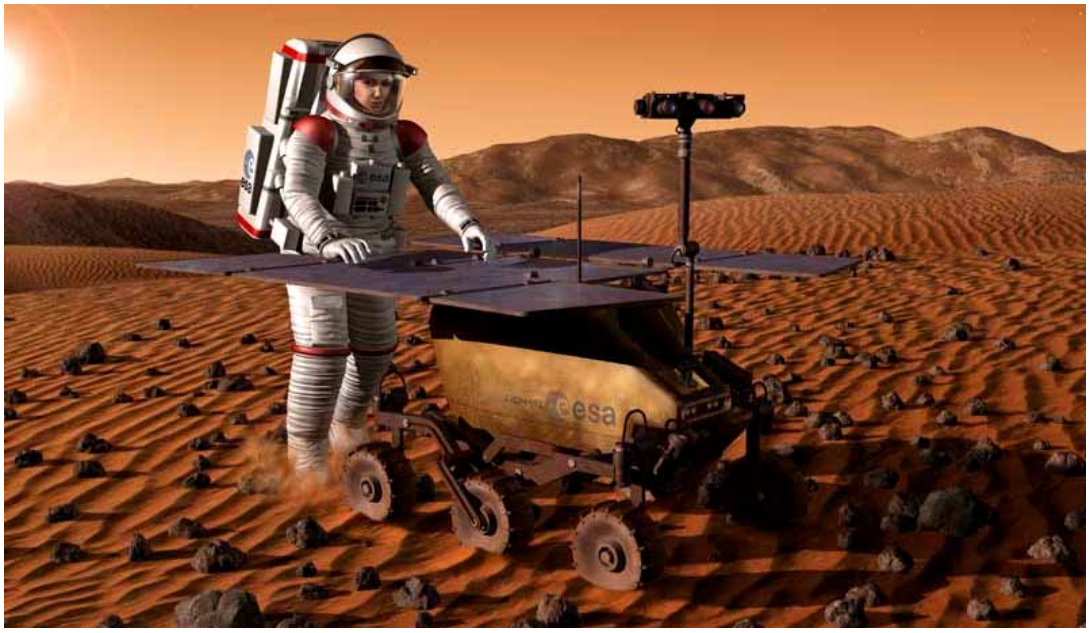

Figure 3.49. Artist's conception of a future European Space Agency astronaut examining the ExoMars rover.

In Asia, the Japanese have consolidated most space robotics work at NEC/Toshiba, who have several proposals submitted but no currently 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 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 Figure 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, reboost and stabilization system to go after the market in commercial satellite life extension. In the U.S., 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 significant capability for rover

hazard avoidance, roughly comparable to the U.S. 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.

Table 3.1
A qualitative comparison between different regions and their relative strengths in space robotics

	U.S.	**Canada**	**Japan**	**Europe**
Basic:				
Mobility	****	*	**	***
Manipulation	**	***	***	***
Extreme Environment	***	**	**	**
Power, Comm, etc.	***	*	**	**
Applications:				
Rovers	****	*	**	***
Large Manipulators	*	****	****	*
Dexterous Manipulators	***	****	***	****
Free-Flyers	***	*	***	**

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 U.S. 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 defined yet, but may be substantial. Table 3.1 gives a qualitative comparison between the different regions of the world and the relative strength of their respective activities in Space Robotics. One star means that there is very little activity going on in this area; four stars means there is a deep body of expertise.

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, dexterous hands, despite multi-second time delay.

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CHAPTER 4

HUMANOIDS

Robert Ambrose, Yuan Zheng, Brian Wilcox

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 Capek 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.

Figure 4.1. Capek Paris Production, 1924; Asimov, Will Smith, *I Robot*, 2004.

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. The above figures show 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 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 U.S. and Europe. Humanoid robotics, beyond science fiction, began thirty years ago, with increased momentum in the last ten 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.

DEFINITIONS OF THE HUMANOID SYSTEM

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.

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

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 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 non-anthropomorphic 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.

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.

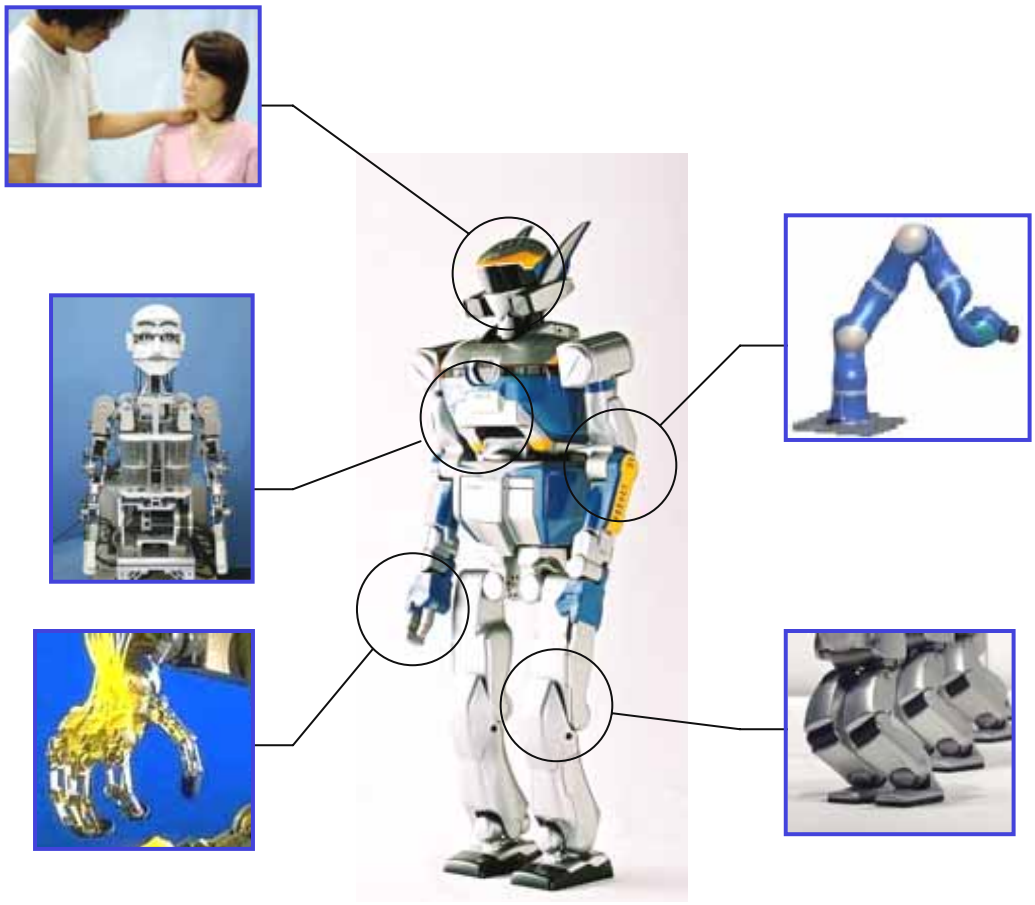

Figure 4.3. Gross anatomy of the humanoid—heads, torsos, arms, hands, legs.

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 non-critical 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.

CURRENT CHALLENGES IN HUMANOIDS

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 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 (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).

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

Figure 4.4. Honda, MIT, Sarcos, Toyota, NASA.

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.

Bipedal Walking

The majority of the biped walking systems are humanoid in form, and use the Zero Moment Point (ZMP) algorithm (Vukobratovic and Frank, 1969, Vukobratovic et al., 1970). In this algorithm, the tipping point of the system is managed forward or backwards to walk.

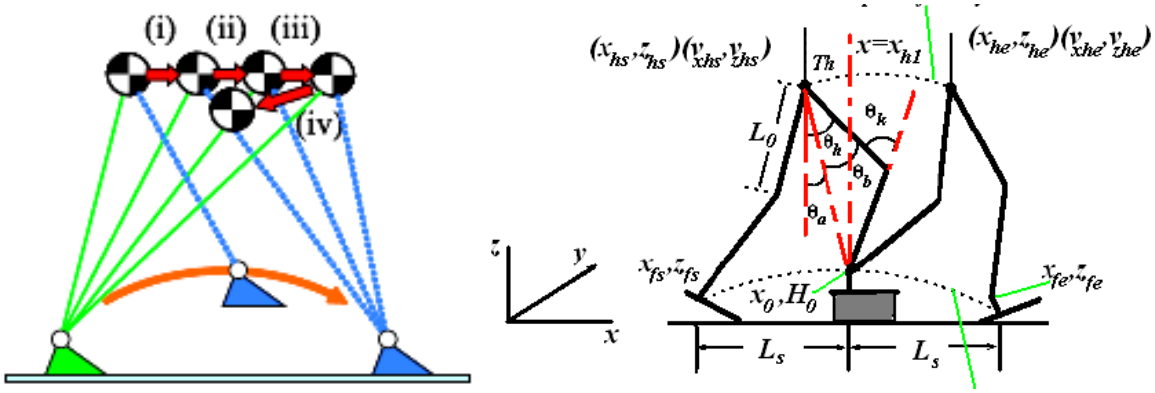

Figure 4.5. ZMP Mechanics.

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 testbed for developing and refining the ZMP walking systems. The Honda systems have many generations of success.

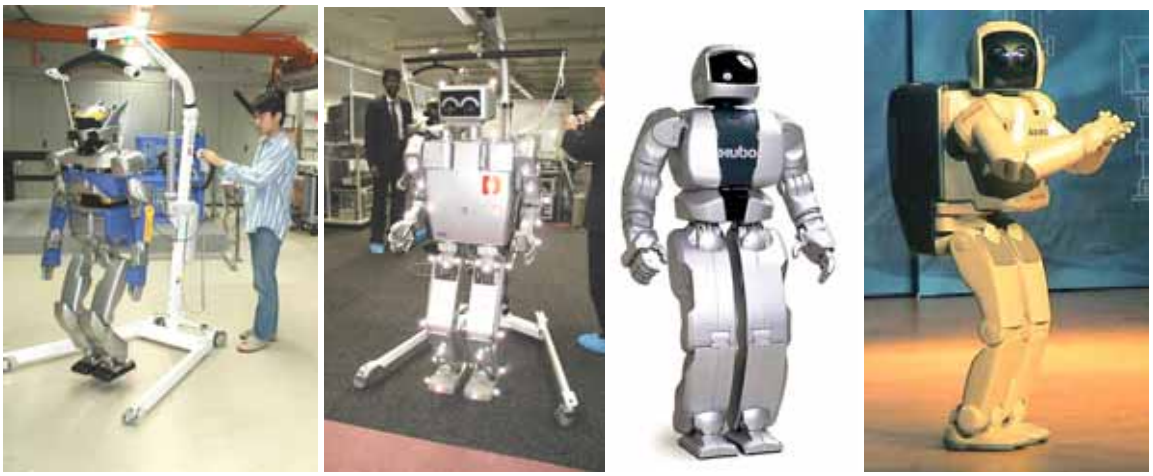

Figure 4.6. ZMP Walkers at AIST Tsukuba, AIST Waterfront, KAIST, Honda.

A more dynamic form of walking has been postulated (Zheng and Hemami, 1984, Pratt et al., 1997), 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.

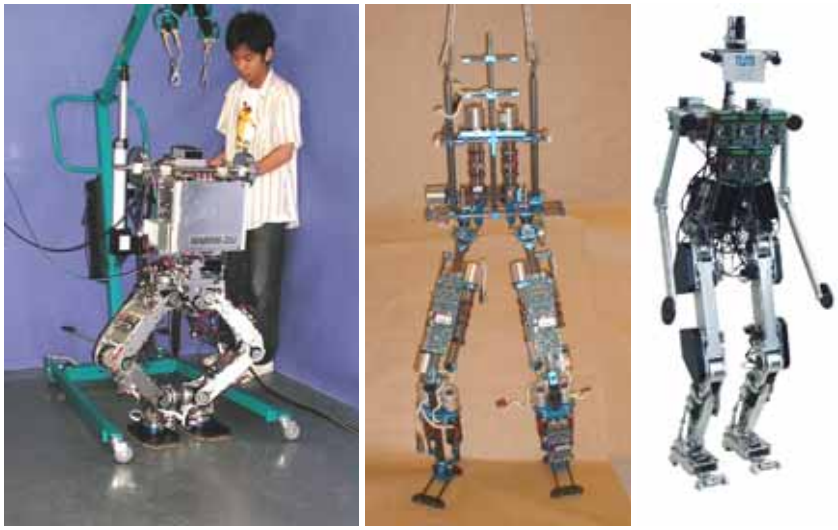

Figure 4.7. Dynamic Walkers at Waseda, MIT, TUM.

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 the figure below.

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

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.

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

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 stored in sensori-motor 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. The fundamental research in biologically inspired actuators will likely transform the nature of this domain in the next ten to fifteen years.

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

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 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 <6 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.

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

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 on the order of 5 kg or higher. They have embedded avionics allowing for dense packaging and modular application.

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 complimentary 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.

Figure 4.12. Mobile Manipulation at CMU, Stanford, RWTH Aachen and DLR.

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.

Figure 4.13. Human-Robot Interaction at Honda, Osaka Univ., MIT and KAIST.

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 1970, where the degree of human-like form and motion in human faces (Minato et al., 2004) is found to have a local minima 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 last several years.

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

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
e) Improved force control for whole body dynamics
f) Better tactile skins for sensing contact, touch and proximity to objects in the environment
g) Advanced navigation that perceives and selects footfalls with 1 cm scale accuracy at high body speed
h) Vestibular systems for coordinating upper limbs and head-mounted sensors on dynamic bodies
i) Dexterous feet for dynamic running and jumping
j) Dexterous hands for tool use and handling of general objects

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 so 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.

Fundamental Research Challenges

A fully capable and embodied humanoid makes a strong research testbed. 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?

REVIEW SITES

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.

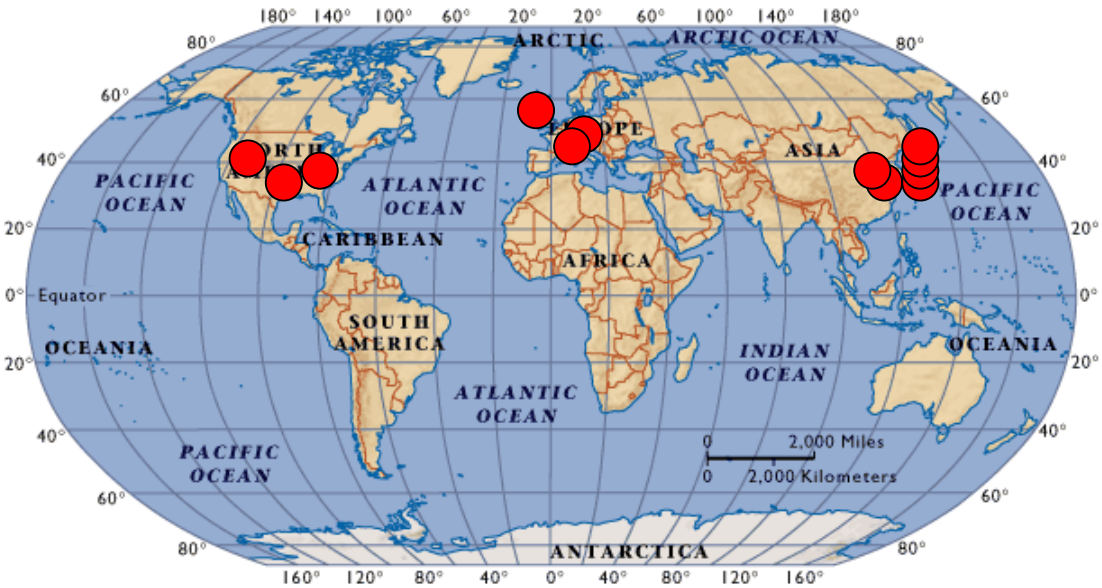

Figure 4.15. Humanoid systems reviewed.

OBSERVATIONS, APPLICATIONS, AND CONCLUSIONS

Quantitative Observations

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

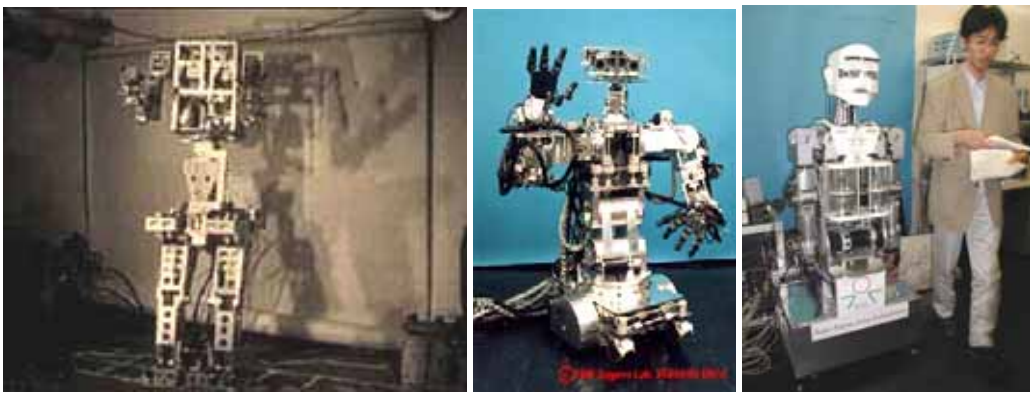

Figure 4.16. Humanoid systems Waseda, past and present.

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 the then the public release of the P series in 1997, was a major turning point in humanoid history. The evolutionary approach was remarkably organized and strategically guided. Recent work at Toyota indicates a similar interest and desire to build multiple forms of humanoids.

Figure 4.17. Honda and Toyota humanoids.

The prototypes at AIST Waterfront and AIST Tsukuba are the class of the field. These systems have taken a novel evolutionary path, developing the HRP-1 and HRP-2 systems with sub-generations that were legs only, then with arms, then re-integrated 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.

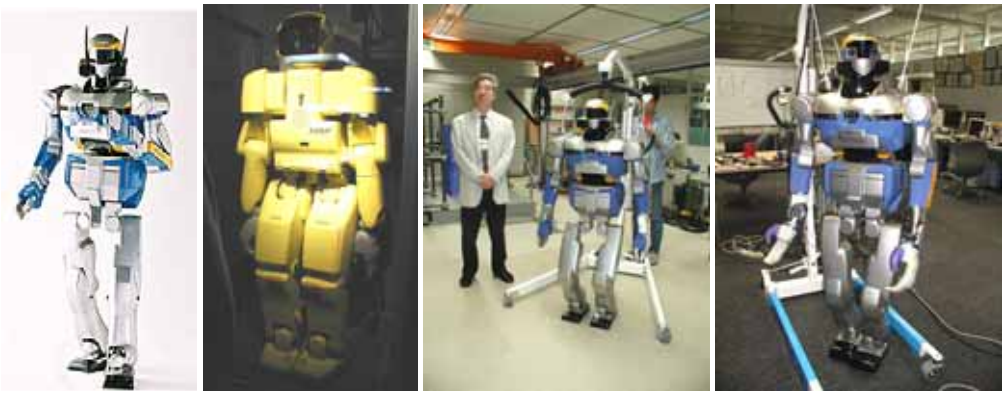

Figure 4.18. AIST humanoids.

Both Sony and Fujitsu were very gracious in hosting our study team, and presented business plans for their products. 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. The systems have high strength to weight ratios, and are tolerant of falls. The Sony system has 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.

Figure 4.19. Sony and Fujitsu humanoids.

The study team was impressed by the Korean population of humanoid systems, many of which were in quiet development during our visit. These 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. These robots demonstrate that Korea is a power to be reckoned with in 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 study team, and is being developed by a team with a deep understanding of dynamics and control that has informed their design work.

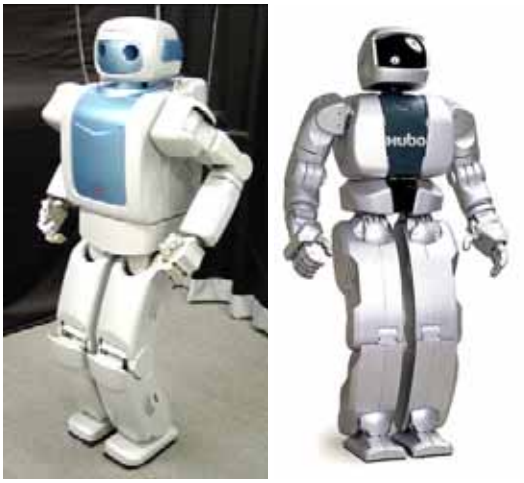

Figure 4.20. KIST (NBH-1) and KAIST (KHR-3) humanoids.

Qualitative Observations

Japan has the strongest program in the world, but Korea has the best first derivative, making major strides in the last five 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 U.S. leads in algorithm development for the control of limbs, but with few testbeds this theory is not being proven, and is being re-discovered 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 U.S. has the

lowest first derivative, with few active programs, and will soon to be overtaken in these final areas of dominance.

Like the U.S., the European work has been lacking a larger scale organization, plan or strategy. Also like the U.S., 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.

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, logistics, and direct weapons use
- *Medical* Search and rescue, patient transfer, nursing, elder care, friendship
- *Home Service* Cleaning, food preparation, shopping, inventory, home security
- *Space* Working safely with space-walking astronauts, caretakers between crews
- *Dangerous Jobs* Operating construction equipment, handling cargo, firefighting, security
- *Manufacturing* Small parts assembly, inventory control, delivery, customer support

Conclusions

Humanoids are now being developed in Asia, the U.S., 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 towards building machines that look and work like humans. The Japanese eager embrace of robot technology is equaled only by the U.S. 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 can not 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

Vijay Kumar, George Bekey, Yuan Zheng

INTRODUCTION

Robots can be classified into different categories depending on their function and the market needs they are designed for. Here we identify two major classes of robots, *industrial robots* and *service robots.* Within the later class of robots, we will divide service robots into *personal* service robots and *professional* service robots depending on their function and use (see Fig. 5.1 for example).

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 semi or fully autonomously to perform 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.

Figure 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).

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 can sometimes easily perform these tasks. Human workers often don't like tasks that don't 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 by robots with a 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. See Figure 5.2 for the ratio of robot to human workers in the manufacturing industry.

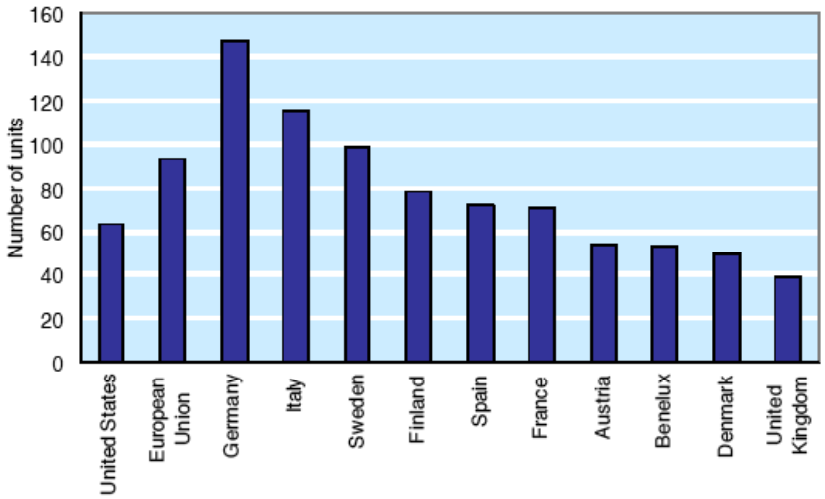

Figure 5.2. Number of industrial robots for every 10,000 human workers.

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.

MARKET ANALYSIS AND TRENDS

Industrial robots account 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. See Figure 5.3.

Industrial robots are improving in quality and the ratio of price to performance is falling. As Figure 5.4 shows, while prices have fallen over 40% over the last 15 years, the accuracy and payload rating of robots have almost doubled in the same period.

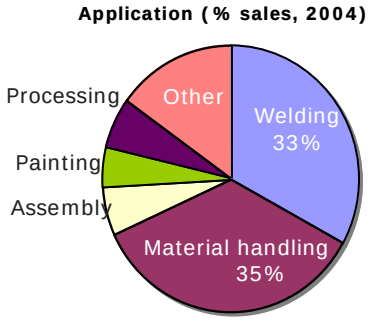

Figure 5.3. Industrial Robot Sales (2004).

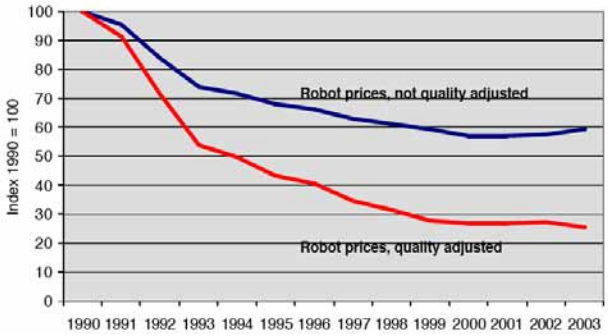

Figure 5.4. Trends in robot price and performance.

According to the United Nations Economic Commission for Europe (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 is well over $3.5 billion. The UNECE estimates that the annual sales of service robots (both professional and personal) in 2005 will be around $5B.

Table 5.1
Service Robots Industry: Number of units currently in operation and 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
Total	21060	2443

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 the weight with accuracy to a fraction of a millimeter. Sophisticated control algorithms are used to perform positioning tasks exceptionally well in structure environments.

FANUC, the leading manufacturer of industrial robots, has an impressive array of industrial robot products ranging from computerized numerically controlled (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 is 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 work cell. Typically the end-effector cost is often around 25% of the cost of the industrial robot. Further, the cost of the robot is usually around 40% of the cost of the entire workcell.

The nature of robotic workcell has changed since early days of robotics. Instead of having a single robot synchronized with material handling equipment like conveyors, robots now work together in a cooperative 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 capability that is 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, 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. Some examples are shown in Fig. 5.5.

Figure 5.5. Examples of service robots.

The challenges in service and personal robotics include all the challenges for industrial robotics. Dexterous manipulation and integration of force and vision sensing in support of manipulation is 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 on two-dimensional, even, indoor environments. Because service robots must be mobile, there are challenges for designing robots that are capable of carrying their own power source. Further, operation in domestic environments imposes constraints on packaging. Finally, service robots, especially personal robots, will operate close to human users. Safety is extremely important. And because interaction with human users is very important in service robotics, it is clear the industry needs to overcome significant challenges in human-robot interfaces.

INTERNATIONAL ASSESSMENT

U.S.

Most of the industrial robotics industry is based in Japan and Europe. This is despite the fact that the first industrial robots were manufactured in the U.S. At one time, General Motors, Cincinnati Milacron, Westinghouse and General Electric made robots. Now, only Adept, a San Jose-based company, makes industrial robots in the U.S.

However, there are a number of small companies developing service robots in the U.S. iRobot and Mobile Robotics, companies in New England, are pioneering new technologies.

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 annual revenue of $1.5B. ABB spends 5% of their revenues on 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, which emphasize vertical integration.

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

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

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 Yasakawa. FANUC is also the leading manufacturer of CNC machines, with Siemens as its closest competitor.

Unlike the U.S. and Europe, the service robotics industry includes big companies like Sony, Fujitsu, and Honda. The industry is driven by the perceived need for entertainment robots and domestic companions and assistants (Fig. 5.7).

Figure 5.7. Personal robots in the Japanese industry.

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

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

INTERNATIONAL COMPARISONS

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 the large majority of industrial robots (around 40%) are operating in Japan, but this number was around 60% in 1990. It is clear from Figure 5.10 that the demand for industrial robots is widespread, with Asia leading other regions. In Figure 5.11 the increase in Japanese demand is comparable to the increase in Europe with the U.S. lagging behind slightly. The countries with above-average growth rates are Korea and Taiwan.

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 U.S.; iRobot Corporation, Mobile Robotics, and Evolution Robotics to name a few. Similarly, in Europe, commercial products include rehabilitation robots on wheelchairs, tennis ball collectors, pool cleaners, window cleaners, and lawn mowers. The Japanese and Korean robotics industry has developed many personal robots, some for entertainment and others as domestic assistants. 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 U.S. lags behind in this area with only a handful of humanoid projects and virtually no commercial products.

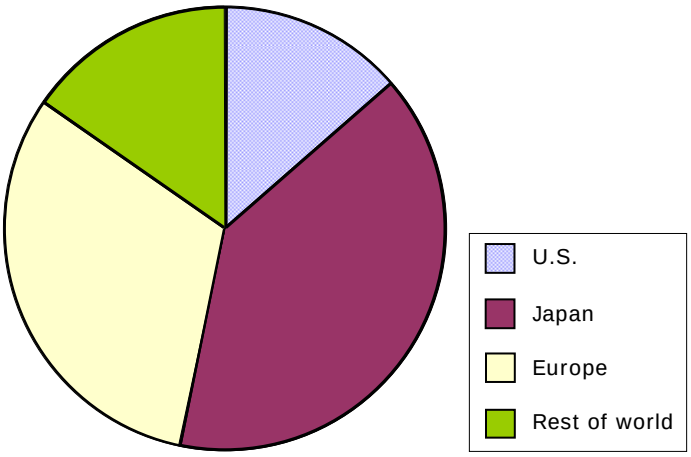

Figure 5.9. Industrial robots installed worldwide (2004).

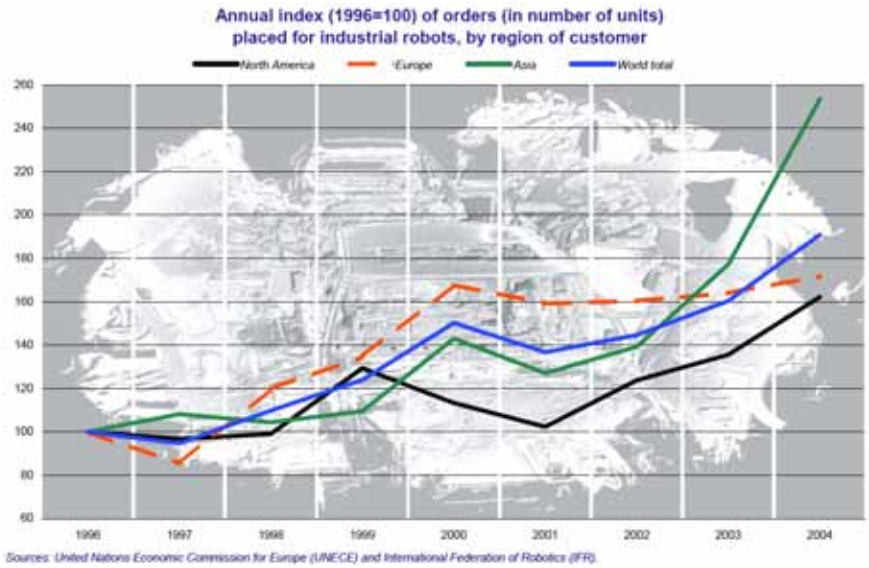

Figure 5.10. Annual index of orders for industrial robots by region.

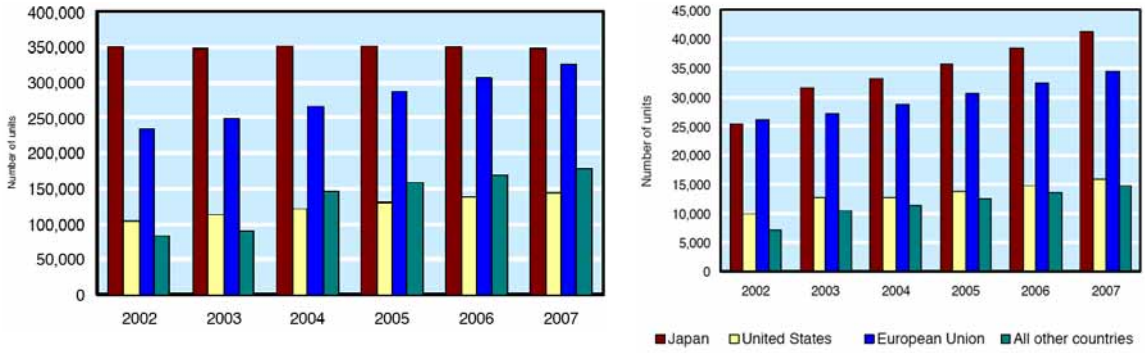

Figure 5.11. Number of installed industrial robots (left) and number of robots installed annually (right).

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 ten 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. The European Robotics Platform (EUROP) is a major new research initiative in Europe driven by a joint academia/industry program. 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 U.S., and there is no national strategy for developing robotics in the U.S.

Second, it is also clear that Japan, Korea, and European countries have stronger professional associations and national networks. The Japan Robot Association and the European Union Robotics Network (EURON - http://www.euron.org), are examples of national networks.

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 U.S. is known for its entrepreneurial culture, there appear to be more start-ups and spin-offs from research labs in the Europe than in the U.S.

Finally, it is worth remarking on technical strengths and emphases in the different continents. While the U.S.-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 U.S. seems to have the lead in this area. The fundamental driver for robotics in the U.S. comes from military programs and Department of Defense (DoD) interests. In Europe, Japan and Korea, these drivers are social and economic factors. Robotics is viewed as an important industry, while Asians have identified an important role for robots in an aging society.

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 based on perception 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, which 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 pre-determined 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 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.

CHAPTER 6

ROBOTICS FOR BIOLOGICAL AND MEDICAL APPLICATIONS

Yuan Zheng, George Bekey, Arthur Sanderson

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 fifteen years ago while for biological applications it is rather new (about five 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 U.S., Japan, Korea and Europe are introduced.

WHY ROBOTS AND AUTOMATION IN BIOLOGY AND MEDICINE

Biological Applications

The primary purpose for use 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 bio-solution mixing and dispensing for membrane protein crystallization. Without robots and automation, biosamples/solutions must be handled manually by human hands, which is not only tedious but also slow. Various robotic systems have been developed in laboratories that are either specially developed for a particular application (Fig. 6.1) or integration of commercially available robots, general purpose tools and sensors.

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 (Zheng and Chen, 2004).

Medical Applications

Research on robotics for medical applications started fifteen years ago and is very active today. The purpose is three-fold. 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 non-invasive 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 hospitals in the United States (International Journal of Emerging Medical Technologies, 2005). Fig. 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.

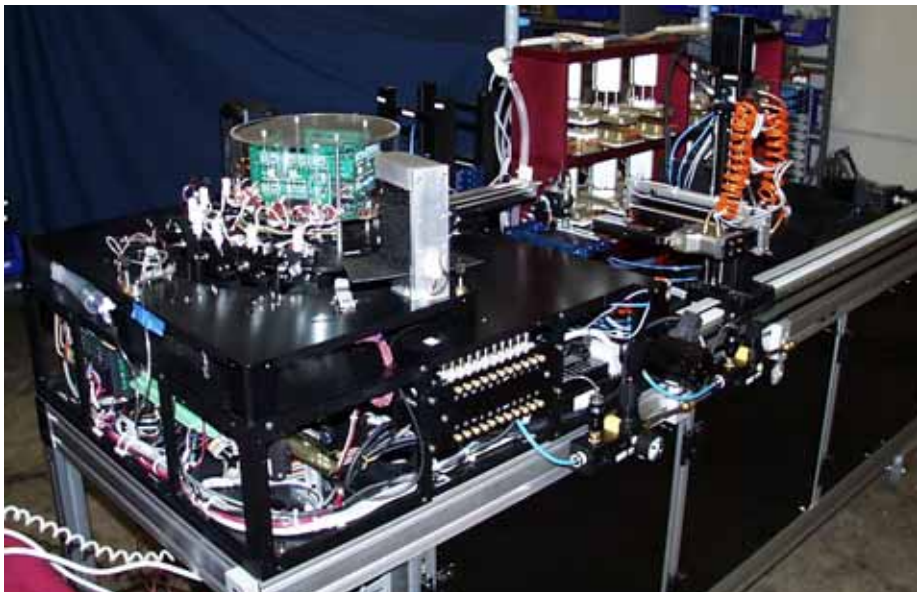

Figure 6.1. High-throughput systems for DNA sequencing (U. Of Washington) (Meldrum and Kavraki, 2004).

Figure 6.2. Doctors perform knee surgery using a robotic system (Taylor, 2004).

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 non-invasive 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 (Fig. C.71) and on prosthetic hands (Fig. C.72). The latter is basically an exo-skeleton for a non-functional hand. Prosthetic hands are also

being developed at 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 wheeled chairs, walking-assistance machines, and limb-empowering robotic devices. For example, a new type of powered walker was developed at Waseda University. It is capable of sensing pressure from both the left and right arms (see Figure 6.6 on page 68).

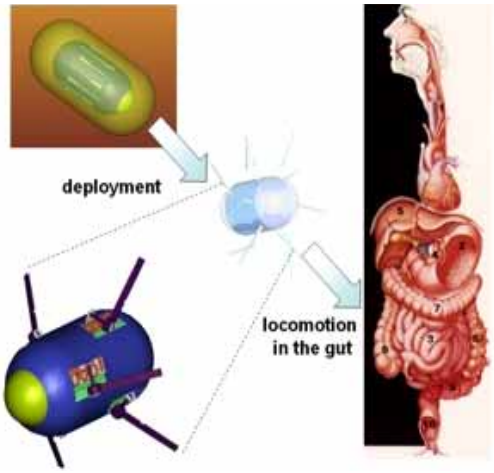

Figure 6.3. Robotic capsular endoscope for examination of gastrointestinal tract (Polo Sant'Anna Valdera of the Sant'Anna School of Advanced Studies, 2005).

In addition, rehabilitation robotics can help patients recover physical functions more effectively after injury. Robotic devices and systems can also help elderly people move around; this includes intelligent wheeled chairs, walking-assistance machines, and limb-empowering robotic devices.

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 (Meldrum and Kavraki, 2004). In robotic surgery, commercially available robots are often a part of an integrated system.

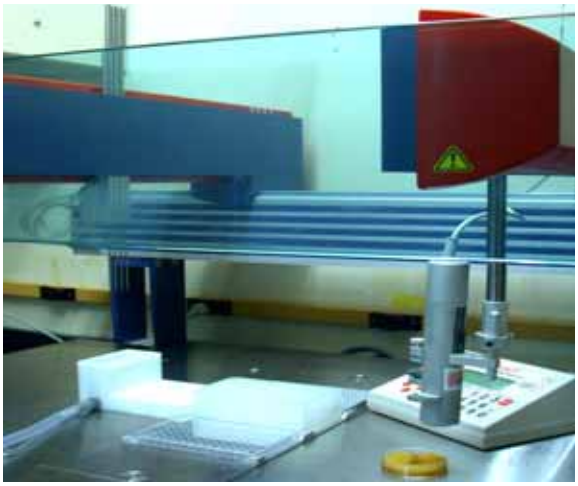

Figure 6.4. Off-the-shelf robot is a part of a biosolution dispensing system (Ohio State U.).

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 neuro-sensing. Biosensors 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 non-traditional principles are also developed to handle bio-solutions or to manipulate cells. For example, Nagoya University in Japan used local photo polymerization on a chip to immobilize individual cells.

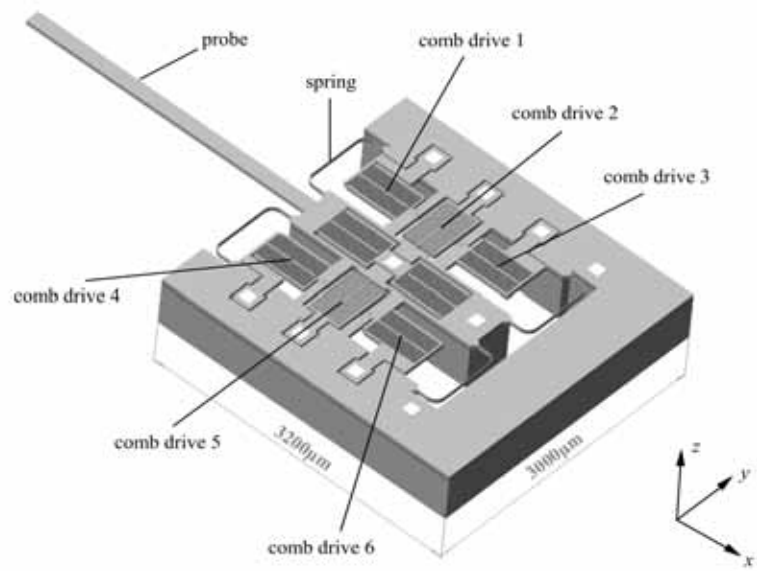

Figure 6.5. Microforce sensor using integrated circuit (IC) fabrication technology, U. of Minnesota (Nelson and Zheng, 2004).

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 an important topic of research. The purpose is to develop patient-specific models for performing precise surgery.

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 use micromachining methods.

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 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 micro sensors and actuators, from tools and devices to algorithms. For molecular-level study of biological systems, nano-devices and actuation are key technologies as well.

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. There is still a lack of effective tooling and sensing technologies to deal with 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) is extremely challenging because of the tiny size of the cells.
- Automated protein characterization and functional analysis is 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 detect 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 (Taylor, 2004):

- For modeling and analysis, the emphasis is on developing computationally effective methods for patient-specific modeling and analysis.
- For interface technology, the emphasis is to fundamentally extend 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 (Meldrum, 2000). 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 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.

REGIONS VISITED BY THE ASSESSMENT TEAM

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

United States

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

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

It should be noted that the number of U.S. organizations involved in robotics for biological and medical applications mentioned by the three presentations is more than thirty. Some of the research activities performed by these organizations have been described earlier in this chapter. In biological applications, for example, the U.S. 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 U.S. 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 U.S. (in the world as well) for robotic knee replacements and prostate and heart surgeries.

Japan and Korea

In Japan, the assessment team visited in Japan 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 non-contact 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.

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

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.

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 Technology, which is led by Dr. Brad Nelson, who is also 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 non-human-sized situations to improve accessibility and range of distance, dexterity and speed for applications 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 robotic for biological and medical applications. The group consists of eight laboratories and centers which are: 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 currently going on explore biomorphic and anthropomorphic solutions for robotic devices in general, and biomechanics, neuro-robotics, and rehabilitation and assistive devices in particular. One such a project investigates implantable microdevices which can detect neuron signals from human arms to directly control robotic devices (Fig. 6.7).

The CIRM laboratory focuses on the design and development of micro- and nano-devices, 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 equipment such as a Kern HSPC micro-computerized numerical control (CNC) machine, an electrical discharge machine, a plastic injection molding machine, and a microerosion system. The robotic capsular endoscope mentioned earlier (Fig. 6.3) was developed by the laboratory using the technologies just mentioned.

Figure 6.7. Human arm implantable microprobes.

Another large group the assessment team visited 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 the research, founded at IPK, is not matched in the U.S. (see Figure 6.8).

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

Dr. Lüth leads a group called Berlin Center for Mechatronical Medical Devices, which focuses on three areas of surgerical 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 inter-ocular baseline to a small distance (~0.4m). This is mounted on a small roller mount that takes up only a small amount 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 U.S.

QUANTITATIVE AND QUALITATIVE OBSERVATIONS

Quantitative Observations

In terms of quantity, the U.S. 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 U.S. there are at least thirty research organizations performing research on robotics for biological applications. The U.S. is leading the world in the following areas: DNA sequencing, cell manipulation, protein crystallography, DNA and protein chip production and analysis, and 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 U.S. Many university hospitals study and perform robotic surgery on hearts, brains, knees, prostates, or 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, and University of Illinois at Chicago, among many others. Many non-university hospitals routinely use robotic devices for minimally invasive surgery.

There is no doubt that the U.S. 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).

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 U.S. is as good as any other country in the world. For biological applications, the U.S. 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 went to 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 nano technologies, which unfortunately have proved slow. Finally, collaboration between engineers and biologists is still new and challenging. For medical applications, the U.S. is most active for robotic surgeries. The U.S. 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 U.S. government has to maintain the level of investment or to invest even more to keep the leading position.

Conclusions

Research on robotics for biological and medical applications is still young. Scientists in the U.S. 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 (International Journal of Emerging Medical Technologies, 2005). In the U.S., the number of institutions involved in the research of robotics for both applications is significantly higher than 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 U.S. 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

Vijay Kumar, George Bekey, Arthur Sanderson

INTRODUCTION

Networked Robots refers to multiple robots operating together in coordination or cooperatively[1] 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 while 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 happens through a network.

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

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

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 Figure 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

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

exploiting the efficiency that is inherent in parallelism. They can also perform independent 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 to 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. (See Fig. 7.3.)

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.

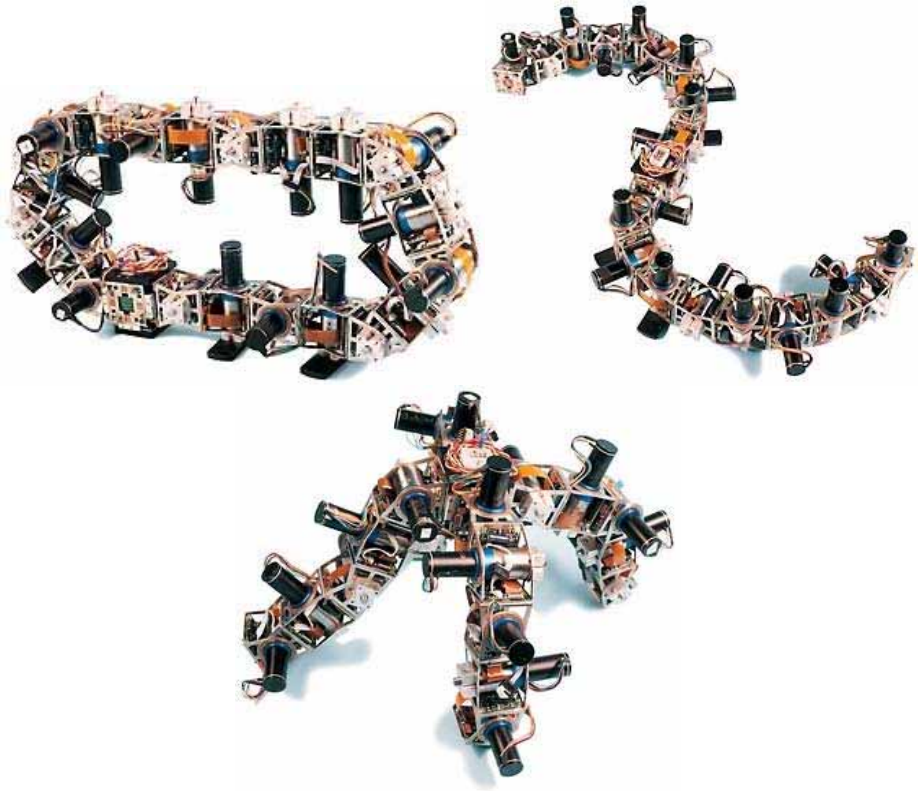

Figure 7.2. Robotic modules can be reconfigured to "morph" into different locomotion systems including a wheel-like rolling system (left), a snake-like undulatory locomotion system (right), a four-legged walking system (bottom).

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.

Applications for networked robots abound. The U.S. 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 commonplace, it is natural to see these robots working with sensors and appliances in the house while cooperating with one or more human users.

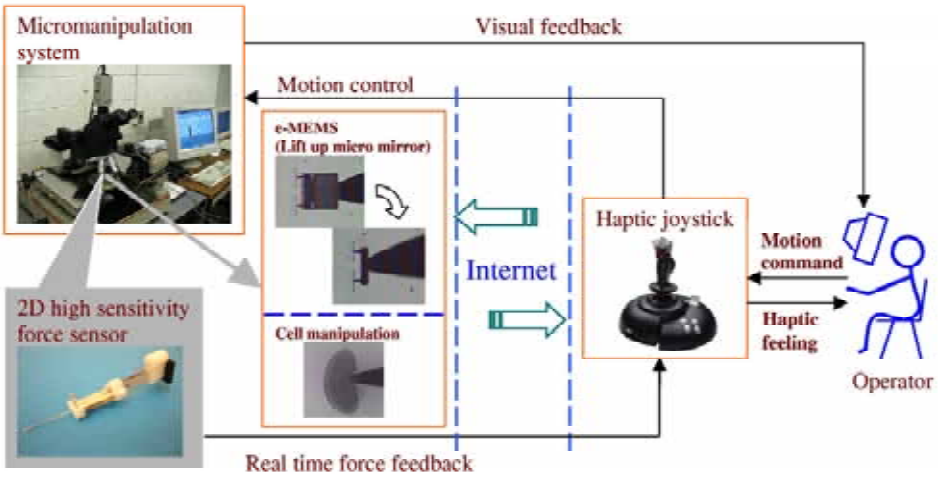

Figure 7.3. A human user communicating with remotely located expensive robots that can manipulate objects on the micro- or nanoscale. These robots can have multiple users without requiring collocation of the robots with the users.

SIGNIFICANCE AND POTENTIAL

The Network Robot Forum, established in Japan in 2003, estimates the Networked Robot industry to grow to over ¥19.8 trillion by 2013, approximately five times the industrial robot market for manufacturing applications. This growth is spread 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. There are significant efforts in CSIRO to exploit synergies between robot networks and sensor networks using networks of small vehicles (Figure 7.4).

Figure 7.4. A quad-rotor micro air vehicle with onboard cameras and inertial units and off-board processing (left), and a hybrid autonomous underwater vehicle (right).

Networks allow healthcare 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 via wireless networks. There is a noticeable trend towards robots interacting with each other and cooperating with humans.

Figure 7.5. 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.

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 of 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 intelligent robots. (See Fig. 7.5)

STATE-OF-THE-ART IN THEORY AND PRACTICE

There are already many impressive successful demonstrations of networked robots.

In the manufacturing industry, work cells are comprised of 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).

Figure 7.6. Human operators can interact with remotely located manufacturing workcells with multiple robotic devices (left). A vision of mining and construction machines of the future (right) showing a similar network of autonomous vehicles controlled by human operators in a remote control station.

The U.S. military has a big Future Combat Systems initiative to develop network-centric approaches to deploying 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 to 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. 7.7)

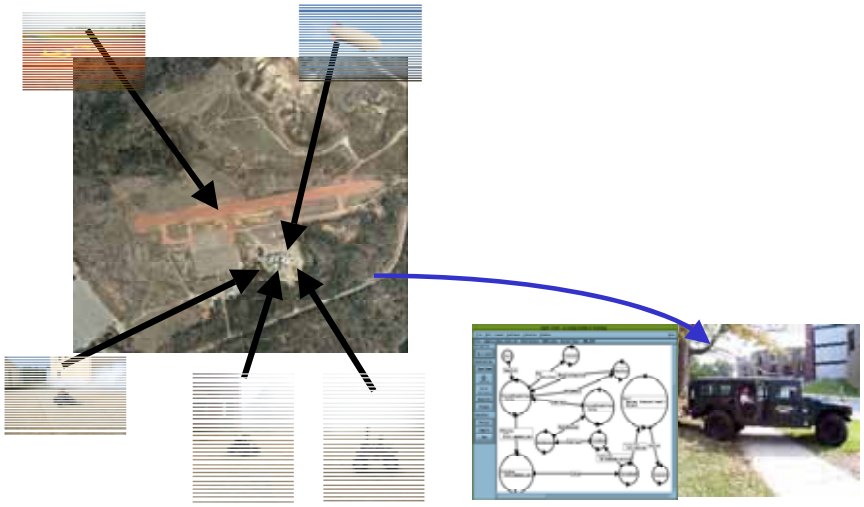

Figure 7.7. A single operator commanding a network of aerial and ground vehicles from a C2 vehicle in an urban environment for scouting and reconnaissance in a recent demonstration by University of Pennsylvania, Georgia Tech., and University of Southern California.

Mobile sensor networks are finding use in 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. The main benefit is to speed up the collection of data and increase 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)

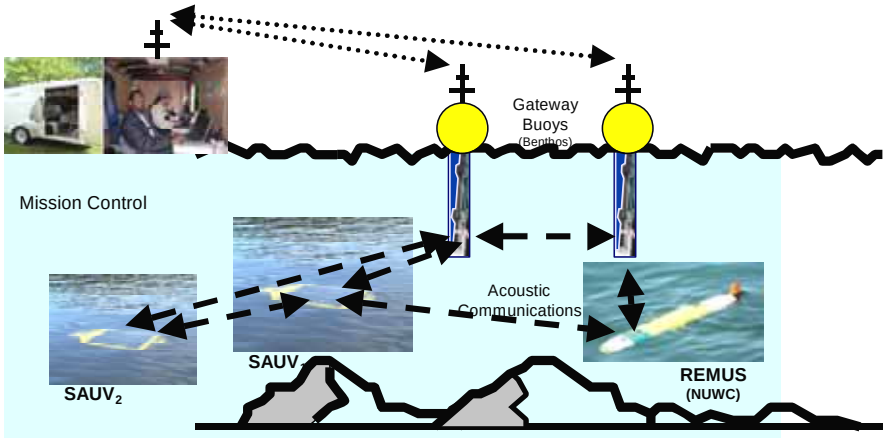

Figure 7.8. A network of buoys and underwater vehicles used for measuring oxygen content, salinity and cholorophil on the Hudson Bay (top) and the Neptune project (right) off the west coast of N. America.

The European Union has several EU-wide coordinated projects on collective intelligence or swarm intelligence. The *I-Swarm* project at Karlsruhe and the *swarm-bot* project at École Polytechnique Fédérale de Lausanne (EPFL) are examples of swarm intelligence.

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 firefighting. (Fig. 7.10).

Figure 7.9. The Software for Distributed Robotics Project demonstrated the ability to deploy 70 robots to detect intruders in a unknown building (University of Tennessee, University of Southern California, and SAIC).

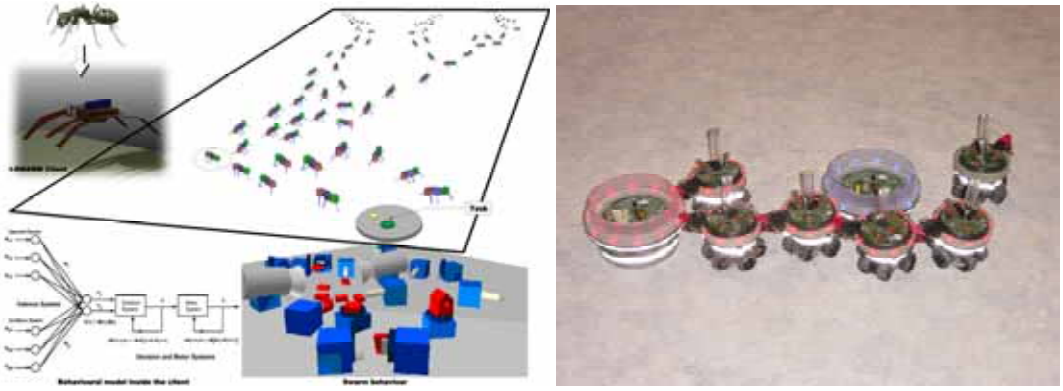

Figure 7.10. EU project on Swarm Intelligence: the I-Swarm project in Karlsruhe (left) and the *swarm-bot* project in EPFL with multiple robots forming physical connections for manipulation and locomotion (right).

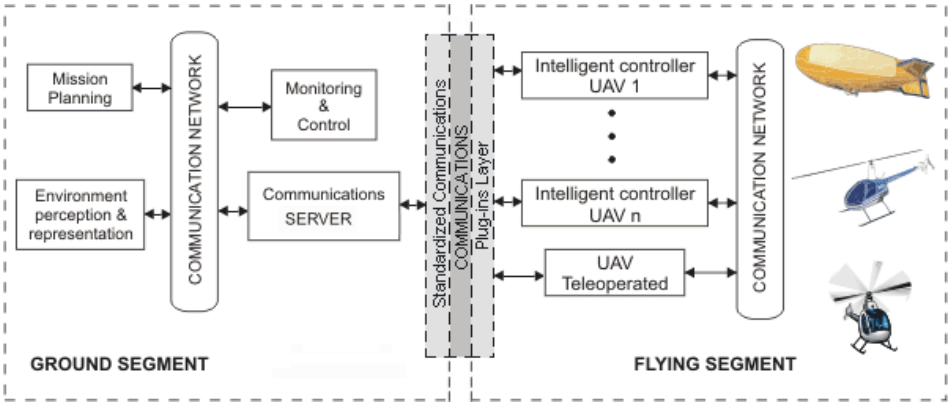

Figure 7.11. The COMETS project at INRIA (led by Rachid Alami) seeks to implement a distributed control system for cooperative detection and monitoring using heterogeneous UAVs with applications to firefighting, emergency response, traffic monitoring and terrain mapping.

SCIENTIFIC AND TECHNICAL CHALLENGES

While there are many successful embodiments of networked robots with applications to the 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 that they respond to specific instructions provided by human users. Increasingly robot networks are becoming 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.

INTERNATIONAL COMPARISONS

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

While there are more mature efforts in Japan and Europe to develop better sensors and robot hardware to facilitate the development of robot networks, the U.S. has more impressive embodiments and imaginative applications of networked robots. Although it is hard to make such sweeping generalizations, U.S. arguably still maintains the lead in control and networking, while Europe and the U.S. may have an edge over Japan in perception. 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.

Figure 7.12. The Australian Center for Field Robotics UAV fleet with 45 kg aircraft of 3 meter wing spans with reconfigurable sensor payloads.

Pioneering work on decentralization state estimation, localization, and tracking has been done by the Australian Center for Field Robotics at the University of Sydney in Australia. Indeed, their paradigm for decentralized data fusion and simultaneous localization and mapping has served as the foundation of many practical algorithms being used today. They also have exceptional strength in coordinated unpiloted aerial vehicles having demonstrated many impressive capabilities with multiple vehicles (Figure 7.12).

FUTURE CHALLENGES

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

Technical challenges to scalability: We don't have a methodology for creating self-organizing 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 last 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 interfacing, 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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APPENDIX A. PANELIST 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 the faculty at USC in 1962. He served as chairman of the Electrical Engineering Systems Department from 1978 to 1982, as chairman of the Computer Science Department from 1984 to 1989, and as associate dean for research of 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 of the American Association for Artificial Intelligence (AAAI). He is editor-in-chief of the journal Autonomous Robots, and founding editor of the IEEE Transactions on Robotics and Automation. During 1996 and 1997 he served as president of the IEEE Robotics and Automation Society.

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

George 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. Effective September 2005, he will also be an adjunct professor of engineering at California State Polytechnic University in San Luis Obispo.

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 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 post-doctoral year at the University of Texas, he was a co-investigator 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 contract 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 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 co-investigator 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 over 60 papers on topics in robot design, space environmental modeling, actuator development, kinematics, kinetics, bio-mechanics, interactive design software and non-linear 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 on the 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 co-founder 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 multi-agent 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.

Arthur Sanderson

Dr. Sanderson received his BS degree from Brown University, Providence, RI, in 1968, and MS and PhD degrees from Carnegie Mellon University, Pittsburgh, in 1970 and 1972, respectively. Dr. Sanderson held faculty positions at Carnegie Mellon University from 1973 to 1987, where he was co-director of the Robotics Institute, the largest university-based robotics research center in the U.S. 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 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 professor and served as department head of the Electrical, Computer and Systems Engineering Department from 1987 to 1994. He was co-director of the Center for Advanced Technology in Automation and Robotics, and co-principal investigator of the Center for Intelligent Robotic Systems for Space Exploration, and developed real-time hierarchical architectures for space flight applications. He developed the "Tetrobot" system of modular distributed robotics that provides flexible reconfiguration of robotics capability for different applications.

Dr. Sanderson is the author of over 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; *Tetrobot: 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*, co-authored with R. Subbu, World Scientific Publishers, is currently in press.

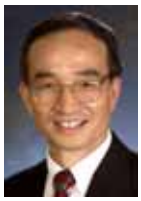
In January 2000, Dr. Sanderson was appointed the vice president for research of Rensselaer Polytechnic Institute. In this role, he is responsible for coordination of all research programs on the campus. He has a leadership role in the development of strategic priorities for research at Rensselaer, and 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.

Brian 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 over 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 U.S. patents. He has a BS degree in physics and a BA degree in mathematics from the University of California at Santa Barbara, and an MS degree in electrical engineering from the University of Southern California.



Yuan Zheng

Professor Yuan F. Zheng received MS and PhD degrees 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 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 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 May 10–15, 1999. Professor Zheng received the Presidential Young Investigator Award from President Ronald Reagan in 1986.

APPENDIX B. SITE REPORTS—ASIA

Site: **AIST – Digital Human Research Center**
National Institute of Advanced Industrial Science and Technology (AIST)
Tokyo Water Front 3F
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Date Visited: October 6, 2004

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Dr. Satoshi Kagami, Senior Research Scientist, Email: s.kagami@aist.go.jp

OVERVIEW

AIST Tokyo Waterfront is the newest laboratory of the National Institute of Advanced Industrial Science and Technology (AIST), an independent administrative institute. The laboratory has been in existence from 2001 and approximately 30% of the lab work is in the area of robotics. Government funding (40%) and industrial funding (10%) account for half the funding, while intramural funding provides the remaining 50%. The Digital Human Research Center, a center at the AIST, is directed by Dr. Takeo Kanade, with a research budget of approximately $5 million. This supports postdocs, students and equipment. The 14 research staff members are supported by a different budget.

Figure B.1. The Digital Human Research Center at AIST, Tokyo.

DIGITAL HUMAN RESEARCH

Introduction

The Digital Human Research project addresses research at three levels.

1. Digital Partner research emphasizes human cognition and psychology, addressing behaviors, emotion, expression, stress and pain.
2. Digital Cadaver addresses the physiology and anatomy of the human body and has an organ-level focus.

3. Digital Mannequin focuses on biomechanics and dynamics including biped walking, postures, grasping and manipulation.

The research is organized into four teams:

a. Human-centered design
b. Human behavior understanding
c. Humanoid interaction
d. Human modeling

Human-centered Design

The human-centered design team addresses the development of software and hardware tools and algorithms that can support the design of human-worn devices. The center has specialized equipment for data acquisition including laser scanners for geometric information and magnetic resonance imaging (MRI) for obtaining kinematic measurements from skeletal data. This allows them to design customized shoes and eye glasses using computer-aided design technology. The Digital Hand project, for example, focuses on obtaining anatomical, geometric, and physiological models of the human hand, including models of fingertip deformations and compliance. The center interacts with industrial partners interested in the design of handheld devices such as cellphones and cameras.

Human Behavior Understanding

The primary goal of this thrust is to design and deploy networks of sensors for studying human behavior and algorithms for understanding and modeling human behavior. The center has a room with sensor networks including a sensorized bed for healthcare applications. They have developed sensors for location and motion sensing and equipped a ubiquitous sensor room. The sensors are either active or passive ultrasound sensors and allow measurements of trajectories.

Humanoid Robot Interaction

The humanoid research team adopts a holistic view of humanoids spanning many different areas including:

a. 3D vision
b. Human-like walking
c. Motion planning
d. Real-time motion synthesis
e. Comparative studies of human versus humanoid walking

More details are provided in the ‘Humanoid Research’ section.

Human Modeling

This aspect of research focuses on psychological and cognitive issues in tasks performed by humans. One of the innovations of this center is the concept of a motion print (analogous to a finger print) which enables the visualization of intention and emotion, and the use of segmentation techniques solving the signal-to-symbol problem to infer the properties of the motion.

Humanoid Research

Dr. Kagami presented an overview of humanoid research. The humanoid walking is based on the Zero Moment Point (ZMP), which allows a posture-based, geometric control strategy (in contrast to force/position-based trajectory control) for biped locomotion. Most importantly, it is compatible with stiff, position-controlled humanoids and lends itself to real-time trajectory generation.

He showed research on optimized footstep planning, generation of 2.5D maps, and vision-based 2.5D slam. The coordination of the humanoid torso, legs and arms in contact tasks is impressive. His team has given

particular attention to comparing humanoid motion and human motion, carefully studying the many qualitative discrepancies.

Figure B.2. Humanoid Research at the Digital Human Center at AIST, Tokyo.

Figure B.3. The Kawada Humanoid: The Digital Human Center maintains an active collaboration with Kawada Industries.

Dr. Kagami's humanoid consumes 300–400 watts (including 100 watts to power the CPU), weighs 58 kg, has a height of 1.58 m, and walks at 2.1 km/hr. He showed impressive results on dynamically stable motion planning that uses C-space-based representations with Rapidly exploring Random Tree (RRT)-based planning techniques. His results are among the best in the robotics community. His team collaborates closely with Kawada Industries.

Dr. Matsui presented research on a distributed and real-time information-processing system for humanoid robot control. This research focused on three technologies to support humanoid control: (a) large-scale integrated circuitry with a multi-threaded CPU; (b) real-time operating system; and (c) parallel and distributed computations. His team maintains collaborations with the University of Tokyo (Professor Ishikawa) and Keio University (Professor Yamasaki).

SUMMARY

The major achievements of the digital human research center include:

- Ultra Badge—a 3D location tag for tracking indoor behaviors
- Sensor network middleware
- Breath sensor bed
- 3D acoustic field generation
- Fingertip deformation sensor
- High-speed scanner for whole body and face
- 3D vision and motion-planning for humanoid walking

The center has interactions through collaborative graduate school programs and visiting scholar exchange with institutions like Carnegie Mellon University (CMU), Stanford, and l'Institut National de Recherche en Informatique et en Automatique (INRIA).

The center has generated many patents. Patent royalties are split into four equal parts, the revenue going to the Technology Licensing Office, AIST, the Center, and the inventor(s).

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Date Visited: October 8, 2004

WTEC Attendees: B. Wilcox (Report author), R. Ambrose, Y.T. Chien

Hosts: Shigeoki Hirai, Director, Intelligent Systems Research Institute,
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OVERVIEW

Shigeoiki Hirai offered a welcome and overview for the WTEC team. The National Institute of Advanced Industrial Science and Technology (AIST) emplys 2,400 researchers, 55 of which are foreign. In the robotics field only, AIST is supported by a government subsidy of ¥573 million, which covers salaries and other expenses. An additional ¥143 million comes from agency grants (e.g. Ministry of Economy, Trade and Industry (METI), and the Ministry of Education, Culture, Sports, Science and Technology (MEXT)) that are received based on competitive proposals. An additional ¥39 million comes from industrial companies.

Shigeru Kokaji gave an overview of the Automated Vehicles research program. The Autonomous Transport (intelligent car) project has been underway for many years. In 1967 they demonstrated a system based on an inductive cable buried in a road, achieving speeds of 100 km/h. This was considered too heavy an infrastructure modification to be economical. By 1978 they had demonstrated speeds of 30 km/h using vision-based control. In 2000 they demonstrated autonomous platooning of five vehicles by means of inter-vehicle communications and light detection and ranging (LIDAR) to achieve 40–60 km/h.

Kohtaro Ohba gave an overview of the Ubiquitous Functions program, which seeks to apply ubiquitous computing and sensor networks to robotics. This includes the Knowledge Distributed Robot and the Mental Commit Robot (PARO). In distributed knowledge representation and reasoning systems (DKRS) every object has a chip tag (RFID), and distributed knowledge storage is interrogated to determine the properties of each object. The PARO mental commit robot is a small seal-like robot that cheers people up and reduces stress.

H. Kurokawa gave an overview of distributed system design. A modular robot is being developed with motion, intelligence, and communications in each module. This system is able to reconfigure itself into many different geometries, in a fashion somewhat related to other work at Carnegie Mellon University (CMU), University of Southern California (USC) (Wei-Min Shen), and the University of South Denmark. A metamorphosis of one of these robots occurs, for example, when it detects the buckling of an ankle in a walking configuration, decides that the slope is too great to climb for that geometry and reconfigures itself, perhaps as an inchworm (a live demo was given later in the day).

Fumiaki Tomita gave an overview of 3D vision systems. A program in 3D vision provides structural analysis of the scene. Stereo vision, normally with three cameras, allows shape representation. An example shows banana tracking. A hand-eye system demonstrates can and banana picking from a cluttered ensemble. A further example shows autonomous parking in a crowded parking lot.

Takashi Suehiro described research in task intelligence. This includes dexterous manipulation, as is exhibited by a skill-based nuclear power plant maintenance robot. There is a substantial effort on robot technology (RT) middleware (at about $1 million a year). RT components include Linux, Common Object Request Broker Architecture (CORBA), C++, a graphical user interface (GUI) used for force control, and super distributed objects (as defined by the Japan Robot Association (JARA) Working Group).

Kiyoshi Komoriya described the research program in field systems, including outdoor intelligent systems. This covers robots for mining, construction, forestry, rescue, and safety. An example shown was for automated scooping for loading by wheel loader. This system uses stereo vision to make a model of a sand/dirt pile (a column model where the horizontal plane is divided into grid cells with the top of the pile at each point representing a vertical column of sand). Models of the pile estimate the resistance force to the scoop that depends on the shape of the pile. The robot has a two degree-of-freedom (DOF) scoop so that the depth of each bite can be controlled to ensure that the scoop can be filled without the resistance to motion becoming too great. Dr. Komoriya also described a riding-type wheeled platform. They studied the Segway (at 38 kg), and are building a Personal Mobile Platform. This vehicle, unlike the Segway, has no steering bar. It is controlled entirely by the motion of the center of gravity (CG) of the rider. The mass goal for this system is 2 kg. The prototype mass is 36 kg, uses 150 W at 48V, and uses a 50:1 harmonic drive. It has four force sensors to measure the CG location of the rider. The second prototype is expected to be 12 kg, including a 2 kg battery, and will again use 150 W.

H. Hirukawa and S. Kajita presented an overview of humanoid robots at AIST. The HRP-2 designed and assembled by Kawada has a mass of 58 kg, can achieve 2 km/h walking, and is 1.54 m tall. Each of the arms and legs allow 6-DOF, and the head and waist each have 2-DOF. The hands have 1-DOF. The pitch and yaw at the chest represent a difference from the Honda version. The "open HRP architecture" includes the integrated simulation environment plus CORBA plus VMRL plus the physical parameters that describe the system. The robot can currently walk over a surface with up to ±2 cm unevenness. The chest degrees of freedom allow it to get up from lying flat in a dynamic rolling motion (a completely preprogrammed motion). Another behavior is to use hand-plus-machine vision to grab a handrail. Yet another behavior is to tuck while falling over backwards to reduce the impact shock on the gearheads. The robot is able to push a 25.9 kg box (with about 10 kg pushing force). The "humanoid shape gives lots of inspiration," say the researchers. They also state that there is "lots of debate in Japan over the utility of humanoid robotics." Among the unique things they are doing with humanoid robots is to teach them to crawl. Currently their robot is crawling at 1 km/h. The robot can walk for one hour on a set of batteries. They showed very impressive footage of the robot working as a "construction assistant" performing cooperative panel handling and emplacement as led by a human worker.

K. Yokoi and A. Kheddar presented a summary of a joint Japanese and French robotics project. On November 22, 2001, AIST agreed to a collaboration with Centre National de la Recherche Scientifique (CNRS), and on December 8, 2003, the joint labs were established—the CNRS-STIC in France, and AIST-ISRI in Japan. The cooperation includes an exchange of researchers on multimodal perception and interaction, 3D vision, human-machine interaction, the HRP-2 humanoid robot, the Kawasaki 6-DOF haptic device, whole-body teleoperation, autonomous motion (3D) planning, 3D vision (3D point cloud), and haptic interaction. The AIST lab has an HRP-2, and France will have one "soon." They are seeking researchers in France that are interested in humanoids (e.g. at CNRS, l'Institut National de Recherche en Informatique et en Automatique (INRIA), École Polytechnique, etc.).

During an open discussion the key point made was that manufacturers should describe what they are building in some standard way, both for robots and also for "inanimate objects," e.g. so that the radio frequency identification (RFID) tags information can be used in a standardized way.

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2-2-2 Hikaridai, Keihanna Science City, Kyoto-fu 619-0288
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Date Visited: October 5, 2004

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Hosts: Dr. Nobuyoshi Fugono, President of ATR International
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Dr. Gordon Cheng, Head of Dept. of Humanoid Robotics and Computational Neuroscience

BACKGROUND

The Advanced Telecommunications Research Institute (ATR) was established in 1986 with the support from several sectors including industry and government. The first main ATR laboratories were opened in 1989 in the Kansai Science City known as "Keihanna"—an area in western Japan within 30 miles of the center of the tri-city area of Kyoto, Osaka, and Nara. In the ensuing years, ATR has achieved a reputation as one of the world's best research centers (BusinessWeek, 1997) (ATR, 2005).

As the research environment and funding sources evolved, ATR has undergone several organizational changes in the last 10 years. Currently the research is done under the rubric of eight laboratories, ranging from traditional communications topics to more contemporary areas such as spoken language translation, network informatics, media sciences, and the two labs our panel visited: Intelligent Robotics and Communication Laboratories and the newly established Computational Neuroscience Laboratories. There are roughly 330 researchers at ATR and 20% (68) of them are from overseas, mostly from Europe, Asia and North America. With this international workforce, ATR International seems to live up to its vision of "promoting basic and creative research that would contribute to the international society … and future human life."

The Computational Neuroscience (CNS) Laboratories is one of the recent additions to ATR, and was officially established in May 2003. Dr. Mitsuo Kawato, Director of the Lab, was the host for our visit.

SCOPE OF CNS RESEARCH

The goal of research at CNS, as Dr. Kawato describes in his presentation, is "understanding brain function using a computational approach." That is, "understanding the brain by creating one." Dr. Kawato's vision is long-standing as he was the director of the Dynamic Brain Project from 1996 to 2001, funded under Japan's Exploratory Research for Advanced Technology (ERATO) program (see Kawato Domain Brain Project, 2001 and below). Robotics comes into his visionary work in his definition of "computational neuroscience" as a science to "elucidate information processing of the brain to the extent that artificial machines, either computer programs or robots, can be built to solve the same computational problems solved by the brain, essentially in principle." As an ATR lab, the real mission of the research in CNS is to apply their findings to the development of innovative communications technologies.

Work at CNS is organized into three main areas (departments). Two of the areas are closely related to robotics. One is cognitive neuroscience, focusing on computational mechanisms of neural circuits and molecules. Its long-term goal is to understand how human intelligence, such as cognition and learning, and communication skills, such as language and motor control, work. Examples of this research are: neural mechanisms of action learning, parallel learning mechanisms in multi-agent society, and computational paradigms for neuroscience in which software models and tools are developed for simulating signal transmission through intracellular dynamics.

Another major area of research is at the intersection of humanoid robotics and computational neuroscience in a department headed by Dr. Gordon Cheng. The goal here is to reproduce human-like behaviors on humanoids within similar contexts. In doing so, the hope is to elucidate a better understanding of the inner workings of human information processing. Examples of this research include developing methods for transferring highly skilled human tasks (e.g., three-ball juggling) or complex human movements (e.g., walking) to humanoid robots. Another example is to study biologically inspired biped locomotion in which biological principles are examined in order to produce better control algorithms for humanoid robots to walk more naturally, like human beings.

THE DYNAMIC BRAIN (DB) PLATFORM

Much of the research in CNS is centered on a humanoid platform developed from the Dynamic Brain Project (1996–2001). This humanoid "DB" has the following features:

- Thirty degrees of freedom (DOF) (seven on each arm, three for the neck, two for each eye, three for the torso, and three for each leg)
- 190 cm in height, 80 kg in weight
- Two cameras on each eye for emulating the peripheral (wide-angle) and fovea (narrow-angle) region of human vision
- Many computers: more than six for controllers, two for vision processing

The DB platform was co-designed and built by SARCOS (Steve Jacobson) for the DB project. Among the recent work being done on the platform includes active perception and the design of new legs (2x7-DOF legs) making its walk closer to that of a human's than any other humanoid robots in the world—in size, range of motion as well as in performance (speed, power).

TOUR OF LABORATORIES

The visit concluded with a tour of the laboratories, highlighting several demos.

1. Air Hockey play between a human and the DB platform. This is to demonstrate tasks and skills transfer from human to machine. The DB learns the movements by observation using a set of primitive movements in dynamic situations. Performance improvement is possible by primitive selection and practice.

Figure B.4. Image from (Robotics Technology at ATR, 2003) showing a match between the DB and a CNS Researcher, similar to that demonstrated during the visit.

2. Demonstration of biologically inspired biped locomotion. One of the objectives here is to produce natural and agile movement as found in humans. This has led to three levels of studies:
   - Identifying key properties of central platform generator (CPG)
   - Examining fundamental elements of walking
   - Investigating the learning of walking control schemes
3. Demonstration of visual tracking, as an example of reproducing a fundamental human behavior.

OBSERVATIONS

CNS has an ambitious vision, strong leadership, and an impressive record of accomplishments, considering its relative young age (one year old). The research style is much like that typically found in a top U.S. laboratory, and this should not be surprising. We were told that about 70% of the researchers in the Department of Humanoid Robotics and Computational Neuroscience are non-Japanese. Among those institutions with personnel represented here are Carnegie Mellon University (CMU), University of Southern California (USC), École Polytechnique Fédérale de Lausanne (EPFL), U. of British Columbia, and U. of Montreal. That special blend of local and outside talents has uniquely contributed to the vision and research work of this young organization.

Site: **ATR Intelligent Robotics and Communication Laboratories**
2-2-2 Hikaridai, Keihanna Science City, Kyoto-fu 619-0288
http://www.irc.atr.jp

Date Visited: October 5, 2004

WTEC Attendees: Y.T. Chien (Report author), A. Sanderson, M. Dastoor

Hosts: Dr. Nobuyoshi Fugono, President of ATR International
Dr. Norihiro Hagita, Director of the IRC Laboratories, Tel: +81-774-95-1401, Fax: +81-774-95-1408, Email: hagita@atr.jp
Dr. Kiyoshi Kogure, Deputy Director of IRC; Group Leader, Dept. Knowledge Creation
Dr. Kazuhiro Kuwabara, Group Leader, Dept. Assisted Communication
Dr. Hiroshi Ishiguro, Visiting Group Leader of ATR/IRC Labs; Also Professor of Osaka University

BACKGROUND

The Advanced Telecommunications Research Institute (ATR) was established in 1986 with the support from several sectors including industry and government. The first main ATR laboratories were opened in 1989 in the Kansai Science City known as "Keihanna"—an area in western Japan within 30 miles of the center of the tri-city area of Kyoto, Osaka, and Nara. In the ensuing years, ATR has achieved a reputation as one of the world's best research centers (BusinessWeek, 1997) (ATR, 2005).

As the research environment and funding sources evolved, ATR has undergone several organizational changes in the last 10 years. Currently the research is done under the rubric of eight laboratories, ranging from traditional communications topics to more contemporary areas such as spoken language translation, network informatics, media sciences, and the two labs our panel visited: Intelligent Robotics and Communication Laboratories and the newly established Computational Neuroscience Laboratories. There are roughly 330 researchers at ATR and 20% (68) of them are from overseas, mostly from Europe, Asia and North America. With this international workforce, ATR International seems to live up to its vision of "promoting basic and creative research that would contribute to the international society … and future human life."

The Intelligent Robotics and Communication Laboratories (IRC) are directed by Dr. Hagita who joined ATR in 2001. He served as the principle host for our visit.

SCOPE OF IRC RESEARCH

Dr. Hagita first outlined IRC's vision and the ongoing research projects. The overall goal of IRC's research is, in his words, "to create communication robots that provide more user-friendly communication with people, as well as helpful assistance and information (including Internet-based information) for our daily lives." A focus of this research is facilitating and directing communication. One example of this is having humanoid robots that encourage non-verbal communication through eye contact and gestures. Another example is to use context and space for communication, as provided by the "ubiquitous computing environments," consisting of numerous computers and sensors over a networked space. Major projects undertaken since 1998 include:

- Robovie Series 1998–2004. This research focused on robots that facilitate interactions with other robots and with people and their environments. A series of eight versions of Robovie has been developed; several of them have made it to the marketplace.

- Media for Sharing 2001–2005. This project focuses on creating interactive environments that allow anybody to observe and share human experiences anytime, anywhere, and in any way. The work is done in collaboration with ATR's Media Information and Science Laboratories.
- Networked Robotics 2004–2009. This is a new five-year national R&D project. The goal is to develop robots that operate through the linkage with ubiquitous networks. Its aim is to promote research and development on an open platform for networked robots, facilitating collaboration and interaction among them, as well as engaging in behavior and environment recognition, and human-robot communication. This effort is also closely related to two separate national projects: Ubiquitous Networking Project 2003–2008 and Sensor Network Project beginning in 2005.

ISSUES AND UNSOLVED PROBLEMS

Dr. Hagita suggested that three important research issues face his lab and robotics work in general. The first and foremost is the issue of facilitating communication between humans and robots. Such communication must cover a range of modalities in normal or human-like behaviors, skills, and intelligence—speech, perception, etc. Second, there is the issue of robots communicating with other robots and their environments through ubiquitous sensors, networks, and other computing devices such as PCs. Third and perhaps the least pursued in robotics research is the issue of how to analyze whether and how humans could accept robots as their living companions. This last issue is important if robots are to play a significant role in society and human life.

As for unsolved research problems, Dr. Hagita offered the following: (1) Cognitive mechanisms of human-robot interaction; (2) How does a robot establish social relationships with people? (3) Uncanny valley problem in robots (how much human-like appearance does a robot need?).

In this context, Dr. Hagita also offered an opinion on the comparative strengths of robotics research in Japan and the United States. In his view, Japan is strong in humanoid robots, and the U.S. is very strong in sensor network research.

DEMOS AND LAB TOURS

Several demonstrations were shown to the visitors. This first included a video clip depicting possible scenarios in 2015 in which robots and humans work together in healthcare situations and in elderly assistance.

Figure B.5. Image from showing a typical interaction of a Robovie and a human involving touching and speech communication, similar to that shown during the lab tour (Robotics Technology at ATR, 2003).

The lab tours consisted of several demos of Robovie robots interacting with humans. One was about communicating with a human (female) using a speech interface that has a limited vocabulary of 300 words. The interaction also involved some hugging and touching (with on/off touch sensors). The Robovie is also connected to the Internet via a wireless network. In another demonstration, the Robovie was equipped with a tactile sensor (soft skin) that has 64 levels of sensitivity, allowing the robot to sense a "squeeze" or "hit" by humans. The robot uses this type of interaction primarily to estimate a person's interest and react to that appropriately.

The overall theme of these demos is to emphasize that Robovies are a "platform" used for experiments in human-robot interactions. They need not be a fixed design, but should always be interesting and helpful in facilitating experimentation.

THE NETWORK ROBOT FORUM

Dr. Hagita's lab is also very much involved in the Network Robot Forum (NRF). Such involvement is natural due to the nature of the research done at IRC and the high level of interest and support by the national project on network robots. The NRF is chaired by Professor Hideyuki Tokuda of Keio University (see site report on Keio University). Its purpose is to promote network robots at an early stage through convergence of networks and robots. Current work of the forum includes promotion of R&D and standardization, support for surveys and verification experiments, and promotion of information/personnel exchange with international communities. The NRF has a large number of local government and industrial participants, contributing to the dialogue in developing an emerging robotics market.

One of the interesting outcomes of the NRF activities is the development of a vision and roadmap for the future of network robotics and its role in society and economy. Below is what NRF sees as the timeline (2005–2013) of advanced network robots (Network Robot Forum, 2005):

2005: Network Robotics in Its Infancy

Single-function robots at home would come to be connected to networks; interactions between robots and consumer electronics would be realized. Key characteristics:

- Single-function robots (cleaning robots, healing robots, etc.) will become popular.
- Single-purpose robots, which can be remotely controlled via network, will gain popularity.
- Networking of consumer electronics and technologies for advancing systems functions will be realized.
- Home LANs will be advanced.
- Technologies for network interactions with mobile telephones, etc., including mobile terminals, will be enhanced.

2008: Phase of Growth

Robots will become diversified (virtual, unconscious and visible types), will mutually interact and become available for multiple-purpose use. Key characteristics:

- By interacting with information consumer electronics, robots will be able to expand functions over networks.
- Technologies for real-time remote operation will be realized which will be available for multiple purposes at disaster sites, etc.
- Technologies for robot open platforms will be realized which will enable expansion of functions.
- Friendly human-machine communication will be realized by analyzing tastes, characteristics, etc., through communication with humans.

2013: Mature Phase

Robots can be used even outdoors via ubiquitous networks; interact with two or more robots; and free function expansion will be realized. As such, interactive services by network robots will become full-fledged. Key features:

- By freely interacting with networks outdoors, cooperation with two or more robots will be realized.
- By interacting with two or more robots, robots will freely expand functions; multiple-purpose use of robots will be realized.
- Technologies for advanced platforms will be developed which will enable free expansion of functions.
- Through learning of human tastes and patterns of behavior, behavior recognition technologies will be developed.

OBSERVATIONS

The most interesting observation from this visit (and visits of other sites with similar or related work) is the broad definition of "robots" in the context of a ubiquitous network environment. In order to provide the multifaceted and diversified services envisioned for an information society, three types of robots have been articulated: the visible-type (physical) robots, the virtual-type robots (e.g., software agents), and the unconscious-type robots, typically devices or systems deployed as sensors or as actuators in the environment but largely "invisible" to the humans. The combination of these three types of robots has significantly enlarged the landscape of robotics research.

The focus on networked robots is another aspect of robotics that is also unique here in Japan, as demonstrated at the ATR/IRC laboratories. By merging robots with communications and sensor networks with access to information appliances, databases, etc., the realm of robotics is again expanded and possibly made more challenging for both basic research and technology innovation. The Japanese government is in its second year of significant budgets planned for supporting network robotics research (NSF Tokyo Office Memoranda, 2004), coupled with other related initiatives such as ubiquitous computing networks and sensor networks. This new push, not yet happening in the U.S., may have a huge impact on both the scientific and economic fronts. According to the NRF, Dentsu Communication Institute of Japan put the market size of network robots and related business in 2013 (after maturation) at ¥19.8 trillion (roughly $190 billion), an astonishing figure by any measure. (This is five times the market size compared to a forecast of the Japan Robot Association for 2013.)

Site: **Electronic and Telecommunications Research Institute (ETRI)**
161 Gajeong-Dong, Yuseong-gu, Daejeon, 305-700, Korea
http://www.etri.re.kr/www_05/e_etri/

Date Visited: October 12, 2004

Attendees: Y. Zheng (Report author), G. Bekey, R. Ambrose, Y.T. Chien

Host: Dr. Sang-Rok Oh, Project Manager, Intelligent Service Robot, Ministry of Information and Communication (MIC)
Dr. Young-Jo Cho, Vice President, Intelligent Robot Research Division, ETRI, Tel: +82-2-860-1500, Fax: +82-2-860-6790, Email: youngjo@etri.re.kr
Dr. Hyun Kim, Team Leader, Software Robot Research Team, ETRI
Dr. Jaeyeon Lee, Team Leader, Human-Robot Interaction Research Team, ETRI
Dr. Jung Soh, Team Leader, Intelligent Task Control Research Team, ETRI
Mr. Jaiho Kim, International Collaboration Team, ETRI

BACKGROUND

The Electronic and Telecommunications Research Institute (ETRI) of Korea just formed the Intelligent Robot Research Division about one year ago. The visit to ETRI was primarily occupied by two presentations, one by Dr. Sang-Rok Oh, and the other by Young-Jo Cho. Since Dr. Oh is responsible for the Intelligent Service Robot Project of the Ministry of Information and Communication (MIC), his presentation was more global and reflects the Korean government's point of view, while Dr. Cho focused more on technologies. The assessment team also visited the exhibition room of ETRI which featured many interesting inventions related to electronics and telecommunications as well as intelligent robots.

Presentation by Dr. Oh

Dr. Oh mentioned that the Korean government has an ambitious plan to increase the GDP from $10,000 per person to $20,000 in the next ten years or so. Considering the fact that $10,000 has been the figure for eleven years, the $20,000 goal is extremely challenging. It is interesting to see that the ten growth engines set by the government for that purpose (including intelligent robots) are:

- Digital TVs
- Displays
- Intelligent robots
- Future automobiles
- Next-generation semiconductors
- Intelligent home networks
- Next-generation mobile telecommunication
- Digital content
- Next-generation batteries
- New biomedicine

Dr. Oh also introduced the "839" strategies for the information technology (IT) industry, which seek to introduce *eight* services, build *three* infrastructures, and develop *nine* IT new growth engines as shown below:

1. Introducing and promoting *eight* services
   a. WiBro service
   b. Digital multimedia broadcasting (DMB) (terrestrial/satellite)

   c. Home network service
   d. Telematics service
   e. Radio frequency identification (RFID)-based service
   f. Wideband code division multiple access (W-CDMA) service
   g. Terrestrial digital television (DTV)
   h. Internet telephony (VoIP)
2. Building three infrastructures
   a. Broadband convergence Network (BcN)
   b. u-Sensor Network (USN)
   c. IPv6
3. Developing *nine* IT new growth engines
   a. Intelligent robots
   b. Digital TV
   c. Home network
   d. IT System-on-Chip (SoC)
   e. Next-generation PC
   f. Embedded software (S/W)
   g. Digital content
   h. Telematics
   i. NG mobile communication

The 839 strategy also includes the field of intelligent robots. Dr. Oh further mentioned that the Korean government is sponsoring three programs:

a. Development of core/fundamental technologies, a 10-year program, which is under the administration of the Ministry of Science and Technology (MOST).
b. Intelligent industrial robot, field robot, and personal robot, a 5–10 year program, which is under the administration of the Ministry of Commerce, Industry and Energy (MOCIE).
c. IT-based intelligent service robot, a five-year program, which is under the administration of MIC. The term "intelligence robot" appears in many places.

Dr. Oh also introduced the concept of Ubiquitous Robot Companion (URC) which provides various services whenever and wherever possible to human beings. The core technology of URC is intelligent service robots. More importantly, the Korean government has developed a strategy to become a top-three country in manufacturing intelligent service robots.

Dr. Oh presented the R&D scope for achieving the goal of URC, which includes four major aspects as follows:

- Developing infrastructure for URC which includes technologies related to software robot, real-time network communication, and network server-based service.
- Developing network-based humanoids that focus on human-like self-locomotion and network-based intelligence.
- Developing embedded components technology and standardization. Technologies related to this area include environment understanding and self-navigation, high-speed/high-accuracy image recognition, natural speech recognition, and intelligent robot sensors.
- Developing a network-based robot platform which includes information/contents service robots and public service robots.

Dr. Oh stressed that the URC plan and effort had created many business opportunities for various types of companies including network, hardware, software and service industries. Finally Dr. Oh called for international collaboration for developing a new robot market to solve standardization, policy and law issues related to the future market.

Presentation by Dr. Cho

Dr. Cho's presentation was about IT-based intelligent robotics research currently conducted at ETRI. Dr. Cho first introduced the organization of ETRI, which has twelve divisions and one laboratory. The Intelligent Robot Research Division is one of the divisions. Dr. Cho envisions that the creation of IT-based intelligent robots could be achieved by overcoming the restrictions of legacy robots and utilizing the leading technologies of IT. That combination needs R&D efforts to create personal robot systems with more functions, but at lower prices. The latter two combined will extend business opportunities created by the URC concept. It is interesting to notice that Dr. Cho compared the so-called legacy robots and networked robots. The legacy robots are monolithically designed in drive, control, sensor, recognition, decision, and interaction, etc., and are large and expensive, while networked robots offer flexible design in drive, control, sensor, and actuator, and are smaller and cheaper. In terms of the service, the legacy robots have a proprietary platform, which is rigid and difficult for function changes, while networked robots have a common platform, and their content of service is easily changed. In terms of performance, legacy robots are incomplete in terms of robot technology, limited in functional implementations, and their costs outweigh their benefits, while networked robots have network combination technologies, offer implementation of server usage functions, and their benefit/cost ratio is better.

ETRI is an active participant in the URC Grand Project sponsored by MIC which has four components: URC infra system technology and embedded component technology, both of which ETRI is responsible for, information service robots, which five industry consortiums are responsible for, and humanoid technology, which the Korean Institute of Science and Technology (KIST) is responsible for. The goal of the Grand Project is to develop core competency, standardization, and commercialization. ETRI also has identified R&D issues for the two areas which ETRI is responsible for, i.e., URC Infra System Technology and Embedded Component Technology.

ETRI has 71 researchers in its Intelligent Research Division, which are organized into seven teams, of which the robot software architecture research team, the URC hardware component research team, the intelligent task control research team, and the human robot interaction research team work on embedded component technology. The software robot research team, the intelligent service platform research team, and the knowledge and inference research team focus on URC infra system technology. Dr. Cho further introduced the research of the two areas.

The URC Infra System research exists to develop the IT Infra System which supports robots and provides them with all necessary services at any time and any place. Research on the URC Embedded Component Technology develops core H/W or S/W components constructing URC, focusing on enabling technologies that maximize the commercial value of the IT-based networked robots. Currently, ETRI is studying four technologies: intelligent task control, human robot interaction, robot software architecture, and robot hardware components.

From Drs. Oh and Cho's presentations, one can observe three important features of robotics research in Korea, which we found true during out visits at other Korean institutes. First, the R&D activities are closely related to the economy of the country; second, the R&D activities are heavily sponsored by the Korean government; and third, the government, research institutions, and industries collaborate closely.

LABORATORY VISIT

Our host did not show us the laboratory, but instead led us to an exhibition room which had quite a number of inventions by the ETRI researchers. Of all the displays we were particularly impressed by an intelligent home with a kitchen and a sitting room equipped with home appliances connected to the Internet and

controlled by computers. The space, doors, and windows have sensors embedded to monitor the environment. ETRI envisions the intelligent home to become commonplace in the future, which will create a great market for various industries. In the exhibition room the visiting team also saw a robot-guider that guides visitors on public tours such as museums.

SUMMARY

The ETRI visit revealed two pieces of information. The first piece is the ten growth engines of the Korean government which include the field of intelligent robots. The other piece is the Ubiquitous Robotic Companion concept. To develop technologies which support URC, MIC is sponsoring a URC Grand Project, which has four components, namely, URC infra system technology, embedded component technology, information service robots, and humanoid technology, and ETRI is responsible for the first two. The Intelligent Robot Division of ETRI has 71 members, which are organized into seven teams to cover the two areas of the URC Grand Project. The visit to ETRI further solidifies our observations on the close collaboration between government, research institutes, and universities in robotics research, and the perceived importance of intelligent robots in driving the Korean economy in the next 10 years.

Site: **FANUC Ltd. Headquarters**
3580 Shinokusa, Oshino-mura,
Yamanashi-ken 401-0597, Japan
http://www.fanuc.co.jp/en/product/robot/

Date Visited: October 8, 2004

WTEC Attendees: V. Kumar (Report author), Y.T. Chien, Y. Zheng

Hosts: Dr. Eng. S. Inaba, Honorary Chairman, Email: inabas@mb.infoweb.ne.jp
Dr. Eng. Yoshiharu Inaba, President and CEO, Email: Inaba.yoshiharu@fanuc.co.jp
Mr. Atsushi Watanabe, Executive Vice President, Group Executive, R&D – Robot Group, Email: watanabe.atsushi@fanuc.co.jp
Dr. Eng. Shinsuke Sakakibara, Senior Development Engineer, Honorary General Manager, Robot Laboratory, Tel: +81-555-84-5363, Fax: +81-555-84-5879, Email: sakakibara.shinsuke@fanuc.co.jp

OVERVIEW OF FANUC

FANUC Ltd. is a privately held company manufacturing computerized numerically controlled (CNC) machines, industrial robots, servo motors and amplifiers, machining centers and robot-integrated work cells integrating robotics with standard manufacturing technology like drilling, injection molding or cutting. It has sales of over $2 billion with establishments in North America, Asia, and Europe. It has a long history of innovation going back to 1956. GMFANUC Robotics Corporation was established with General Motors in 1982, with FANUC buying GM's share in 1992. GEFANUC Automation was established in 1986. FANUC has 17% of the industrial robotics market in Japan, 16% in Europe and 20% in North America. Its biggest competitors in Japan are Kawasaki and Yasakawa, and ABB in North America. It is the leading manufacturer of CNC machines with Siemens as its closest competitor. Dr. Inaba, who is the president of the Japan Robot Association, noted the increasing interest and application of robotics in non-industrial sectors (service, entertainment, and healthcare). However, FANUC has no plans of going beyond industrial robotics. Dr. Inaba stated that FANUC will never become distracted with non-industrial robots.

FANUC's competitive edge today can be attributed to superior servo motor and amplifier technology, relatively flexible end-effectors and integration of vision and force feedback for flexible manufacturing. The company believes in using artificial intelligence (we interpret that as the integration of vision and force feedback into the control software) technologies and plans to continue investing in this approach in the future.

INDUSTRIAL ROBOTS

FANUC 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. Their pride is the R-2000*i*A, the so-called "intelligent robot for versatile applications," which includes such features as collision detection, compliance control, and payload inertia/weight identification. The control software supports networking and continuous coordinated control of two arms. With a resolution of 0.3 mm and a payload of over 200 kg, it can be used for a wide range of applications.

The cost of end-effector tooling still remains a large fraction of the total cost of the work cell. Typically the end-effector cost is often around 25% of the cost of the industrial robot.

We saw several interesting demonstrations; three of the most impressive are reported below:

- Vision-guided grasping: A camera attached to the end-effector is used to identify the position and orientation of the part, enabling the robot to pick up the part. To do this, the robot first views the part from different angles. By picking up the part and placing it down with a new orientation and repeating the image capture from different angles, the robot acquires a database of 2,000 or so images in 10 minutes. This database is then used to estimate the orientation and position of the part in any given position/orientation. In the demonstration, the robot was able to pick up a 3D part from a collection of identical parts thrown onto a surface. The vision-based pose estimation and grasp calculation algorithms took approximately one second.
- Force-based assembly: Force feedback was used to assemble a sprocket in a clutch assembly by inserting it, pushing down with compliance and vibrating the sprocket gently in a rotary motion for assembly. We found this task to be extremely difficult to perform using our hands, and the robot consistently got it right.
- Vision-guided fixturing: Two robots, each equipped with a structured light source and a camera at the end-effector, are able to locate a casting that has been placed on a pallet without any *a priori* alignment. The robots use 2D vision to estimate the location of the casting, approach closer, and then use 3D vision to determine the exact position and orientation to perform finishing (deburring) operations with the appropriate tool. The task requires an accuracy of 0.1 mm, and the system is able to effectively perform the task.

The force sensor is based on a design similar to the one used by Lord Automation nearly 20 years earlier, with an improved structural design and temperature compensation. The structured lighting system is similar to the one used by Perceptek, and the technology is at least 20 years old. The integration of these basic pieces of technology produces remarkable results. Mr. Watanabe claims the vision system for grasping performs with 99.9% accuracy, or in other words, not picking up the part correctly only once in 1,000 tries. The force feedback-based assembly system can assemble cylindrical pegs in holes with a 1 mm chamfer with clearances that are a fraction of the repeatability, clearly not relying on position control.

WORK CELL INTEGRATION

Mr. Watanabe described the current level of machining integration as third generation. The 1980s saw the first generation of automation where indexing mechanisms (typically rotary tables) were used to house fixtures. This resulted in the machining center being operated intermittently. All the workpieces were fixtured before the machining center could be started and run, after which all the workpieces had to be unloaded. The 1990s saw the second generation where continuous machining was possible because of an automated warehouse for fixtured workpieces that could be retrieved depending on the availability of machining centers and returned to the warehouse after the machining operations were completed. However, this required many expensive fixtures and a large automated storage and retrieval system. The third generation developed over the last several years is a system where the same workpieces can be stored on ordinary, inexpensive pallets. The availability of vision-based 3D localization and fixturing algorithms allows the tedious and expensive process of fixturing to be automated. The FANUC factory for heavy machining of housings for the robots and servo motors, and platens (for molding) has all three levels of machining integration. The third generation accommodates simple pallets, robots with a single effector, workpieces positioned with relatively large tolerances, and with different parts or different pallets or even multiple parts on the same pallet.

There is obviously a lot of hard work that must go into the integration, and it is not clear how much time is spent in programming the workcell. In one of the demonstrations, Mr. Watanabe said that the system takes about 10 minutes to acquire a database of 2,000 images and after that the pose estimation works satisfactorily with a single camera at approximately 99.9% accuracy. There was much less information shared about the development and programming time for more complex system integration.

SUMMARY

FANUC Ltd. is a privately held company with strong company loyalty that is not uncommon in Japan. Of the 1,800 or so personnel at the facility, 1,300 work in the research laboratories and over 600 of these are engineers. Only 10 or so are PhDs. They must be strongly motivated, smart engineers because they used fairly sophisticated (albeit well-known) tools in control theory, matrix algebra and computer vision. The turnover is less than 1%, and the company appears to be growing.

We saw technology that not only demonstrated an impressive level of integration with remarkable results, but also a philosophy of complete automation without resorting to hard tooling. Robots assemble robots, with each robot assembly taking less than 10 hours. Robots coordinate motions, realizing visions of the research community going back to the late 1980s. The robot to human worker ratio is 5:1. In fact, 1,300 of the 1,800 employees work in the research labs, with only 300 engineers in the factories.

Site: **Fujitsu Autonomous Systems Lab**
4-1-1 Kami-Odanaka, Nakahara-ku,
Kawasaki City 211-8588, Japan
http://www.labs.fujitsu.com/en/theme/robot/robot.html

Date Visited: October 5, 2004

WTEC Attendees: R. Ambrose (Report author), Y.T. Chien, J. Yuh, B. Wilcox, D. Lavery, V. Kumar

Hosts: Satoru Komada, Director, Autonomous Systems Laboratory, Tel: +81-46-250-8815, E-mail: komada@stars.flab.fujitsu.co.jp

BACKGROUND

The lab has a long history of robotics achievements, from space to factories to service to humanoid systems. FANUC was started as a subsidiary of Fujitsu. Fujitsu made the Micro Arm in 1981 and the M6 arm in 1986. Fujitsu was involved in the Hazardous Environment Robot from 1983 to 1991 under funding from the former Ministry of International Trade and Industry (MITI). Fujitsu built the 0 g simulator in 1990, and a two-armed cooperative robot in 1993 for satellite capture and repair. These arms were 7 degree-of-freedom (DOF) systems that Fujitsu built for National Space Development Agency (NASDA). MITI funded Fujitsu to work on the Engineering Test System (ETS-VII) in 1996.

In 1998, Fujitsu was commissioned to work on the Humanoid Robotics Project (HRP) program by the Ministry of Economy, Trade and Industry (METI). During Phase 1 (4/98–3/00) Fujitsu developed the virtual platform for use with the Kawasaki cockpit and the Honda P3. During Phase 2 (3/00–3/03), Fujitsu made the HRP verification unit. This was a full-up humanoid that was used to fill the void caused by Honda's lack of provided units, and the parallel development of the HRP-2 units by Kawada. This system was used, and then sold to Professor Nakamura from Tokyo University. In 1998, Fujitsu developed a hospital delivery robot for MITI and the Ministry of Health. They found that this robot had an estimated commercial cost of ¥14 million, and that this price point was too high for the market. This activity led to a series of lower-cost products Fujitsu developed for commercial markets.

COMMERCIAL ROBOTS

- Mascot Robot
  - 1999
  - Named 'Touch Ojisan'
  - Price of ¥3,800
  - Sold 100,000 units
- HOAP Series
  - HOAP stands for Humanoid for Open Architecture Platform
  - HOAP-1 Built 9/2001
    - 50 cm, 7 Kg, 20 degrees of freedom (DOF)
  - HOAP-2 Built 8/2003
    - 25 DOF
    - Price of ¥25 million
    - 80 units sold, including overseas sales (possible sale to Jet Propulsion Laboratory (JPL))
    - Uses commercial actuators
      - ¥150,000 each
      - 60, 150 and 160 gram units

- 0.4, 4.5, and 6 W units
  - Integrated controllers
- Price includes simulator

HOAP-3 is now in development.

Figure B.6. HOAP-2 unit and close-up of legs.

- MARON Series
  - MARON stands for Mobile Agent Robot of the Next Generation
  - MARON-1
    - Home security, can control appliances, and has camera
    - Robot can be controlled from cell phone
    - Price of ¥300,000
    - 100 units sold
  - MARON-2 now in development
    - Ready for market in 2004
- Wheeled Office Service Robot
  - Offered to market in June 2005
  - Price of ¥20,000
  - To be sold by another Fujitsu company called Frontec
  - Features and functions
    - Two arms and a head with three pairs of stereo cameras
    - Mobile indoor wheeled base
    - About 1.2 m tall
    - Works with elevators, seeing and pushing buttons
    - Has no touch recharge system
    - Can push carts

LAB TOUR

Fujitsu was very open to our panel. Considering that companies have the most to lose and least to gain from our study, we are very grateful that they agreed to see us at all. They were very kind to take us into their labs, where we saw many engineers working on all sorts of robots. We were shown a demonstration of the Humanoid for Open Architecture Platform 2 (HOAP-2) system, including walking, dancing and balancing on a single limb. The robot stood up from a prone position.

We were also shown a demonstration of the MARON-2 and office robots. Around the lab we saw many of the actuators and electronics that are used in various Fujitsu robots. Mr. Komado was kind enough to share many digital movies of the robots performing the same tasks we saw in the lab our, as well as other functions.

Site: **Hanool Robotics**
Daeduk Atomic Energy Valley, 461-68, Jeonmin-Dong
Yuseong-Gu, Daejeon City, 305-811, Korea

Date Visited: October 12, 2004

Attendees: Y. Zheng (Report author), R. Ambrose, G. Bekey, Y.T. Chien, V. Kumar, A. Sanderson, L. Weber, B. Wilcox, J. Yuh

Host: Dr. B.S. Kim, President of Hanool Robotics, Tel: +82 42-478-9090, Fax: +82 42-478-9094, Email: bskim@robotics.co.kr

BACKGROUND

Hanool Robotics is the only small company the team visited during the entire trip to Japan and Korea. The trip revealed an important piece of information, i.e., some small companies are taking the business of services robots seriously, which is consistent with Korean government program for developing the technologies of intelligent service robots. The team listened to the presentation by the president of the company and saw a number of home service and special service robots, some of which were still under development while others were on the way to market.

Hanool Robotics Corporation

Hanool Robotics is one of fifty or so new start-up companies in Korea that targets the service robot market. The company was founded in 1998 in Daejeon, Korea, and established the Intelligent Robot Laboratory in 2000. In 2001 the company increased its capital investment to $2.6 million. In 2002 the company received ISO9001:2000 certification, and in 2003 Hanool moved its head office to the current new building in Daeduk Atomic Energy Valley, which has three above ground and one underground floors. The company currently employs 30 people. Hanool Robotics announced the development of the cleaning robot "OTTORO" in July 2003, and it has since been put on the market. The company has consistently participated since 2002 in technical conferences and exhibitions, such as IROS (International Conference on Intelligent Robots and Systems) and CES (Consumer Electronics Show), to advertise their products.

Hanool Products

Hanool has two primary fields of operations: Home Service Robots and Special Service Robots, respectively. The field of Home Service Robots has three products; this includes the home cleaning robot "OTTORO" (Fig. B.7), the Home Service robot "iComar," which is a joint project with Samsung, and the Information and Contents robot, which is still under development. The field of Special Service Robots has a number of products: basic robot education system, research and education robots including: HANURI-RS, HANURI-RD, and military robots including: HANURI-T, HANURI-RC, HANURI-MC, and a transformable track-type robot that was being developed at the time of the visit.

Figure B.7. OTTORO cleaning robot cleaning the floor.

OTTORO is the most developed product of the company. The robot appears well designed and looks in harmony with home appliances. We also saw a demonstration of OTTORO cleaning the floor of a kitchen (Figure B.7). Hanool uses two technologies in OTTORO. One is intelligence, and the other is strong and fast cleaning capability. For intelligence, the robot is capable of self-localization and obstacle avoidance, and uses a path planning method based on auto map building. The robot has an innovative design in its cleaning tool that is capable of cleaning corners of a house. The robot has three times the cleaning power of other robots on the market. Another important difference is that other cleaning robots take random paths to clean a house, while OTTOTO takes a planned path which depends on the area and shape of the floor. With all these advantages, OTTORO is more efficient and effective than the competition.

To achieve self-localization and map-building, OTTORO uses multiple sensors including a vision sensor for extracting the features of ceiling edge configuration, which are compared with pre-known data to determine cleaning strategy (path planning). The robot also uses multiple sonic sensors to obtain a map of obstacles. A sensor fusion method for integrating the data of the vision and sonic sensors is also used.

Figure B.8. The iComar Robot (courtesy Hanool Robotics).

Another robot which Hanool introduced is the Internet Communicable Mobile Avatar Robot (iComar) (Figure B.8). iComar is 60 cm tall, weighs 10 kg, and is a PC-based home robot. The robot has a semi-autonomous navigation capability, and can recognize voice commands. It provides security service by equipping itself with a camera, a microphone, and multiple human recognition sensors. In addition, it can provide home monitoring through the Internet.

The third product is the Information and Contents robot which has a seven-inch monitor, a speaker, a security camera, various function buttons, and a cleaning brush. Apparently, the robot is more capable than OTTORO, which just cleans. The robot is also equipped with two-wheel differential as well as a microphone. One can imagine that such a robot would be more useful to a family than OTTORO, and more justifiable to own by ordinary households. The visiting team saw the prototype of the Information and Contents Robot although it is still under development (Figure B.9).

Figure B.9. The Information and Contents robot.

The company also introduced three other products: the Basic Robot Education System, the Research and Education Robot, which included various versions as mentioned earlier (Figure B.10 shows one of them), and Military Robot. For the latter, Hanool has developed an Anti-Terror Robot called Hanuri-T-ML as shown in Figure B.11. Like the first three robots, the Research and Education robot and the Anti-Terror robot are all mobile robots equipped with various sensors for navigation and operation according to the purpose which they were designed for.

Figure B.10. Research and Education Robot.

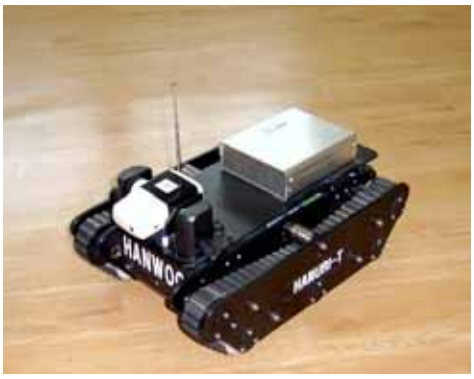

Figure B.11. Military Robot.

SUMMARY

Hanool Robotics is the only small company the assessment team visited in this Japan-Korea trip. From the visit, we can see that Korea has taken the new robotics industry seriously. Not only has the government set up a policy defining Intelligent Service Robots as one of the ten growth engines of the economy, but in addition, many small companies have started to develop new robot products. Hanool represents one of the 50 service robot companies in Korea that have collectively developed 20 robot product lines, of which Hanool has two. It appears that Hanool is one of the more successful ones among all the start-up companies.

From the five products, we saw that the intelligence technology has important uses and great potential in the service robots. We saw a great deal of high technologies used in service robots. Although some of them were seen by team members earlier in North America, the development and implementation of the technologies for application purposes by Hanool Robotics and others is impressive and commendable. In this regard, Japan and Korea, especially Korea, are ahead of many countries. Experts in Korea expect the robot market to grow based on three reasons; half of the households in South Korea reside in apartment-type homes that have structured environments; Korea has a widespread network infrastructure that can support the operation of robots; and people have a positive attitude towards the robot market. The start-up robot companies expect the market of service robots to grow like that of mobile telephones in the near future. The team had to agree after the visit to Japan and Korea.

Site: **Japan Agency for Marine Earth Science and Technology (JAMSTEC)**
Marine Technology Center (MARITEC)
2-15 Natsushima-cho, Yokosuka
Kanagawa-ken 237-0061, Japan
http://www.jamstec.go.jp

Date Visited: October 4, 2004

WTEC Attendees: V. Kumar (Report author), Y.T. Chien, A. Sanderson, J. Yuh, Y. Zheng

Hosts: Dr. Ikuo Yamamoto, Leader, Autonomous Underwater Vehicle R&D Group, Marine Technology Research and Development Program, MARITEC, JAMSTEC, Tel: +81-46-866-3811, Fax: +81-46-867-9055, Email: iyamamoto@jamstec.go.jp
Dr. Satoshi Tsukioka, Sub Leader, Autonomous Underwater Vehicle R&D Group, Marine Technology Research and Development Program, MARITEC, JAMSTEC, Email: tsukiokas@jamstec.go.jp

OVERVIEW

Japan Agency for Marine Earth Science and Technology (JAMSTEC) has an annual budget of ¥331 billion, and includes Tokyo Oceanology University. It consists of 962 people, 347 of whom are contract research staff, 92 are crew, and 78 are research staff.

JAMSTEC consists of three divisions: (1) The Yokohama Institute for Earth Sciences; (2) Mutsu Institute of Oceanography; and (3) Yokosuka Headquarters. The Yokosuka Headquarters has four main divisions: (a) Institute of Observational Research for Global Change; (b) The Institute for Research on Earth Evolution; (c) Extremobiosphere Research Center; and (d) Marine Technology Center (MARITEC). Drs. Yamamoto and Tsukioka represent MARITEC.

MARITEC (Dr. Makoto Okusu, Director) consists of a team of 155 people with a budget of roughly ¥3 billion. The goal of MARITEC is (a) to develop basic systems for marine R&D and advanced technology; and (b) to operate and maintain ships and large shared experiment facilities for supporting JAMSTEC observation and ocean research.

MARITEC operates several research submersibles between 1500 and 8500 tons in capacity. More information about the vessels can be obtained at: http://www.jamste-c.go.jp/jamstece/web_movie/menu_index.html.

URASHIMA—THE EXPERIMENTAL PLATFORM FOR AUV RESEARCH

The team devoted most of its time to presentations and a tour of the Urashima. The Urashima is a new underwater vehicle with the ability to automatically collect ocean data such as salinity and temperature. It will be used to study the interaction of the ocean and the atmosphere and to infer ocean circulation from the amount of carbon in sea water.

With its ability to submerge to waters 3,500 m deep, it can traverse and map 80% of the ocean bottom in the world (the average ocean depth is around 3,000 m).

Its closed-cycle fuel cell power source and its relatively high-precision inertial navigation system make it unique. It is equipped with side scan sonar and a digital camera to obtain topographical data on the ocean floor.

Specifications

- Urashima (2000) AUV
- Length 9.7 m
- Width 1.3m
- Height 1.5 m
- Depth 3,500 m
- Range 300 km
- Weight 10 tons

The vehicle is propelled by a 1.5 kW main propeller, two vertical thrusters, a horizontal and vertical rudder, and elevators. It needs approximately 60 personnel to launch and test the vehicle. The vehicle was built in cooperation with Mitsubishi Heavy Industries with the hull built in Kobe and the fuel cell built by Mitsubishi.

The Urashima has three key technologies:

1. An underwater navigation system relying on an Inertial Navigation System (INS)
2. An energy source consisting of a primary Polymer Electrode Fuel Cell (PEFC) (300 km range) with a Lithium ion battery for secondary storage (100 km range)
3. An energy storage mechanism using metal hydride

Remote control of the vehicle can be achieved by optical or by acoustic links.

Figure B.12. Research Vessel operated by JAMSTEC (left) and Urashima, the AUS developed by MARITEC (right).

AUV RESEARCH

The MARITEC team has conducted effective research and development on the following.

Improving Telemetry

- acoustic communication until maximum operation depth (depth 3,500 m, 100 m altitude)

Vehicle noise induces acoustic noise. By installing an optical fiber to get direct feedback from the Autonomous Undersea Vehicle (AUV), they were able to analyze the effect of vehicle noise, attributing it to a propulsion gear and then modifying the transmission (including changes of spur gear to helical gear) to reduce noise. Currently the modulation scheme allows communication at 2000 bps (at 8.5–10.5 kHz, a relatively noise-free region) at the 4,100 m range.

Navigation system

Instrumentation includes:

- doppler velocity sensor which can measure either ground speed or water speed (only water speed can be measured above altitudes of 100 m, but ground speeds, when available, are characterized by smaller errors (errors around 5%, but water speed errors can be around 10%))
- inertial navigation system (INS)
- homing sonar
- depth sensor

Urashima also has instrumentation for sea floor imaging (side scan sonar and a snapshot digital camera). The side scan sonars (50–100 m altitude) and digital cameras (40 m under clear conditions) are not used for navigation.

The positioning algorithm

- calculates position with INS
- corrects position error by homing sonar and transponder at a known location

The homing sonar conists of three hyprophones at 6.9, 7.2, and 7.5 khz and has a range of 10 km for detection.

Recent (June 2004) tests recorded four round trips lasting 44 hrs and extending 220 km. The AUV is navigated using two transponders with estimates of 1 km errors between transponders.

Kaiko 7000 vehicle

The Kaiko 7000 is a remotely operated vehicle (launcher separate), 3.1 m long, 2.0 m wide, and 2.3 m in height weighing 5.6 tons, capable of operating in waters 11,000 m deep. The sensors include a TV station-class TV camera, three panoramic TV cameras, and a black-and-white camera aft-looking camera. It is also equipped with two 7 degree-of-freedom (DOF) manipulators. JAMSTEC lost a Kaiko remotely operated vehicle (ROV) last year during high tide due to a broken tether (cable).

UROV7K

The UROV7K is a 1.8 m wide, 2.0 m high, and 2.8 m long, 2,700 kg ROV capable of operating at waters 7,000 m deep.

MR-X1

The Marine Robot MR-X1 is an experimental vehicle designed to explore handling of AUVs in low temperatures and operation in the deep seas.

Specifications

- 4200 m depth
- 2 knots
- 2.5 m length
- 0.8 m width
- 1.2 m height

Power:

- oil filled Li-ion rechargeable
- Actuators: 1 thruster (400 W)

- 2 horizontal (150 W)
- 2 vertical (150 W)

The only sea trial of the MR-X1 was held in June, 2002, to adjust buoyancy and manual control of thrusters. Future trials will explore autonomous operation.

Undulatory Locomotion

Dr. Yamamoto has developed several prototypes of robot fish that are capable of swimming using undulatory locomotion. These fish are around 60 cm in length and powered by Lithium ion batteries. They are capable of locomotion using sinudoidal motion of their tails. By varying the amplitudes and phase of this motion, they can steer and control the speed of the fish. This project, which is about eight years old now, has been conducted in collaboration with Mitsubishi. The team found the video demonstrations very impressive.

Ten percent of the total budget is devoted to MARITEC research.

Site: **Korea Advanced Institute of Science and Technology (KAIST)**
373-1 Guseong-dong, Yuseong-gu
Daejeon 305-701, Republic of Korea
http://rcv.kaist.ac.kr/

Date Visited: October 12, 2004

WTEC Attendees: B. Wilcox (Report author), G. Bekey, J. Yuh, Y.T. Chien, R. Ambrose

Host: Jong-Hwan Kim, Director, Intelligent Robotic Research Center, Tel: 042-869-2114
In So Kweon, Professor, Department of Electrical Engineering, Tel: 042-869-3465, Email: iskweon@kaist.ac.kr,
Z. 'Zenn' Bien, Professor, Department of Electrical Engineering & Computer Science, Email: bien@kaist.edu
Jun Ho Oh, Professor, Email: jhoh@kaist.ac.kr,
Dong-Soo Kwon

OVERVIEW

Korea Advanced Institute of Science and Technology (KAIST) started robotics research in 1979. The Human-friendly Welfare Robot System (HWRS) program is funded at the rate of $1 million/yr, by the Ministry of Science and Technology (MOST), the Ministry of Information and Communications (MIC), and the Ministry of Commerce (MOCIE). They have recently instituted a bio-robotics program (for brain research, etc.). There are 20 professors involved, along with 80 graduate students. A key project is the Intelligent Sweet Home (ISH), a robotic "house" for the medical patients and the aged. This particular one is named Joseph (after Joe Engleberger). It uses voice command to deliver meals, clothes, and to bring a sling into position to move an invalid from the bed into a wheelchair, which was demonstrated during the lab tour. "Joseph" is a large face on a video screen who responds to these voice commands with a voice or actions of the systems in the room.

KAIST has established a new interdisciplinary program in robotics, and is offering a PhD in the field.

Jong-Hwan Kim, the director of the Intelligent Robotic Research Center (IRRC), described the ubiquitous robot, which is an IT-based service robot. The key issues are interface, intelligence, and motion. They are developing a dog robot that shows emotional states, the Hansaram-V humanoid robot, and personal digital assistant (PDA)-based commanding of a microrobot.

In So Kweon described computer vision research. A key area of study is vision processing in the brain. They have developed a bi-prism camera to help solve the correspondence problem in stereo vision using optical means. Also, they are developing a statistical model for color variation between adjacent points in a scene. In addition, they are working on the technique of appearance-cloning, which gives better reconstruction than other state-of-the-art vision algorithms (20 minutes for one scene on one Pentium 4). Their budget is $600,000 a year.

Professor Jun Ho Oh described the Machine Control Lab, which is part of the Mechanical Engineering (ME) department. There they are working on the KHR-2 walking robot. Dong-Soo Kwon described the Telerobotics and Control Lab. A key research topic is applications of haptic technology to Human-Robot Interactions (HRI). Perhaps their greatest success is a "fishing simulator" funded by industry, which gives a fishing rod "feel." They have also developed a very compact laproscopic camera system that provides autotracking, knowledge of surgical procedure and surgeon preference. For HRI they want to develop a higher "emotional quotient" (as opposed to a higher IQ). Their budget is $1.5 million/yr for 10 years on HRI, courtesy the Ministry of Science and Technology.

During the lunch conversation, there was a comment that the WTEC team may not be as impressed having gone to Japan first—Japan is doing a lot of research (the analogy was made to visiting Rome last on a tour of Europe).

KAIST is operated under the Ministry of Science and Technology, as opposed to the Ministry of Education. They offer degrees but they are not a university—they are more like the Massachusetts Institute of Technology (MIT).

The South Korean government has selected Intelligent Robotics as one of 10 "growth engines" (like HDTV/flat panel displays) for funding at the level of somewhere close under $100 million/year. MIC contributes $30 million/year, MOST contributes $10 million/year, and MOCIE contributes $10 million/year. The total is about $85 million/year on intelligent robotics. By comparison, Japan is spending approximately $100 million/year in this research area. MOCIE spends $60 million/year on a network service robot, to be achieved by next year.

Samsung is said to have its own research program. Venture companies are working with KAIST, but the "Killer App" does not appear to be in the near future. The closest thing to a "killer app" is the elder care robot. The KAIST president is worried about safety issues, however.

The Agency for Defense Development (ADD) is like the "DARPA" for South Korea. Starting this year they want to investigate issues for military robotics—including applications of humanoid robots, navigation, etc.

In Soo Kweon stated that KAIST has vision work for ADD that they cannot show. (In terms of priority, defense and security is first, robotics is second, and culture technology is third.) A tentative title for the program is "21st century intelligent robotics," and they are now preparing proposal for large amount of money. They have several professors from other countries. They have space for start-up companies such as from the cultural industry (e.g. content: movies, entertainment, music) on the KAIST campus with very inexpensive rent.

Site: **Keio University – Kawasaki Campus**
144-8 Kokura, Saiwai-ku, Kawasaki City
Kanagawa-ken, 211-0984, Japan
http://www-oml.sum.sd.keio.ac.jp/eng/index_e.html

Date Visited: October 5, 2004

Attendees: Y. Zheng (Report author), G. Bekey, R. Ambrose, V. Kumar, B. Wilcox, J. Yuh, H. Miyahara

Host: Kohei Ohnishi, Professor, Dept. of System Design Engineering, Tel: +81-44-580-1580, Email: ohnishi@sd.keio.ac.jp

BACKGROUND

Robotics Research at Keio University is known for the motion control work done by Dr. Ohnishi. Dr. Ohnishi's efforts are in the area of haptic communication and haptic control, which is necessary for robots with limited degrees of freedom but which work in environments that may have infinite modes. While the research in the area started more than 10 years ago, Dr. Ohnishi has further deepened the field by developing new theories as well as applications which have to take environmental information into consideration.

The University and the Center of Excellence

Keio University was founded in 1858 and is the oldest private institution in Japan. About 60 years ago, the College of Engineering was formed, and about 10 years ago the Department of System Design Engineering was founded. Recently, the Japanese government funded the Center of Excellence at University of Tokyo, which includes 22–23 research programs, and at Keio University, which has 13 programs. Considering the huge disparity in size between the two institutions, the engineering program at Keio is obviously formidable.

Research Activities by Dr. Ohnishi

Dr. Ohnishi has studied the area of motion control for many years. In order to improve the performance of the robot when it works in an unstructured environment, Dr. Ohnishi has developed a number of approaches, including bilateral communication between master and slave, acceleration control, compliance control, force control, etc. The goal of all the approaches is effective stiffness variation of the end-effector. Dr. Ohnishi stated that to have robust behavior of the end-effector, its stiffness must be high. For various practical applications and unknown environments, on the other hand, the stiffness must be adjustable. This presents a challenge, and Dr. Ohnishi's group has generated a series of solutions for solving the problem. These approaches in recent years have expanded to include haptic communications, bilateral motion control, teleoperation over the Internet, etc.

In 1990, Dr. Ohnishi's research group enabled the first endoscopic operation in Japan. In 1998 surgical robots were made available, and in 2000 a Japanese type of "DaVinci" robot for surgery became functional ("Da Vinci" is the name of the U.S. company that manufactured the first surgical robot). Dr. Ohnishi is famous for his work in motion control and organized the first technical conference on the topic in Japan earlier in 2004. A copy of the conference proceedings was provided to the group by Dr. Ohnishi.

During our visit, Dr. Ohnishi presented his theory regarding haptic control. He defined the stiffness of an end-effector by $k = \delta f/\delta x$ where f is the interacting force, and x is the position of the end-effector. When k is infinite, the end-effector is under the mode of position control; when it is zero it is under force control; and anything in between is the compliance control. When the end-effector has a high stiffness, it may lose stability but is robust in position control. When the stiffness is low, the end-effector loses robustness in the position control, which is necessary when the environment and elasticity of the object are unknown. By this definition, stiffness can be used as an index of motion control in a general sense.

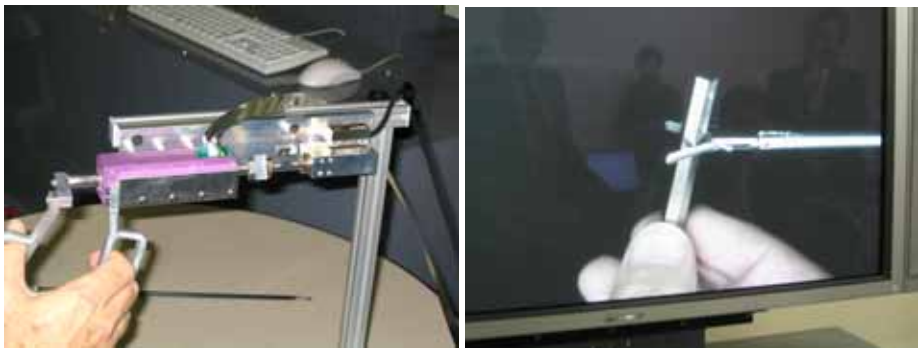

Figure B.13. The master-slave device with stiffness control; (left), the master side of the haptic device, and (right), the end-effector-side of the device.

After the presentation, Dr. Ohnishi showed us his laboratories, which are located in two buildings. In the first laboratory, we saw a master-slave device for remote manipulation. The device implements the bilateral motion control mechanism. On the master side, the operator can feel the stiffness of the object that the end-effector interacts with, and on the object side the stiffness of the end-effector (which has two fingers in this case) can also be adjusted. This particular device should have many applications, such as surgical robots. The picture of this particular device is shown in Figure B.13. We also saw two industrial robots working in the master-slave mode.

In the second laboratory, the visiting team saw another master-slave device with haptic control (Figure B.14), and a parallel mechanism that provides multiple degrees of freedom to an end-effector. The structure has a special mechanical design that provides dexterity as well as compliance of the end-effector. This is shown in Figure B.15.

Figure B.14. A master-slave device.

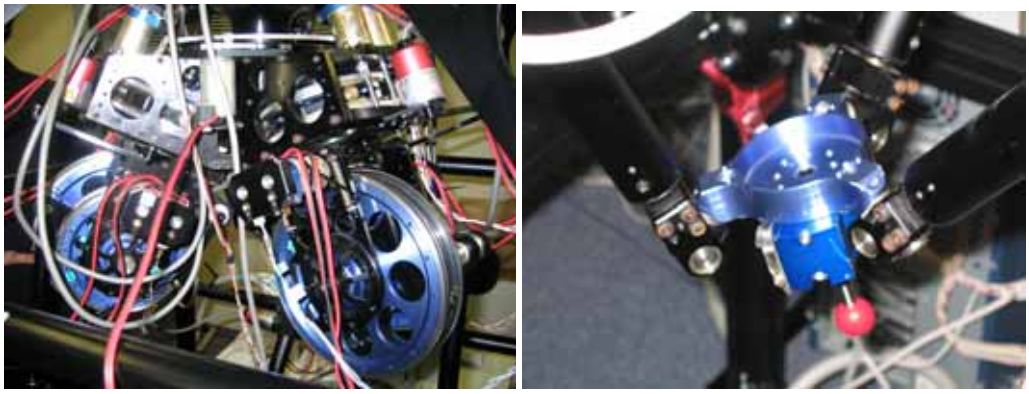

Figure B.15. A parallel mechanism (left) supports the end-effector (right).

SUMMARY

For many years Dr. Ohnishi has studied robot motion control mechanisms and their interaction with unknown objects or movement in unknown environments. It is necessary to provide haptic control to the robots when both robust and adaptive performance is desired. Dr. Ohnishi's group has deepened the theory of haptic control, and developed many devices which implement the theory. The author of this report is not aware of any U.S. scientist who has studied the topic for so long and developed so many practical implementations and experiments with the new approaches.

Site: **Keio University – Shonan Fujisawa Campus**
Endo, Fujisawa City, Kanagawa-ken 252-8520
http://www.ht.sfc.keio.ac.jp/index.html.en

Date Visited: October 4, 2004

Attendees: Y. Zheng (Report author), Y.T. Chien, V. Kumar, J. Yuh, H. Miyahara

Hosts: Hideyuki Tokuda, Professor, Faculty of Environmental Information, Keio University, Chairman, Japan Network Robot Forum, Tel: +81-466-47-0836, Fax: +81-466-47-0835, Email: hxt@ht.sfc.keio.ac.jp

BACKGROUND

The reason for visiting Keio University is twofold. The primary reason is that Dr. Hideyuki Tokuda of the Keio University is the leader of the Network Robot Forum, a newly formed national organization in Japan. The second reason is that Dr. Tokuda is involved in the research of intelligent environments. The team spent most of the time listening to the presentation by Dr. Tokuda about the forum, and spent the rest visiting Dr. Tokuda's laboratory.

THE UBIQUITOUS NETWORK IDEA

A large effort is being made collectively by the Japanese government, industry and academia in the development of the Ubiquitous Network Society, which emphasizes the broad and effective use of the broadband networks, aiming to make Japan an IT-leading country in the world. R&D activities for achieving the goal are conducted by national R&D projects, academia, and industry, including the following:

1. National R&D Projects:
   a. Ubiquitous Networking Project
   b. Network Robots Project
   c. JGN2 Project
   d. Sensor Network Project (which is in preparation)
2. Academia:
   a. Information Processing Society of Japan (IPSJ): SIG on Ubiquitous Computing Systems (SIGUBI)
   b. Institute of Electronic, Information and Communication Engineers (IEICE): Ubiquitous Real-World Oriented Networking (URON)
   c. IEICE: Sensor Networking
3. Industries
   a. Ubiquitous Networking Forum
   b. Network Robot Forum

Dr. Tokuda introduced two forums: the Ubiquitous Network Forum and the Network Robots Forum. For the Ubiquitous Network, Dr. Tokuda stressed a Ubiquitous Network Environment, which in the future will consist of distributed sensor networks, plus a personal terminal and mobile devices. In this way, the ubiquitous networks will include the core network, which we are currently used to, tag/embedded appliance/sensors networks, and access networks, as shown in Figures B.16 and B.17. (taken from Dr. Tokuda's slide).

From Figure B.16, one can see that the Japanese idea has greatly expanded the traditional use and concept of networks. A large number of tags which can sense and transmit the environmental information are attached to

furniture, pets, home appliances and other devices, and connected to the Internet for monitoring and control. Connecting robots to the Internet is the main thrust of the Network Robot Forum.

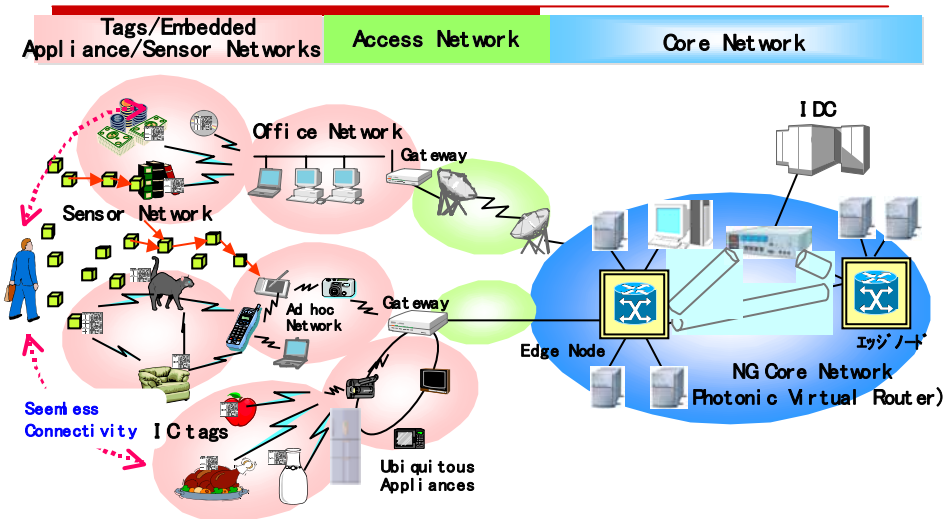

Figure B.16. The Ubiquitous Networks idea.

NETWORK ROBOT FORUM

The concept of the network robot comes from the vision that in the future all robots will be connected to ubiquitous networks, and robots will be widely used in almost every aspect of our life. While the future robots are beyond our conventional definition and understanding of robots, they include the "visible" type of robots such as service robots, robot toys, entertainment robots, etc., and "virtual" robots, which appear in graphics and are displayed on various devices to interact with human beings, and "unconscious" robots, which are not visible, but installed everywhere to sense the motion and existence of the people. These three types of robots are shown in Figure B.17, which is from Dr. Tokuda's slides.

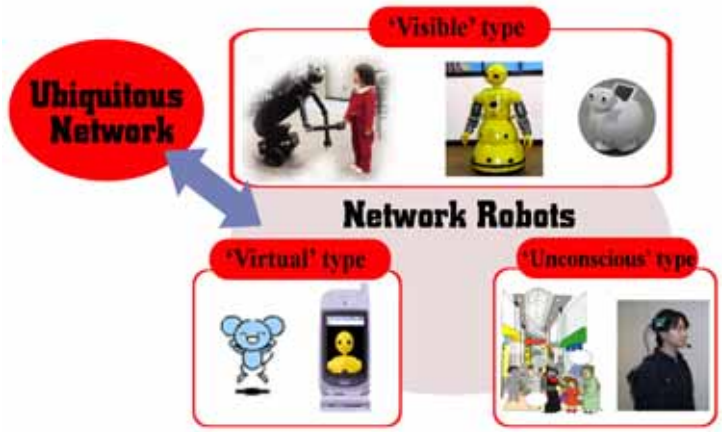

Figure B.17. Three types of robots connected to the ubiquitous networks.

To connect all types of robots together to the Internet, there are many technical and societal problems to be resolved. For industries to work together, for example, it is important to develop standards of many hardware and software components such as communication interface protocols. For that purpose and others, the Network Robot Forum was formed in Japan in 2003.

The mission of the Network Robots Forum (NRF) is multifold and can be summarized by the following bullets:

1. R&D/standardization
2. Support for, and liaison with, relevant organizations concerning network robots
3. Awareness campaigns and promotion of network robots

Dr. Tokuda serves as the chairman of the Network Robot Forum, which now has about 200 members including business organizations, research institutes, academic experts (individuals of the universities) economic organizations, and prefectural and city governments.

According to the vision of the NRF, in 2005, Network Robots will still be in their infancy when only single-function robots at home are connected to networks, and interactions between robots and consumer electronics will have possibly been achieved. In 2008, Network Robots will be in the growth phase in which robots will become diversified to become virtual, unconscious or visible and will mutually interact and be available for multiple purposes. In 2013, Network Robots will be in the mature phase when robots can even be used outdoors via ubiquitous networks and interact with two or more robots. Free function expansion will be realized. When the final goal is achieved, robots will be transformed from single-point in space, solo operation in behavior, individual use of information, individually remote-controlled, to multi-points, cooperation, sharing, and cooperation, respectively, through the network connection. At that time the network robots will work completely through the ubiquitous networks. It is predicted by Dentsu Communication Institute of Japan that by 2013 network robots will create a market of ¥19.8 trillion, which is 5.7 times the market size of industrial robots, as predicted by the Japan Robot Association.

INTELLIGENT ENVIRONMENTS

Dr. Hideyuki Tokuda gave a presentation about his intelligent research as well. In general, Dr. Tokuda's activities are in intelligent environments (IE). Some of the activities include:

- Smart space in which all the objects can be connected through the internet seamlessly
- Intelligent environments which are embedded with various kinds of sensors
- Smart furniture which can sense the needs of the user and interact accordingly
- Department storage information
- Car location sensors, etc.

It can be seen that Dr. Tokuda's research is closely related to the network robots, and his sensor-integrated intelligent environments fit in the broader definition of the three types of robots shown earlier.

During the discussion we were in Dr. Tokuda's office/laboratory, which itself is an intelligent space embedded with many visual sensors detecting people in the environment.

Figure B.18. Dr. Tokuda's office/laboratory embedded with various space sensors and equipped with smart sensors.

SUMMARY

Through this visit, we have found that Japan is making a great effort in making full use of broadband networks, by which network robots have been identified as an important application. Japan has a competitive advantage in developing network robots, largely due to its already strong manufacturing and electronics industries. From our visit to Dr. Tokuda's laboratory and later other laboratories, we found many research projects in Japan are related to intelligent space/environment, devices, appliances, etc., which could lead to a major industry of network robots in the future.

Site: **Korea Institute of Science and Technology (KIST)**
Intelligent Robotics Research Center
39-1 Hawolgok-dong, Seongbuk-gu
Seoul 136-791, Korea

Date Visited: October 12, 2004

Attendees: Y. Zheng (Report author), R. Ambrose, B. Wilcox, J. Yuh

Host: Dr. Hyunag Min Rho, Director, Division of System Technology
Dr. Sang-Rok Oh, Project Manager of Intelligent Service Robot, Ministry of Information and Communication, (formerly with KIST), Email: sroh@iita.re.kr
Dr. Mun Sang Kim, Director Center for Intelligent Robots
Professor Z. Zenn Bien, Director, Department of Electrical Engineering and Computer Science, Tel: 82-42-869-3419, Fax: 82-42-869-8410, E-mail: zbien@ee.kaist.ac.kr

BACKGROUND

The assessment team visited the Korean Institute of Science and Technology (KIST) because of its long-term involvement in robotics research. KIST is a government-sponsored organization that was founded in 1956. The institute has 654 permanent employees, of which 485 are researchers, but employs 1,700–1,800 salaried workers at any time. The organization consists of five research divisions, one of which is the Division of System Technology, under which robotics research resides. KIST currently emphasizes five areas: nanomaterials, intelligent systems, microsystems, microbiology, and environments.

Activities of Robotics Research at KIST

Current activities on robotics research at KIST are motivated by the 21st Frontier Program on Intelligent Robotics by the Ministry of Science and Technology of the Korean government. Dr. Kim introduced the program in details, which was very informative to the team for understanding the strategic plan of the Korean government in developing robotics technology.

The 21st Frontier Program on Intelligent Robots aims to develop fundamental technology in biology (BT), information (IT), nano (NT), and cognition (COGNO) as they are considered the converging technologies for improving human performance by the National Science Foundation (NSF) of the United States. The program is to develop core technologies that make a social/economic impact and have global competitive power. The program will be funded by the government for ten years at a level of $10 million per year.

The program aims to create various applications of robots based on a large spectrum of fundamental technologies, including conventional ones in mechanical, electrical, electronics, control, and computers, as well as cutting-edge ones such as artificial intelligence, brain engineering, advanced materials, bionics, IT, and microelectromechanical systems (MEMS). The strategies for technology development are to establish market-oriented R&D systems and the modularization of developed technologies. The emphasis is on robot intelligence for the robots to interact with humans and environments. There are three important projects for this purpose:

a) Perception and Learning for Robot Intelligence
b) Development of Human-Robot Interaction Technology
c) Adaptive Behavior Control

In developing and testing these new technologies, KIST sees a so-called Silver Mate Platform, an initiative to help elderly people improve the quality of their lives. As part of the modular technologies, various chips that can interact with humans and environments are considered, including facial expression/gesture recognition, voice recognition, reasoning/perception, malfunction diagnosis, motion control, reaction-based control, and

tactile sensing perception. Ultimately, KIST will help create a new industry of intelligent robotics based on core technologies, and perform an important role in fusing technology in IT, BT, and NT.

Current activities at the Intelligent Robotics Research Center of KIST cover many areas, including the Tangible Agent Technology for Tangible Space Initiative, Network-based Humanoid Technology, Silver Mate Robot Platform Technology Visual Sensor System for Intelligent Robots, a Guide Robot for Experience on Science and Technology, Intelligent Agent System Technology based on Bio-mimetic Sensing Control, Control and Recognition Technology for Personal Robots, and Tele-operated Robots for Hazardous Tasks. Total funding for the above exceeded $8 million in 2004.

Figure B.19. Baby-Bot.

Figure B.20. ROBHAZ.

The Center of Intelligent Robots has developed a number of robots which are very impressive, ranging from a humanoid robot called Baby-Bot as shown in Fig. B.19, to ROBHAZ, as shown in Fig. B.20. The Baby-Bot robot is equipped with a charge-coupled device (CCD) camera and two force/torque sensors, and performs biped walking with visual tracking/2.5D pattern recognition and voice-based interaction. ROBHAZ, on the other hand, is a teleoperated robot for hazardous tasks. Its configuration includes Passive Double Track, teleoperated by a small portable remote controller to 1 km, and wireless image transmission by an infrared camera. The most impressive part of the robot is that two of them were sent with the Korean army in Iraq. In addition, it won the best robot award in RoboCup U.S.-Open Rescue Area, in New Orleans in 2004, and is under commercialization by a venture company (Yujin Robotics Co. Ltd., Korea). One ROBHAZ has been exported to the Japan International Rescue Center.

In addition to the above two, KIST has developed a home service robot called Intelligent Sweeping Security Assistant Companion (ISSAC), a tour guide robot—Jenny, a guide robot—BUTLER, a bio-mimetic robot (MIMOT), an active stereo head-eye system, and a human-like robot called CENTAUR.

The Intelligent Robotic Research Center is also involved in the new area of Network-based Humanoids. The objective of the program is to develop a network-based biped humanoid capable of simple human-robot interaction. Research directions include a human-friendly clever humanoid with network-based intelligence, and a humanoid to provide useful services by using the ubiquitous network. The robot will be technologically capable of omni-directional dynamic walking, autonomous walking, human-friendly interaction, and service-on-demand. The program started in 2004 and will be capable of autonomous walking and will be connected with the ubiquitous network by 2007. Research topics in this new program include Human Modeling and Imitation, Network-based Dynamic Walking, Internet-based Dynamic Simulator, Humanoid Platform, Network-based Controller, and Network-based Technology and System Integration.

Laboratory Visit

The assessment team visited the Intelligent Robotics Laboratory of KIST following the host introduction. Robotics research is performed in a number of spaces located in the two buildings. The robots we saw

included the ROBOHAZ, ROBGUIDER which has been put to use at the National Science Museum (Figure B.21a), the Baby-bot humanoid robot shown in Figure B.19, the Guide robot—BUTLER, MIMOT (Figure B.21b), and a human-like robot called CENTAUR, which has four legs but with a human-like body (Figure B.22). In addition, we saw a newly developed humanoid robot that has not been made available to the public yet, but could perform biped walking in stable gaits. All the robots are well designed and built. Some of them are only a short distance away from commercialization such as ROBOHAZ.

Figure B.21. a) The Guide robot (left), b) Bio-mimetic robot (right).

SUMMARY

Robotics research at KIST is very active with various activities represented by a number of well developed robots. For every robot developed, there are a number of fundamental topics well identified to study. Researchers at KIST integrate new and cutting-edge technologies into conventional ones to produce robots with solid performance. The institute puts emphasis on intelligence and calls the laboratory the Intelligent Robotics Research Center. The primary evidence is the use of sensors as well as artificial intelligence technologies in robots. The developed robots are primarily in the area of services, such as a robot guider, robotic assistance to the elderly, and robots working in hazardous environments, while mobility is provided by wheels, legs, or tracks. A great part of the recent effort is on biped walking, which is a hot topic of study in Korea and in the world. It appears that the goals and practices of robotics research at KIST are very similar to other institutions which we have visited in Korea. That is, the goal is to develop market competitive research and development technologies such that Korea can become build a major (top 3) robot industry.

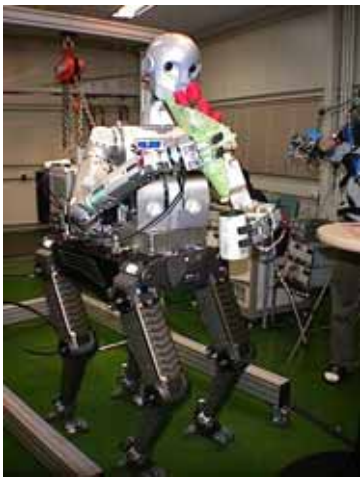

Figure B.22. Human-like Robot (CENTAUR).

Site: **Korea Research Institute of Ships and Ocean Engineering (KRISO)**
Korea Ocean Research and Development Institute (KORDI)
Ocean Development System Lab
171 Jang-dong, Yusung-ku,
Daejeon, 305-343, Korea
Tel: +82-42-868-7532, Fax: +82-42-868-7503

Date Visited: October 12, 2004

WTEC Attendees: B. Wilcox (Report author), J. Yuh, A. Sanderson

Hosts: Dr. Chang Gu Kang, Director General, Email: cgkang@kriso.re.kr
Dr. Seok-Won Hong, Principal Research Scientist, Tel: 042-868-7520, Email: swhong@kriso.re.kr
Dr. Hang S. Choi, Email: hschoi@plaza.snu.ac.kr,
Junhyun Kim, Chong-Moo Lee, A-Ra Cho

OVERVIEW

Prior to the formal beginning of the meeting, the hosts handed out a glossy color brochure describing the Korea Ocean Research and Development Institute (KORDI). On pages 16–17 of the handout the 37 x 55 m test tank (4.5 m deep) is described. It is perhaps the largest single piece of test equipment relevant to underwater robotics. It is equipped with wavemakers. The Ocean Development System Research Division has been working on underwater robotics for some time, starting with a remotely operated vehicle (ROV) that they developed 10 years ago that took pictures of a shipwreck. On pages 18–19 of the brochure the Maritime Safety and Pollution Control Ship handling simulator is described. It has one 330 degree view and one 150 degree view simulator connected together to support the Korean government in the event of a ship accident or oil spill (this was subsequently shown in a lab tour). On pages 20–21 the Marine Transportation Systems program is described, including a ground effect ship like an airplane (pg. 20). At the end of this informal session there was made mention of the discussion on possible joint collaboration that took place with a National Science Foundation (NSF) group three years ago. (This occurred after the Institute of Electrical and Electronics Engineers (IEEE) International Conference on Robotics and Automation, and included NSF representatives Dan Stillwell, Dick Blidberg, Larry Weber, and Junku Yuh).

The meeting formally started with a welcome by Dr. Chang-Gu Kang. He stated that underwater robotics at KORDI started only about 15 years ago. He introduced Hang S. Choi, who is a professor at Seoul National University, and who had been a postdoc at Pohang Science and Technology University (POSTECH), working in advanced control theory. He had also worked with Junku Yuh in Hawaii. Also introduced were Chong-Moo Lee, who works in the area of mechanical design of UW systems, and A-Ra Cho, an undergraduate student at the University Science and Technology, who works in the area of underwater acoustic communications. They showed an animation of the vehicle they are developing going down to 6,000 m to hydrothermal vent. This work is funded by the Ministry of Maritime Affairs and Fisheries. An outside company made a mockup of the device and is now making the ROV itself. They emphasized that the design of the cable is very important. The main umbilical from the ship to the launcher is 8,500 m long. The distance from the launcher to the vehicle itself is either 30, 50, or 100 m. Orion 7P/PE master/slave manipulators are used. They are developing a new velocity-command master. Power is at 3200 VAC/400 Hz 3 phase over 8,500 m cable, which is then converted at the launcher to 240 VDC for the autonomous underwater vehicle (AUV). Ground fault protection is included for safety. A fiber optic cable delivers 1.56 Gbps (8-channel video, 12 RS232 serial lines). The OCS is housed in a 20-foot standard container. Most ROV components are imported from the U.S. or Europe. An underwater hybrid navigation system is under development.

Current research includes underwater docking using charge-coupled device (CCD) cameras and visual serving, navigation using an inertial measurement unit, Doppler velocity laser (which measures relative

velocity), and ultrasonic baseline (<2 m sec round trip latency). Future goals and metrics for this system are given in the handout brochure.

The SNUUV-1 (Seoul National University Underwater Vehicle) is a glider-type vehicle that is not particularly advanced over others built worldwide, rather it is self-built for basic research.

Junhyun Kim (from POSTECH) leads a 20 person lab working on the ROV. They showed a thruster configuration map, and a video of operation (as of two months previously). It is teleoperated, but now (as of October, 2004) has some autonomy using sensors. They use linkage-type manipulators to achieve high mechanical power levels. The manipulator was developed at Korea Institute of Science and Technology (KIST) in Seoul. A small UUV was funded in 2004 jointly by the Korean government and industry. Funding from the government is about $3 million per year for the deep AUV. They expect to finish a deep AUV in 2006, but there may not be any research funding after that. NRL (National Research Lab) funding lasts only five years—there is one year left. Localization and navigation are the key problems—the goal is to get within one meter.

Site: **Ministry of Economy, Trade, and Industry (METI)**
Manufacturing Industries Bureau
1-3-1 Kasumigaseki, Chiyoda-ku
Tokyo 100-8901, Japan
http://www.meti.go.jp

Date Visited: October 8, 2004

WTEC Attendees: A. Sanderson (Report author), J. Yuh

Hosts: Mr. Hiroshi Tsuchiya, Deputy Division Director, Industrial Machinery Division, Email: tsuchiya-hiroshi@meti.go.jp
Mr. Gyo Sato, Deputy Director, Industrial Machinery Division (at the time of the visit)
Mr. Takaki Tsujimoto, Industrial Machinery Division, Tel: +81-3-3501-1691, Fax: +81-3-3580-6394

BACKGROUND

The Ministry of Economy, Trade and Industry (METI) has a strong role in monitoring industry performance in Japan and its relationship to overall economic development and growth. In recent years, the stagnation of the Japanese economy has been of major concern, and METI has been strongly involved in strategies for recovery and the direction of national investment to stimulate new industries and future growth.

OVERVIEW OF THE VISIT

The METI senior personnel met with us for almost two hours. They provided a detailed review of the national strategic policy and the identification specifically of robotics as a theme for future industrial growth in Japan. The discussion focused on two reports:

1. Nakagawa Report: "Toward Sustainable and Competitive New Industrial Structure," METI, May, 2004.
2. Miura Report: "Toward Coexistence of Human Beings and Robots by 2025: The Report for the Future Vision of Robot." Prepared by The Study Group for the Future Vision of Robot, Hirobumi Miura, Kogakuin University, Chair, April, 2004.

In addition, a discussion of the role of several other government ministries provided a wider context of the planned national investment.

An international exposition of robotic technologies will take place in June, 2005, and the national strategic priorities will play a role in defining the program for that exhibit.

Nakagawa Report – Toward a Sustainable and Competitive New Industrial Structure

The aim of the Nakagawa report was to "establish industrial policy to create and accelerate the cycle of demand and innovation based on the future outlook of the industrial structure." The perspective of the report is that the Japanese economy has been successful in innovative development and manufacturing in areas such as consumer electronics and flat panel displays, and what is important to undertake at this time is a strategic effort to identify future areas of potential industrial growth and the policies that will stimulate that innovation.

The report was compiled based on extensive interviews with current industrial leaders and market sectors in Japan, and internationally. In addition, the statistical analysis and predictions of market trends and market sizes were an important part of the study.

The major goals of the report are to:

- Establish the technologies and industries which ensure Japan's leading position in the world market for 20–30 years, while fully utilizing existing technologies and emphasizing their protection.
- Promote integration and coordination among key stakeholders, including industries, government, educational institutions and local communities.

The report identifies three major issues and related approaches:

1. How to ensure global competitiveness?
   Approach: Identify cutting-edge industry areas with strong global competitiveness.
2. How to respond to the demands of society?
   Approach: Identify industries that meet market needs arising from changes to society (service industries, etc.).
3. How to end regional economic stagnation?
   Approach: Develop industry clusters that support regional revival.

The report identifies four cutting-edge industry areas:

A. Fuel cells
B. Digital consumer electronics
C. Robots
D. Content

The report identifies three industrial areas to meet expanding market needs:

A. Health and welfare devices and services
B. Environment and energy devices and services
C. Business support services

The report proposes four policies to advance industrial clusters for regional revitalization:

A. Advanced high-tech industry clusters and supporting infrastructure
B. Development of new businesses in the manufacturing industry
C. Innovation in regional service industries
D. High value-added food industry

Nakagawa Report—Robots as a Cutting Edge Industry Area

The report analyzes each of the four cutting-edge industry areas. For the area of robots, the basic market outlook is defined as:

Table B.1
Market Outlook for Robotics Industry

Market size in 2003	approx. $5 billion (primarily in manufacturing automation)
Projected market size in 2010	approx $18 billion
Projected market size in 2025	approx $62 billion

A detailed analysis of these market projections is provided in the report.

Current situation and challenges include:

- The current market is dominated by industrial automation. A limited number of non-industrial robots have been commercialized for home entertainment. Robots for other applications are in demonstration or experimentation phases and market launch dates have not been decided.
- The current situation lacks a match of cost, function, and technology, and also lacks a clear vision for initial practical applications.
- Robotics requires a broad range of technologies including actuators, sensors, information processing, and software technology as well as related systems integration.
- The parts industry and precision machining industry in Japan are very well suited to the development and support of robotics industries.
- In the long-run, expectations for a broad range of applications and markets for robots include medical care, security, as well as industrial use. It is recognized that it will still be many years before robots and humans share daily living in a manner that supports a large market for robots.

The action program in robotics is presented as:

- Encourage the development of initial applications through model programs in specific areas, for example, medical care and disaster relief fields where demands can be supported by public sector procurement.
- Develop basic elemental technology and common infrastructure technology.
- Develop a consensus on social acceptance of robotics safety and treatment consistent with Product Liability Law and insurance systems.

Miura Report—Toward Coexistence of Human Beings and Robots in 2025

The Miura report surveys a large range of applications of robots and discusses a number of broad technological and social concerns that may influence their adoption.

The report starts from the identification of primary societal issues and suggests areas where robots could meet these primary needs:

1. Issue: Falling birthrate and aging population
   a) Use of robots in assisting the daily tasks of women and the elderly
   b) Use of robots in support of nursing care
2. Issue: Safe and secure society
   a) Use of robots for disaster/accident management
   b) Use of robots in anti-terrorism work and maintenance of security
   c) Use of robots for the enhancement of a safe and secure healthcare service
3. Issue: Convenient and affluent society for self-development
   a) Use of robots to create affluence and convenience
      - example, household robots
   b) Use of robots in spending quality free time
      - examples, entertainment, pets, and sports robots

Future Robot-related Industries

The robot industries are envisioned to include manufacturing and sales of the products themselves, and the usage support and service industries:

Manufacturing/sales ($48 billion estimated market in 2025)

- Domestic duty assistance

- Nursing/caring assistance
- Security assistance
- Infrastructure maintenance assistance
- Entertainment
- Firefighting/fire prevention

Usage support industry ($24 billion estimated market in 2025)

- Applications industry (software, replacement parts)
- Education industry (safety training, technical education)
- Maintenance industry
- Damage insurance
- Second-hand robot sales

The Miura report also identifies a set of issues that will need to be resolved for the integration of robots with humans and society:

- Institutional issues for creating a society coexistent with robots
  - System for assuring the safety of future robots, under various scenarios of communications and physical interactions with humans
- Distribution of future robots in society
  - Support measures for research and development
  - Support measures related to deployment and introduction

The report also identifies technical issues that need to be addressed:

- Basic: actuators, sensors, intelligence, communications technology
- Interdisciplinary: modularization of component elements, standardization

The Miura report also offers three anecdotal "short stories" of robot applications:

- Housekeeping and child-rearing—mother interacts remotely with household robot
- Gold driving range—humanoid robot provides golf swing instruction
- Teaching and programming a modular household robot to enhance use

OVERVIEW OF INVESTMENTS FROM FEDERAL AGENCIES

In addition to METI, a number of other government agencies have current and planned investments in robotics research and development. The estimated annual investments in robotics research and development in 2004 is:

- Ministry of Economics, Trade and Industry $31.3 million
- Ministry of Telecommunications $ 7.3 million
- Ministry of Health, Labor, and Welfare $ 7.0 million
- Ministry of Land, Infrastructure, and Transportation $ 1.5 million
- Ministry of Agriculture, Forestry, and Fisheries $ 7.0 million
- Ministry of Education $29.0 million
- TOTAL (estimated) $83.1 million

INTERNATIONAL EXHIBITION OF ROBOTICS TECHNOLOGIES AND APPLICATIONS, JUNE, 2005

As part of an international exhibition in 2005, METI will sponsor demonstrations of major robotics technologies with emphasis on the applications themes discussed in the Nakagawa report. These demonstrations are planned to show the potential for new industries in accord with the strategic plan. The demonstrations will generally be classified into three types:

a. Robots with primary communications and work assistance functions
   - Ex. Household communications and cleaning robots

b. Robots that carry out physical work for specified people
   - Ex. Nursing care robots

c. Robots that work in a public place while securing general human safety
   - Ex. General purpose humanoid robots.

OBSERVATIONS

The discussion with METI was especially helpful to understand the goals of Japanese national investment and coordination of research programs with industrial development. The fundamental principle of the planning is to develop robots as new products and industries with mature manufacturing and support networks. METI specifically does not plan to invest in the incremental development of current industrial robot systems. They see this as a role for manufacturing industries to do themselves.

Site: **Nagoya University**
Laboratory of Micro-Nano System Control
Graduate School of Engineering Sciences
Furoo-cho, Chigusa-ku, Nagoya 464-8603
http://www.mein.nagoya-u.ac.jp

Date of Visit: October 7, 2004

WTEC Attendees: Y.T. Chien (Report author), A. Sanderson, M. Dastoor

Hosts: Dr. Toshio Fukuda, Professor of Department of Micro-Nano System Engineering and Department of Mechano- Informatics and Systems, Tel: +81-52-789-4478, Fax: +81-52-789-3909, Email: fukuda@mein.nagoya-u.ac.jp
Professor Fumihito Arai, Department of MicroSystem Engineering and Department of Mechano-Informatics and Systems

BACKGROUND

Nagoya University is located in the city of Nagoya, the center of a vibrant metropolis, fourth most populous in Japan after Tokyo, Yokohama, and Osaka. It is also the home of many traditional and modern industries, notably the automobile giant Toyota, which among other things has played a significant role in the advancement of industrial robotics. That has led many of the locals to consider their city as the "Mecca" of robotics. The University's history dates back to 1871 when a medical school and hospital were founded on the site of a local feudal government house. In 1939, the University was established formerly as Japan's seventh imperial university. Since 1949, Nagoya University has pursued a path of physical expansion and academic excellence and is now widely known as one of Japan's foremost national universities. As with all the other national universities, it became an independent administrative organization starting on April 1, 2004. The University has since taken the step of becoming "Nagoya University Corporation," signifying the beginning of a new responsibility and management structure for Japan's public research and educational institutions.

Robotics research at Nagoya University is mainly in the Laboratory of Micro-Nano System Control, headed by Professor Toshio Fukuda. There are two academic departments in which faculty and students reside: the Department of Micro-Nano System Engineering and the Department of Mechano-Informatics and Systems, both are unique in their cross-disciplinary focus. Professor Fukuda hosted our visit.

SCOPE OF RESEARCH ACTIVITIES

The Laboratory was established in the 1980s, but the present faculty and research group began their work only about 13 years ago. At present, the group consists of three faculty members, one engineer, several visiting researchers, eight doctoral students, 20+ MS students, and a number of undergraduates participating in the research. Though the years 1989 to 2002, the laboratory produced some 50 Ph.D. students and published about 1,000 journal or conference papers, a very impressive record.

The research in Professor Fukuda's laboratory is both rich and diverse. A list of ongoing research topics or projects includes:

- Cellular robotic system
- Microrobotic system and micromechntronics
- Nanosystems, assembly robot
- Bio-micromanipulation system
- Telesurgery system for intravascular neurosurgery
- Machine learning of intelligent robotic system

- Study on dynamically dexterous robots with multiple kinds of locomotion
- Intelligent human machine interface considering interactive adaptation
- Intelligent control by soft computing
- Six-leg omnidirectional walking robot with manipulator
- Emotional robotic system
- Parallel link manipulator
- Humanitarian demining robot

During Professor Fukuda's introductory presentation, he described some of the projects undertaken in the laboratory that are unique. One example is the landmine detecting/removal vehicle, which was dispatched to Kabul, on behalf of the Japanese government's mission to Afghanistan to assist in the reconstruction work. Another example is the work done in the bio-inspired robotic control group. This includes stand-up motion control of the multiple-locomotion robot and passive dynamic autonomous control of bipedal walking robots. Two areas of research in the Medical Robotics Group area also one of a kind. One is on regenerative medicine, focusing on methods to regenerate injured or damaged issues. This group has done interesting work in promoting cell differentiation by stretching stem cells for the purpose of tissue regeneration, resulting in a cell-stretching bio-chip. The other area of research is on the modeling of the human cerebral artery, intended for assisting in intravascular neurosurgery. The group has developed an *in vitro* soft membranous model of these arteries, based on conventional imaging modalities such as computed tomography (CT), magnetic resonance (MR) and transcranial Doppler (TCD). Targeted applications of this model are hemodynamic study, radiological investigations, and surgical simulation (for planning or training).

The Laboratory's focus on bio-microelectromechanical systems (MEMS) was also stressed during our visit. The goals here are to develop manipulative systems capable of handling objects at the biological levels: cell, microbe, and DNA molecules. Since human-sized fingers are not appropriate at this small scale, non-contact manipulation with optical and field power is considered. Among the research projects: cell monitoring by microtools of thermo sensitive hydrogel and permeation membrane by photo-crosslinkable resin; immobilization of individual cells by local photo polymerization on a chip; microfabrication of functional microtools using local photo-fabrication; touch sensors for micromanipulation; and evaluation and device application of lead-free piezoelectric ceramics.

Nanotechnology research that relates to robotics focuses on two areas. One is hybrid nanorobotic manipulation inside a scanning electron microscope (SEM) and a transmission electron microscope (TEM) for high-resolution observation and manipulation. The second area is in nanotube sensors and actuators that can potentially revolutionize robotic sensing and actuation. Works in progress include the investigation of field emission properties of individual carbon nanotubes (as opposed to nanotube films and arrays). A better understanding of these properties could lead to the development of a new family of nano-devices, including sensors and actuators.

DEMOS AND LABORATORY TOURS

The laboratory has a large collection of robotic platforms, prototypes and facilities. Some of them are from completed projects; others are for ongoing work. Among the completed projects demonstrated is a robot capable of exhibiting brachiation behaviors, similar to those by monkeys (monkey-type robots).

Another demonstration is for group behavior control by distributed autonomous robotic systems, emulating the behaviors of such animals as ants (line formation), birds, and fish via local communication. Also shown is work on a dexterous manipulator with sensor-embedded soft finger.

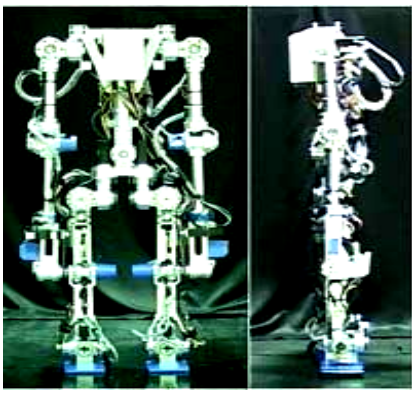

Figure B.23. Image showing stand-up control of a multi-locomotion robot.

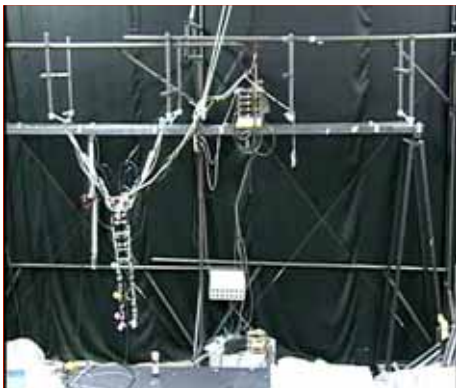

Figure B.24. Image showing a monkey-type robot capable of continuous brachiation.

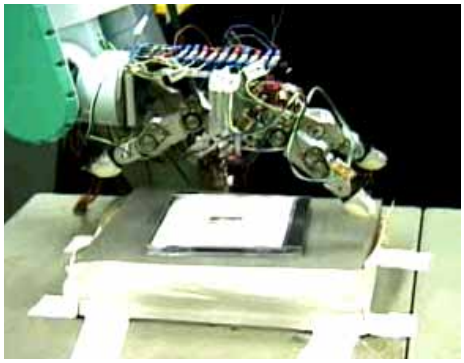

Figure B.25. Image showing dexterous manipulation with a sensor embedded soft finger.

A landmine-detecting vehicle has been developed as a research project to demonstrate the integration of special sensors and actuators, designed for a hostile environment. This is a wheeled vehicle, equipped with a ground penetrating radar (GPR), a four degree-of-freedom (DOF) manipulator for antenna adaptation (to local terrains), and low landing pressure tires.

Figure B.26. Image showing the landmine-detecting vehicle.

The lab tour also included the viewing of several artifacts resulting from research in intravascular surgery: 3D-reconstructed cerebral arterial model based on CT images and an *in vitro* model of human aorta.

Figure B.27. CT slice image.

Figure B.28. Vertical image.

Figure B.29. Reconstructed 3D arterial structure with basilar top (BT) aneurysm.

OBSERVATIONS

The robotics research at Nagoya University is very interdisciplinary and versatile, as reflected in the range of research topics that have been completed and that are in progress. Their research at the intersection of robotics, bio-MEMS, and nanotechnology is also unique. In this context, Professor Fukuda's dynamic leadership and the many contributions of his group make the Laboratory exceptionally visible and influential in the field of robotics.

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Research Activities in Robotics and Mechatronics, Nagoya University publication, 2003.

Laboratory of Micro-Nano System Control at Nagoya University, Presentation by Professor Fukuda.

Site: **NEC/Toshiba Space Systems Division**
10, Nisshin-cho 1-chome, Fuchu
Tokyo 183-8551, Japan
http://www.ntspace.jp/

Date Visited: October 7, 2004

WTEC Attendees: B. Wilcox (Report author), R. Ambrose, Y.T. Chien, G. Bekey, D. Lavery

Host: Shogo Kitahara, Executive Vice President, NEC Toshiba Space Systems
Kazuhide Todome, Division Manager, Project Operation Division
Fumihiro Kuwao, Project Manager-JEMRMS, Tel: +81-42-354-4713,
Email: kuwao.fumihiro@ntspace.jp
Kazuhito Kasuga, Project Manager (moon mission, lunar robot)

OVERVIEW

The discussion started with a note that most of the NEC/Toshiba space hardware (HW) is at the launch sites and space centers, so there is no hardware to show at this facility. So there was no plant tour.

Shogo Kitahara gave an introduction to their organization. NEC/Toshiba Space Systems was formed in April 2001. Together they have launched a total of 59 satellites since 1970 out of a total of 81 Japanese satellites. They are working on the upcoming Lunar-A (planned for 2004) and Selene (planned for 2005). Their products include star trackers, transponders, heat pipes, a standard satellite bus for Earth observation, radios/solid state power amplifiers (SSPA)/antennas, a 90 x 17 m diffraction-limited (lambda/50) S-band antenna, and second-stage guidance for the H2-A.

Fumihiro Kuwao gave an introduction to space robotics. Manipulator flight demonstration (MFD) flew in August 1997 on STS and demonstrated orbital replacement unit (ORU) detachment/attachment and door open/close. ETS-VII flew from 1997 to 1999 and demonstrated rendezvous/docking and space robotics, autonomous satellite capture by manipulator (first ever) using a chase satellite and target satellite. The Japanese Experiment Module Remote Manipulator System (JEMRMS) is planned for a 2007/08 launch, where the Small Fine Arm (SFA) will be grasped by the main arm. The cost of this to the Japanese is about $350 million.

Things that have already been completed in preparation for this flight includes:

- Space robotics basic system
- Force and vision feedback
- Coop target rendezvous
- Ground commanding
- Basic HW

Things that are planned but not yet complete are:

- On-orbit service system
- On-orbit assembly
- Non-cooperative target rendezvous
- Autonomous intelligent control
- Lightweight and modular HW

Things that NEC/Toshiba Space Systems would like to do, but has no immediate government plan/funding/schedule to do, are:

- 2008—assembly of very large structures (e.g. solar arrays)
- 2010—on-orbit satellite repair/maintenance/de-orbit
- 2014—Lunar/Mars exploration
- 2018—large telescope

Japan Aerospace Exploration Agency (JAXA) plans to perform small solar power beaming in seven years, but this is not fully approved yet.

In a presentation of JEMRMS we learned that the main arm has a kinematic configuration of Yaw-Pitch-Pitch-Pitch-Yaw-Roll, is 10 m long, and has six degrees-of-freedom (DOF). The SFA has a kinematic configuration of Roll-Pitch-Pitch-Roll-Yaw-Roll, is 2 m long, and has six DOF with a six-axis force-torque sensor. It is operated by IVA (intravehicular activity, or inside crew in shirtsleeves) via graphical user interface translation/rotation (e.g. the standard space shuttle rotation/translation controls).

The main arm has a 700 kg payload with 50 mm accuracy (and ±1 degree in rotation), speeds up to 60 mm/s, and can exert forces up to 30N. The SFA has a mass of 408 kg and has a 10-year design life, using 3 kW of main power. The SFA has a 300 kg payload, can exert forces up to 30 N, has 10 mm and ±1 degree repeatability, with speed up to 50 mm/s (for payloads <80 kg) or 25 mm/s (for 80kg<payload<300 kg). The encoder-limited minimum step of the arm is ~1 mm. There is a camera-based ranging system, but no laser-based ranging. Ground control of the arm is not a baseline and will occur only in the case of "emergency/malfunction" or as part of "R&D."

ETS-VII (Kiku-7) demonstrated manipulator control that did not disturb satellite stability, inspection, and autonomous rendezvous/grappling. The arm was 2 m long, had a mass of 150 kg, had six DOF, a 430 kg payload, moved at up to 50 mm/s and 5 degrees/s, had an accuracy of 10 mm and 1 degree, and a resolution of 2.5 mm and 0.13 degrees. It was operated successfully despite a four-second time delay between the human operators on Earth and the satellite. There was a 100 km maximum distance between the chase robot and the target satellite. Radar was used for long-range tracking.

The manipulator flight demonstration on the Space Shuttle occurred from August 7–19, 1997. It included ground commanding as well as an aft flight deck element and payload bay element. Compliance control was fully demonstrated.

Current R&D includes:

- Satellite rescue and insertion into proper orbit
  - Satellite capture mechanism
  - Capture payload adapter fitting interface ring
- Motor gear spring-load hyper-redundant modular manipulator arm
  - Prismatic joint and "roll-slant" joint N-times
- Joint control processor—built from commercial-off-the-shelf components (COTS) parts
- Two-arm orbital maintenance vehicle
- Inspection arm and maintenance arm (simulated on air-bearing table)

The current status of the Selene project is that currently there are two university studies underway—one for lander and one for rover. "Lunar A" is expected to be launched in about three years. "Selene A" is expected to be launched in approximately two years. "Selene B" is expected to be launched roughly five years after that. It has not been decided if Selene B will have a penetrator or a rover.

Overall, the JAXA budget is gradually decreasing. There are seven satellites under development now, so the workforce is presently stable. All satellite launches are stopped now, but will restart soon. At that point NEC/Toshiba will ask the Japanese government to start new programs.

NEC/Toshiba Space Systems provided the study team with a copy of a report concerning the possible use of the JFA for use in Hubble servicing missions.

Site: **Osaka University**
Department of Adaptive Machine Systems
Graduate School of Engineering
2-1 Yamada-Oka, Suita City, Osaka 565-0871
http://www.er.ams.eng.osaka-u.ac.jp

Date of Visit: October 6, 2004

WTEC Attendees: Y.T. Chien (Report author), A. Sanderson, M. Dastoor

Hosts: Dr. Minoru Asada, Professor and Robotics Project Leader, Handai Frontier Research Center, Tel: +81-6-6879-7347, Fax: +81-6-6879-7348, Email: asada@ams.eng.osaka-u.ac.jp
Dr. Hiroshi Ishiguro, Director of Intelligent Robotics Laboratory

BACKGROUND

Osaka University is a national university that was established as an imperial college in 1931. Influenced by the rich cultural, commercial and industrial sites surrounding the city of Osaka, the university is a key center of higher learning both domestically and internationally. Its motto of "Live Locally, Grow Globally" sets the tone for much of its education and research activities, including the work in robotics.

The organizational home of robotics work is the Department of Adaptive Machine Systems. Established in 1997, the department covers a wide range of academic pursuits from materials to emerging robotic technologies. It aims to educate students in developing the ability to do interdisciplinary research that draws on knowledge and skills from different fields, from sensors, actuators, to advanced materials processing. Faculty and students often work as teams with the help of researchers or engineers from industry, as "coaches." This collaborative activity extends beyond the industry into other local and international communities.

RESEARCH IN THE ASADA LABORATORY

Dr. Asada's group has a faculty of three professors, several visiting/post-doc researchers, and a sizable number of master's and doctoral-level students. Undergraduate students also participate in project-oriented research. To provide a framework for team research, Dr. Asada defines a robotic system as consisting of three key components: sensors (including skin, tissue), actuators, and an exhibit of intelligent, human-like behaviors. Work on new artificial skin and tissue as part of a smart sensor is in progress, as is the work on new control mechanisms with pneumatic actuators.

A special focus of the laboratory is to explore the benefits of using robotic systems to study humans by studying the interactions between robots and their environments. One goal of this research is to better understand the brain and human behavior. For example, by studying joint activities between humans and robots, it is possible to develop models of learning or skill acquisition by infants. At present, the laboratory pursues research in four areas:

- Sensors and Actuators. An example is the development of a human-like, multi-modal soft finger capable of sensing the texture of objects. The fingertip has two silicon-rubber layers of differing hardness, strain gauges, and polyvinylidene fluoride (PVDF) films that are distributed randomly on the fingertip for tactile sensing.
- Behavior Acquisition by Mobile Robots. This work is exemplified by a series of studies focusing on multi-layered, reinforcement-learning schemes that self-organize their structures automatically. The result of this research has been applied to a real mobile robot in the context of RoboCup (see below).

- Behavior Acquisition by Teaching. One example of this work is incremental behavior acquisition based on self-interpretation of instructions given by a coach. The result of this research has also been tested and evaluated in the RoboCup context.
- Cognitive Development Robots. Included in this research is the development of models for behavior acquisition such as joint attention, infant's vowel articulation, etc. The research requires collaboration with cognitive scientists and developmental psychologists.

ROBOCITY CORE

This is a collaborative project in progress with the city of Osaka. The plan is to provide an open space in the center of town for the public to have live robotic experiences. Known as the Center for Open Robot Experiments (CoRE), the space is a laboratory complex accessible to the public—researchers, artists, businessmen, and ordinary citizens. This complex offers the most advanced prototypes (or concept robots) with which visitors can interact or engage in real experiences. Potential benefits are market exploration, education and entertainment, and public involvement, including the international community. Professor Asada's dream, as he relates, is that "Robots will eventually be embedded in everyday life at economically feasible levels." RoboCity is a first step in fulfilling that dream.

RESEARCH IN THE INTELLIGENT ROBOTICS LAB

Dr. Hiroshi Ishiguro heads up the Intelligent Robotics Laboratory, which also focuses on interaction between robots and humans. In his presentation, he described his vision of robots and robotics research both in science and society, as well as the role of his laboratory in that vision. He sees that robots, in an extended definition, evolve from "tools" of the past to "information media" of the present and future. In that role, robots (humanoids) generate, communicate, and personify information by interacting with humans and their environments. Robots are also a key ingredient of the future of society's infrastructure for social relationships and human activities. The goal of his research is therefore to help build that infrastructure. Some of the research areas are:

- Android science. This is the development of a robot that looks like a human and has human-like behaviors. To evaluate intelligence in androids, Dr. Ishiguro defines a successful "Total Turing Test," analogous to the "Turing Test" used in artificial intelligence (AI) research, as when a person cannot distinguish a robot from a human by meeting and communicating with them. The androids developed in this laboratory allow experimentation of this concept. The ultimate goal of this research is to build an android that can pass the Total Turing Test.
- Social Robotics. This research focused on the use of sensors and networks to connect robots with humans and their environments. The goal of this research is to remove the boundaries between robots and environments so that robots become part of the social infrastructure.
- Perceptual Information Infrastructure. This is a ubiquitous sensor network that helps monitor and recognize real environments and the elements functioning in them. The goal is to help people and robots living and working together in the real world. One of the outcomes of this research is omnidirectional vision. The images from the omnidirectional camera provide a 360-degree description of the environment around the camera. Robots in the environment equipped with such vision can localize themselves in the environment based on a signature computed from omnidirectional images.

Dr. Ishiguro is somewhat atypical as a faculty member or researcher in Japan. He has three appointments: professor at Osaka University, visiting group leader of Advanced Telecommunications Research Institute's (ATR's) Intelligent Robotics and Communications Laboratories (see site report on ATR/IRC), and special advisor to Vstone Co., Ltd., which is a partner in the development of the omnidirectional camera. Mixing scholarship and entrepreneurship in a Western style, Professor Ishiguro seems to carry the tradition of Osaka (Kansai) into the 21st century.

DEMOS AND LABORATORY TOUR

In Professor Asada's lab, four demos were given. One is the prototype of a multi-modal soft finger. The current finger has limited tactile sensing (e.g., it is unable to tell touching from rubbing), but its performance can be improved by integrating tactile and visual sensing. A second demo was pneumatic actuation for the artificial muscle in a robotic walker. The third demo was about robotic cognition. The robot finds its own body through joint attention—not by being taught how to locate it, but by detecting the image and action patterns. The last demo was the kicking movement of a soccer robot.

In Professor Ishiguro's lab, the interaction between androids and humans was demonstrated. The images below, depicting a scenario of the total Turing Test for robotic intelligence, show two of the current prototypes (a woman and a young girl modeled on Professor Ishiguro's daughter) developed for experimentation. Another demo was about sensor networks that use omnidirectional cameras for monitoring and reporting traffic conditions of a train station.

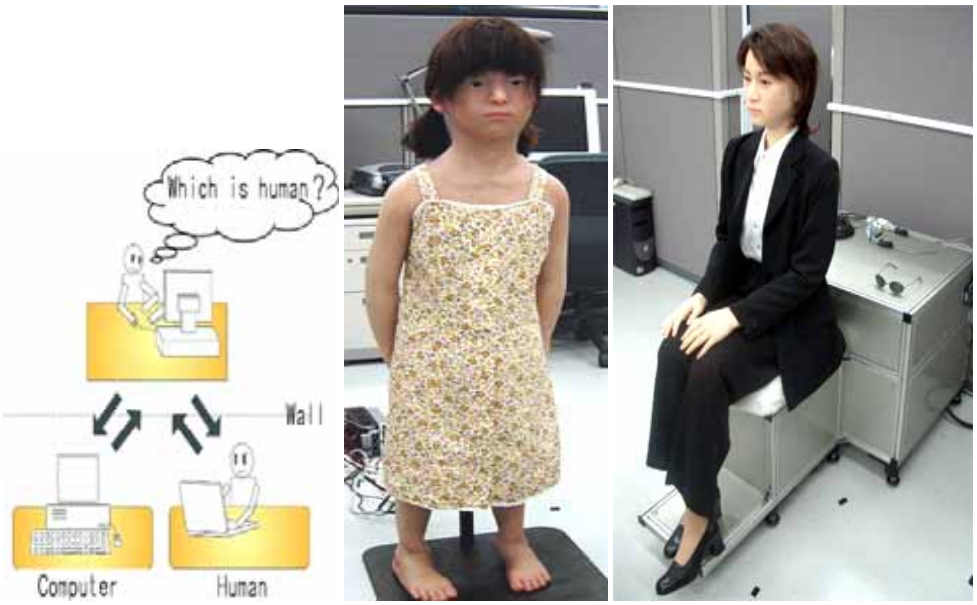

Figure B.30. Images demonstrating the "Total Turing Test."

ROLE IN THE ROBOCUP FEDERATION

RoboCup is an international project to promote robotics, artificial intelligence, and related fields. It is an attempt to foster AI and robotics research and education by providing a standard but challenging problem where a wide range of technologies must be addressed and used. RoboCup has chosen the soccer game as the central topic of research and experimentation in a competitive setting. The ultimate goal of the RoboCup initiative is to develop, by 2050, a team of fully autonomous humanoid robots that can win against the human world champion team in soccer.

Professor Asada is president of RoboCup. Since the next major event, RoboCup 2005, was to be held in Osaka, there will be all-out efforts by members of the laboratories here to be both a fierce contestant and a gracious local host.

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Robocup. http://www.robocup.org (Last accessed January 26, 2006).

Site: **Pohang Science and Technical University (POSTECH)**
San 31, Hyojadong
Pohang 790-784, Korea
http://rnb.postech.ac.kr/

Date Visited: October 13, 2004

WTEC Attendees: R. Ambrose (Report author), Y.T. Chien, J. Yuh, B. Wilcox, Y. Zheng, A. Sanderson

Hosts: President Chan-Mo Park, Ph.D., Tel: +82-54-279-2172, Fax: +82-54-279-5899
Se-Young Oh, Professor, Electrical Engineering Dept.
Youngil Youm, Mechanical Engineering Dept., Email: youm@postech.ac.kr

BACKGROUND FROM REMARKS BY PRESIDENT PARK

POSTECH Stands for Pohang Science and Technology University. POSTECH is a relatively young university that has achieved a high level of excellence in its short history. The university was founded in 1986 with support from the local company POSCO, a giant of the steel industry situated in the Pohang area. On the southeast end of the Korean peninsula, this region has a strip of heavy industries running westerly along the coast of the South Sea.

The university has a small but excellent student body. The population of students includes 1,200 undergraduates and 1,600 graduate students, who are selected from the top 1% of Korean high school graduates. About 20% of the undergraduate courses and 30% of the graduate courses are taught in English, and all textbooks are in English. The campus is new and growing. New facilities include the Tae Joon Digital Library, and the Pohang Accelerator Lab.

RIST LAB

The Research Institute of Industrial Science and Technology (RIST) was founded in 1987, and currently has 161 researchers. The lab has a strong history of technology transfer to local industry, with 34 examples. The lab has produced 319 publications and 366 patents.

RIST Projects include:

- Web-based remote control
  - Mobile phones
- Crane auto run system
- Electric dust collector robot
- Electromagnetic acoustic transducer (EMAT) thickness gauge
- Mobile robot for facility inspection
  - Gas tanks and pipelines
- Integrated/embedded robot controller
- Miniature robot actuator
  - Piezo technology
  - Nanotechnology for cell manipulation
  - Microelectromechanical systems (MEMS) ready
  - In-house development of lead zirconium titanate (PZT) materials
  - Features include high torque

- Ultrasonic rangers
  - Photo of Hanool OTTORO shown
  - PZT and digital signaling processing (DSP) technologies
- Indoor global positioning system (GPS)
  - Ultrasonic
  - Radio frequency (RF) tags

Figure B.31. Tae Joon Digital Library (left) and future site of the Pohang Institute for Intelligent Robots (right).

ELECTRICAL ENGINEERING DEPARTMENT

An overview of the electrical engineering department was provided by Se-Young Oh. The department has seven electrical engineering faculty members working in robotics, with four computer engineering faculty in a collaborative arrangement. Department projects include:

- Mobile robots (Se-Young Oh, J.S. Lee)
  - Service applications
    - Home cleaning
    - Servants
  - AliVE
    - Three generations
    - Won sheep dog contest
    - Blind guidance
- Manipulation (Sang-Chul Won)
- Vision hardware (Hang Jeong)
- Vision software (Ki-Sang Hang, Joon-Hee Han)
- Sound (Seung-Jin Choi)
- Speech recognition (Hong Jeung, Geun-Bai Lee)
- Architectures and applications (Sang-Woo Kim)
- Intelligent vehicles (Se-Young Oh, Sang-Woo Kim, Poo-Gyeon Park)

MECHANICAL ENGINEERING DEPARTMENT

The robotics work within the mechanical engineering department was presented by Youngil Youm, along with background on the university and an overview of the national programs in robotics. His robotics and bio-mechatronics (R&B) lab was founded in 1987, with two professors, 10 MS students and 12 PhD students. The R&B Lab has produced 12 Ph.D. and 24 MS graduates, with many now working at Korean Institute of Science and Technology (KIST). The panel met some of these alumni at KIST, and saw the application of an excellent education in their working collaborations with KIST and RIST, as well as foreign labs and researchers that participate on PhD committees.

The R&B Lab was selected as one of two national labs in 2003, and has been recently selected by another national program, Ministry of Science and Technology (MOST), to be the core of the new Pohang Institute of Intelligent Robotics.

R&B Lab funding includes:

- $4,300,000 government support
- $1,300,000 industry support
- $184,000 RIST and KIST support

R&B Lab research areas

- Robots
  - Mobile robots
  - Underwater
  - Robot control
- Biomechatronics
  - Automated guided vehicle (AGV)
  - Handicap G drive support
  - Drive-by-wire

R&B Lab projects

- Underwater
  - Gold tetrahedron-like robot
  - Submersible with arms
- Auto driving
  - AGV with Hyundai Motors
  - Driving for the handicapped
  - Drive-by-wire with Hyundai Motors
- Hands
  - Three generations
  - Two-three-five-eight ratio in finger bones
- Humanoid
  - Passive walking testbeds have been built and tested
  - Hopping and running test beds have been built and tested
  - POSTECH is behind, but will catch up
  - POSTECH has recently built a new unit

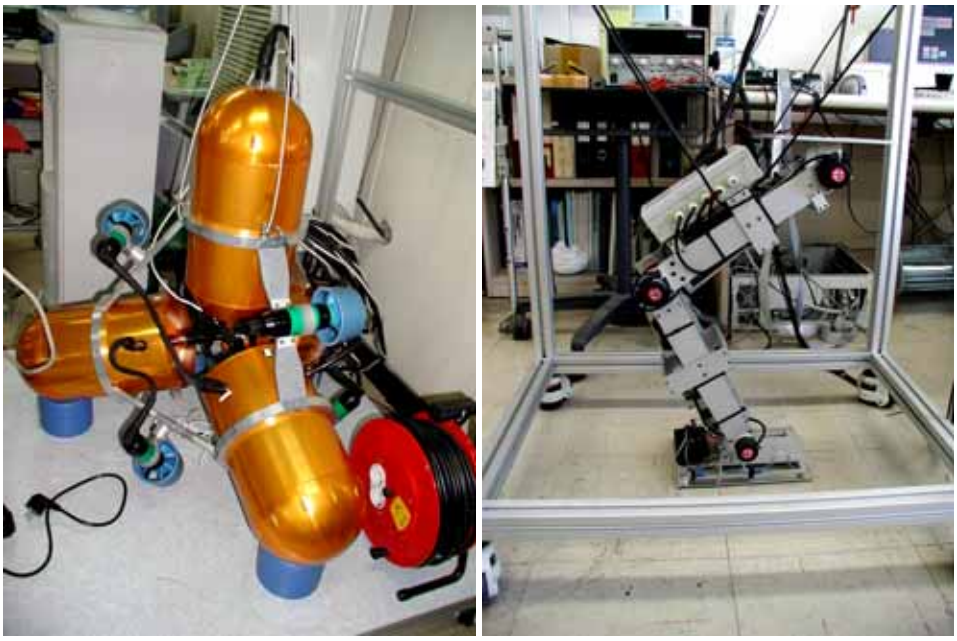

Figure B.32. Underwater vehicle and hopper robots.

PIIR

Professor Youngil Youm then gave an overview of the newly accepted Pohang Institute for Intelligent Robots (PIIR). The PIIR will be a nationally endowed institute with a new building at POSTECH. PIIR will bring together the following participants:

- Labs
  - RIST, BioTech, Pohang Accelerator Laboratory (PAL), Micro Mechanical System (MMS), Marine Biotechnology and Environmental Research Institute (MBERI)
- Industries
  - POSCO is major customer for robots
  - Dajin
  - LG
  - Samsung Electronics
- Local government support
  - N. Gyeongsang, Pohang, Gumi, etc
- Other universities
  - Yeongnam, Kumoh, KNU, Yongjin College

Details were presented on the funding and research targets for the new institute. The new building will be quite impressive, and the plan to build good platforms for use as research test beds makes sense.

- Funding
  - $40,000,000
    - 40% R&D
    - 27% Construction
    - 21% Facilities and equipment
    - 12% Research staff and administration

- Science thrust
  - Good platforms
  - Humanoids
  - Hopping
  - Hands
  - Mobile robots
- Bio Thrust
  - Micromanipulation
  - Haptic feedback
  - Prosthetics
- Robots for Steel Industry
  - Heavy payload handling robot arm
  - Boiler tube inspection robot
  - Storage vessel inspection robot
- Underwater
  - Fish robot
  - Underwater arm control
  - Cooperation with Hawaii University

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BIBLIOGRAPHY OF HOST JOURNAL ARTICLES

POSTECH faculty and students of mechanical engineering have been very active in publication in technical journals (having published 62 papers between 1987 and 2005, as well as presentations in technical conferences (180 papers appearing in proceedings between 1988 and 2005). Complete lists of publications can be obtained on request from POSTECH.

Site: **Ritsumeikan University**
Laboratory for Integrated Machine Intelligence
Biwako-Kusatsu Campus (BKC)
Faculty of Science and Engineering
1-1-1 Noji Higashi, Kusatsu-shi, Shiga-ken, Japan 525-8577
http://www.ritsumei.ac.jp

Date of Visit: October 6, 2004

WTEC Attendees: Y.T. Chien (Report author), A. Sanderson, M. Dastoor

Hosts: Dr. Sadao Kawamura, Vice President, Email: kawamura@se.ritsumei.ac.jp
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Fax: +81-77-561-2665, Web: http://www.ritsumei.ac.jp/se/~hirai/index-e.html
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Email: shimada@ci.ritsumei.ac.jp,
Prof. Hiromi Tanaka, Department of Robotics,
Prof. Ryuta Ozawa, Department of Robotics,
Prof. Satoshi Konishi, Department of Micro System Technology,
Dr. Katsuya Kanaoka, Department of Robotics

BACKGROUND

Ritsumeikan University is one of the leading private universities in Japan. The history of Ritsumeikan dates back to 1869 when Prince Saionji Kinmochi, an eminent international statesman of modern Japan, founded "Ritsumeikan" as a private academy in the Kyoto Imperial palace. The year 2000 marked the centennial anniversary of the establishment of Ritsumeikan as a full-fledged university. Today, Ritsumeikan University offers a wide range of research and educational programs at its two campuses: Kinugasa campus in Kyoto and Biwako-Kusatsu Campus in Shiga. Building on its founding spirit, Ritsumeikan maintains cooperative relationships with 150 universities and education/research institutions in 42 countries around the world. Ritsumeikan University has liaison offices in Seoul, Jakarta, Shanghai, and Vancouver.

Faculty and students in robotics activities largely reside in the College of Science and Engineering and a newly established (as of April 2004) College of Information Science and Engineering, both of which are on the Biwako-Kusatsu campus (BKC). The BKC campus itself is relatively new. A large number of educational programs, research laboratories and facilities are in place to support robotics work.

RESEARCH HIGHLIGHTS

Vice President Kawamura and Professor Hirai, both from the Department of Robotics, were the principal hosts for our visit. After a brief introduction, several other faculty members involved in robotics work gave a series of presentations on their research as an introduction to the range of activities at Ritsumeikan.

Professor Shinichi Hirai spoke first to introduce the department of robotics—its faculty and research areas. He emphasized the collaborative aspects of research with several other departments—Micro System Technology, VLSI System Design, and Human and Computer Intelligence. His own Laboratory for Integrated Machine Intelligence has carried out numerous research projects including robust image registration, soft-fingered manipulation, 3D imaging by varifocal mirror, linear object manipulation, crawling and jumping of deformable soft robots, and field programmable gate array (FPGA)-based real-time vision. A key focus of his research in the context of robotics is towards "sensory-motor coordination."

Also from the Department of Robotics were presentations by Professor Ryuta Ozawa and Dr. Katsuya Kanaoka. Professor Ozawa's research is part of the larger activity in the Arimoto-Kawamura-Isaka (AKI) Laboratory, which carries out numerous projects: robot hand; redundant robot-human torque estimation;

ankle foot orthosis; touch sensing; and power training machine. His presentation during the visit focused on the robot hand. One special effort is developing a manipulation method that requires no object information, either by sensing or models. Using a design based on biomimetrics ("opposition" movement—Napier, 1993), he has developed a controller algorithm to manipulate a 2D rectangle without using force or touch sensors. Ongoing work includes extension to 3D objects of arbitrary shapes. Dr. Kanaoka's presentation focuses on man-machine synergism, especially in solving problems of instability in a user's feedback control system. He has developed a "power finger" incorporated with a novel intelligent limiter attached to the user's control system. This research has led to international patent and commercial products in collaboration with Kansai TLO Co., Ltd, and Japan Science and Technology Agency (JST).

Professor Hiromi Tanaka and Professor Nobutaka Shimada presented some of the research work in the Department of Human and Computer Intelligence, related to robotics. "Haptic Vision" is Professor Tanaka's main interest. His goal is to develop vision-based haptic exploration towards the automatic construction of virtual environments used for simulation or other applications. Professor Shimada, on the other hand, focuses on "interaction-oriented" robotics. Her goal is to explore the use of computer vision and speech as an effective interface between the robot and user. Applications in service robots, such as robotic wheelchairs, are being used as experimental testbeds for evaluating the concepts, their implementation, and usability.

A new department, established in April 2004, is Micro System Technology in the College of Science and Engineering. Professor Satoshi Konishi described the scope of research in this department and its contribution to robotics. He and other members of the department are also a part of the Research Institute for Micro System Technology that anchors interdisciplinary work involving chemistry, bioscience and technology, optics, as well as robotics. Examples of work that related to robotics include the development of micro force-moment sensors and the fabrication of high aspect ratio microstructure using the lithography, electroplating and moulding (LIGA) process at Ritsumeikan's Synchrotron Radiation Center (see below). Professor Konishi's own research is in micro- and nanomechatronics, with ongoing work in micro end-effectors—actuators and grippers in biological (nerve and cell) interfaces. Much of this work is in collaboration with and supported by industries.

DEMOS AND LABORATORY TOURS

The visiting team toured several research centers and facilities that support robotics research and related work.

1. Research Center for Advanced Robotics in the Techno-Complex. This center houses much of the cross-disciplinary work in robotics, with faculty and student researchers from various departments. Several projects were demonstrated. One is Professor Hirai's work on tip position control of a flexible arm using high-speed (1,000 fps) visual feedback. The second is on a soft robot capable of crawling and jumping. The key idea here is to develop an alternative method for robots to move over rough terrain, one that employs deformation of the robotic body. Professor Hirai has done much of the pioneer work in deformable objects. Here he is applying this work to show a circular soft robot can craw and jump using the principle of deformation. The team was also shown some of the past and ongoing research on underwater robotics.
2. Synchrotron Radiation (SR) Center. The SR Center is one of Japan's leading synchrotron radiation facilities, with 14-beam line superconducting SR equipment. Using light radiation, the SR center undertakes structural analysis of materials, analysis of surfaces and boundaries, hyperfine structure processes, and other advanced research. Four of the beam lines are provided for lithography at high aspect ratio, LIGA exposure, and for etching in micro/nanofabrication.
3. Micro System Center. This is a brief tour of the microsystem design room and the microprocess laboratory, which includes various items of equipment and facilities typically used in semiconductor and micromachine fabrication. These facilities and the SR Center support much of the microelectromechanical systems (MEMS) research at Ritsumeikan, well known to the MEMS research community. According to Professor Konishi, Ritsumeikan is the only Japanese university that has an undergraduate major in MEMS.

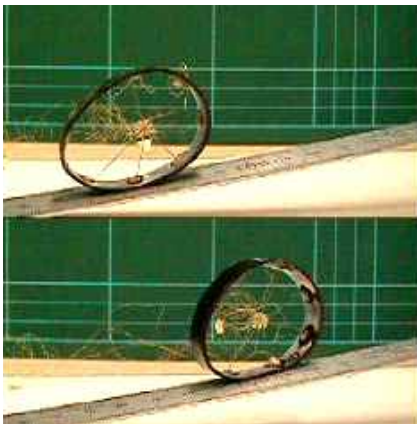

Figure B.33. A circular soft robot capable of crawling and jumping, similar to that seen in the Hirai lab.

OFFICES FOR IP AND VENTURE INCUBATION

As a private university, Ritsumeikan functions more like a Western-style institution that places high priority on intellectual property management and the promotion of venture incubation. Two offices that focus on these functions have been established to cultivate the entrepreneurial spirit among the university faculty and build a productive and financially rewarding relationship with society in general. The two offices work very closely with the industry and the local communities in the Kansai area.

OBSERVATIONS

Ritsumeikan is a one-of-a-kind university in Japan that stands out in many ways. The word "ritsumeikan," according to a university publication means "a place where people do their best to improve themselves while awaiting Heaven's will," which is derived from ancient scripture that has defined the university's founding philosophy and continuing mission: global reach, local interaction, and constant improvement. The programs in research, education, and institutional development, as related to robotics at Ritsumeikan, all seem to reflect that philosophy and mission well.

REFERENCES

Napier, J. 1993. *Hands.* Princeton, NJ: Princeton University Press.

Site: **Samsung Mechatronics Center**
Corporate Technology Operations
416, Maetan-3Dong, Paldal-Gu
Suwon-si, Kyungki-Do, Korea 442-742
Seoul, Korea

Date Visited: October 12, 2004

WTEC Attendees: R. Ambrose (Report author), Y.T. Chien, J. Yuh, B. Wilcox, Y. Zheng

Hosts: Hakkyung Sung, Vice President/ Director of Institute, Tel: +82-31-200-2400, Fax: +82-31-200-2467, Email: hakksung@samsung.com
Yeon Taek Oh, Principal Engineer

BACKGROUND

The Samsung Mechatronics Center has a history of building robots primarily for the use of other Samsung divisions. The first robot arm was a Selective Compliant Assembly Robot Arm (SCARA) built in 1989, and the Mechatronics Center proceeded through a significant chain of development that was centered on surface mount technology and other microelectronics manufacturing devices. These have included both mobile and manipulative robots, including combinations such as a cleanroom robot that can pick up and move materials in a fabrication facility. The Mechatronics Center has 720 members, with 220 in the Intelligent Systems Institute.

The Mechatronics Center has recently begun work in the area of service robots for the home and office. The non-industrial group led by Mr. Oh has 18 employees. They see multiple dimensions to this design space, with home vs. lifestyle improvement and interactive vs. autonomous as choices used to locate new robots in the domain. Like many Koreans working in this domain, they are seeking the "Killer App" and note that it might not be the same as in Japan. The U.S. market does not seem to be of interest to them. After speaking of cleaning, security and home applications, the conversation ended with a short discussion of vacuuming robots. They identified Hanool and Yajin Robotics companies as Korean competition, and iRobot, Evolution Robotics, Fujitsu, and Mitsubishi as foreign competition.

LAB TOUR

Samsung was very security conscious. They did not allow us to use still or video cameras, and required our laptops (which were being used to take notes) to be scanned on exit. Considering that companies have the most to lose and least to gain from our study, we are very grateful that they agreed to see us at all. They were very kind to take us into their labs, where we saw many engineers working on mobile and manipulative systems. Without divulging any secrets, we can say that their service robot prototype was demonstrated in a realistic setting, and Samsung's focus on 24-hour-a-day operation and testing is impressive.

Site: **Seoul National University**
Automation and Systems Research Institute
San 56-1, Sillim-dong, Gwanak-gu,
Seoul 151-742, Korea
http://asri.snu.ac.kr

Date Visited: October 11, 2004

WTEC Attendees: A. Sanderson (Report author), G. Bekey, Y.T. Chien, L. Weber

Hosts: Dr. Wook Hyun Kwon, Professor, Former ASRI Director, Vice-President National Academy of Engineering of Korea, Director of Control Information Systems Laboratory, Tel: +82-2-885-3930, Fax: +82-2-871-2527, Email: whkwon@cisl.snu.ac.kr
Dr. Beom-Hee Lee, Professor, Director of Robotics and Intelligent Systems Laboratory, Tel: +8211-899-1250, Email: bhlee@asri.snu.ac.kr
Dr. Frank C. Park, Professor, Director of Robotics Laboratory, Email: fcp@robotics.snu.ac.kr

BACKGROUND

Seoul National University (SNU) has been an academic leader in Korea with programs in all major disciplines, including medicine and law. The College of Engineering was founded in 1946 and included ten academic departments at that time. These programs are currently organized into six schools:

1. Chemical Engineering
2. Civil, Urban and Geosystem engineering
3. Computer Science and Engineering
4. Electrical Engineering
5. Materials Science and Engineering
6. Mechanical and Aerospace Engineering

Four departments:

1. Architecture
2. Industrial Engineering
3. Naval Architecture and Ocean Engineering
4. Nuclear Engineering

And five interdisciplinary programs:

1. Biochemical Engineering and Biotechnology
2. Medical and Biological Engineering
3. Urban Design
4. Techno-Economics and Policy
5. Technology and Management

The total enrollment of the College of Engineering was 5,246 undergraduate students and 3,426 graduate students in 2003. The College moved into a new engineering complex with modern facilities in 1996.

There has been a strong administrative emphasis on improving the quality and increasing the quantity of research in the College of Engineering in recent years. The number of tenure-track faculty has increased from 244 in 1999 to 272 in 2003. Currently, more than 75% of the tenure-track faculty received their Ph.D.

degrees from U.S. universities. The increase in research activity is indicated by the growth in refereed international journal papers (703 in 1998 to 978 in 2001) while the number of international conference papers doubled in the same period. Total research funding increased from approximately $35 million in 1999 to $59 million in 2001. The largest portion (about 75%) of these funds is from Korean government sources. Funding from international sources included $2.2 million from the United States (government and corporate sources) in 2002.

The Automation and Systems Research Institute (ASRI) is one of thirteen interdisciplinary research institutes with faculty participants from several different departments. The ASRI also serves as a mechanism to attract corporate support of research and works with both large and small companies.

Overview of the Visit

Our visit to SNU included an initial meeting with Professor W.H. Kwon, one of the distinguished faculty of the college and a vice president of the Korean National Academy of Engineering. Professor B-H. Lee then provided an overview of the College of Engineering and the role of robotics and automation research. Professor Frank Park presented detailed summaries of research by 22 faculty of the college who are active in robotics research. Our program included brief visits to eleven laboratories. These individual programs and laboratories are described in the cited materials (Lee, 2004).

OVERVIEW OF CURRENT ROBOTICS RESEARCH

For purposes of this summary, the research projects that were described in detail and included in the laboratory visits may be organized into five major fundamental areas of work:

1. **Robotic and Automation Systems and Control**

   Six of the laboratories had a primary focus on areas of systems with emphasis on several different themes in robotics and automation. These included:

   a. Control and Systems Laboratory—Prof. C.H. Choi
      - Biped walking robot
      - Face recognition: feature selection, feature extraction
      - Wireless LAN

   b. Intelligent Computing and Controls Laboratory—Prof. J.Y. Choi
      - Behavior decisions based on emotion models
      - Machine learning
      - Object detection using neural networks
      - Path planning for mobile robots

   c. Control Information Systems Laboratory—Prof. W.H. Kwon
      - Adaptive and learning control systems
      - Real-time networking and information systems
      - Applications to industrial automation
      - Involvement in small company start-ups

   d. Robotics and Intelligent Systems Laboratory—Prof. B-H. Lee
      - Force reflective control for mobile robots
      - Task planning and control using multi-agents
      - Map building using structure laser light
      - Automation systems—assembly time optimization

e. Optimal Robust Control Laboratory—Prof. J.H. Seo
Control and Dynamic Systems Laboratory—Prof. H.B. Shim
- Mathematical control theory
- Nonlinear control algorithms and applications
- Control of biological systems

2. Mechanics and Mechanisms

a. Robust Design Engineering Laboratory—Prof. J.W. Kim
- Parallel kinematic mechanisms
- Design and control of motion simulator
- Micromachines

b. Robotics Laboratory—Prof. Frank C. Park
- Geometry and multibody system dynamics
- Movement coordination and learning
- Movement tracking and recognition

3. Microelectromechanical Systems and Microsystems

One laboratory was primarily working on nano/microsystems, while another included related work (labeled "secondary"):

a. Nano/Micro Systems and Controls Laboratory—Prof. D.I. Cho
- Nano and MEMS, including bioapplications
- Control using MEMS intertial sensors

b. Robust Design Engineering Laboratory (secondary)—Prof. J.W. Kim
- Control and calibration of micromachines

4. Image and Signal Processing

a. Computer Vision Laboratory—Prof. K.M. Lee
- Vision-based robot self-localization, mapping, and navigation
- Object recognition (2D/3D)
- Visual human-computer interface

b. Control and Systems Laboratory (secondary)—Prof. C.H. Choi
- Face recognition

c. Robotics Laboratory (secondary)—Prof. Frank C. Park
- Physics-based animation

5. Computer and Software Systems

a. Real-Time Operating Systems Laboratory—Prof. S. S. Hong
- Real-time embedded operating systems
- Distributed embedded middleware
- Robust software communications architecture

Overview of Principal Applications

In reviewing the research in these five major areas, it was also evident that several categories of applications were prominent in the work. These included:

1. Biological and Biomedical Applications

These applications were most evident in the F. Park, J. Seo, and H. Shim laboratories.

2. Industrial Automation

These applications were of particular importance in the J. Kim and B-H. Lee laboratories.

3. Human-Robot Interactions

Several of the research programs in image and signal processing included emphasis on human-computer and human-robot interaction, including the C. Choi, J. Choi, K. Lee, and F. Park laboratories.

RELATIONSHIP TO KOREAN NATIONAL INITIATIVES

In recent years the Korean government has increased support for special projects and programs in the areas of robotics and automation. Additional resource investments are planned for the coming years. The SNU programs have participated in these national initiatives, and a number of the SNU faculty have been involved in advisory roles.

One such project is the 21st Century New Frontier Project on Robotics Innovation and Creativeness. This national project is led by Professor B-H. Lee of SNU. The program includes a set of fundamental research projects that are intended to support innovation in support of future robotics research. The program includes a lead project, "Real time coordination navigation technology for multiple moving robots," directed by B-H. Lee, and eleven other projects involving five other universities in addition to SNU.

OBSERVATIONS

The research programs at SNU seem to strongly reflect the U.S. background of many of the researchers. Projects tend to be centered in individual laboratories with a strong emphasis on fundamental research and academic publications. The laboratory work tends to emphasize experimental demonstration of principles and theories, rather than prototyping of practical applications-oriented systems.

Also, the largest group of researchers that we met brought an electrical and computer engineering background, to strong programs in systems, controls, and signal processing. There are also strong individual programs in mechanisms and devices, but there were no large programs described that bring all of these capabilities together in an integrated application or focus.

REFERENCES

Lee, B-H. 2004. Robotics Research Overview in Seoul National University. Prepared by Professor B-H. Lee with cooperation of associated faculty of the Automation and Systems Research Institute.

Site: **Sony Corporate R&D Laboratory**
Digital Creatures Laboratory
6-7-35 Kita-Shinagawa, Shinagawa-ku,
Tokyo 141-0001, Japan

Date Visited: October 5, 2004

WTEC Attendees: V. Kumar (Report author), J. Yuh, R. Ambrose, D. Lavery, G. Bekey, B. Wilcox, Y. Zheng

Hosts: Yoshihiro Kuroki, General Manager, Motion Dynamics Research Laboratory, Information Technologies Laboratory, Email: kuroki@pdp.crl.sony.co.jp
Yasuhiko Ichino, Research Planner, Planning and Control Group, Information Technologies Laboratory, Email: ichino@nbiz.sony.co.jp
Hideki Shimomura, Senior Researcher, Sony Intelligence Dynamics Laboratories, Email: simomura@idl.sny.co.jp

ORGANIZATION OF SONY CORPORATE R&D LABORATORY

Presentation by Yasuhiko Ichino

Sony Corporation has a Corporate R&D Laboratories division. It consists of two big laboratories:

- Material Laboratories (Dr. Y. Nishi, Leader)
- Information Technologies Laboratories (Mr. A. Iga)

The Information Technologies Laboratories consist of:

- Intelligent Systems Research Laboratory
- Motion Dynamics Research Laboratory

Most of the work in entertainment robotics is being done in these two laboratories.

ENTERTAINMENT ROBOTICS

Presentation by Yoshihiro Kuroki

Sony's first robot, the SRX (1982), was a four degree-of-freedom (DOF) selective compliant assembly robot arm (SCARA) industrial robot with six tools on its end-effector. It was used to develop integrated workcells (called Smart System), which were used for the assembly of products such as the Walkman. Eventually in the early-to-mid 1990s, the robot was phased out and replaced by hard automation with manual assembly.

The next milestone was the AIBO (robot dog) project started in 1994. Over 110,000 AIBOs have been sold worldwide. The AIBO project has had a significant impact on robotics research worldwide and has attracted many students to work in robotics.

The Small Biped Entertainment Robot involves entertainment at two levels. First, it requires a body and motion of the body that is "entertaining" (pleasing), which Sony calls Motion Entertainment. Second, the communication between the robot and the human, or the human-robot interaction, must be entertaining. This is called Communication Entertainment.

A significant milestone for the Small Biped Entertainment Robot project was SDR-3X, a 500 mm, 5.0 kg, 24 DOF biped. Sony demonstrated the ability to coordinate three SDR-3X robots in a team dance without communication.

The QRIO or SDR 4XII is a 580 mm, 7 kg, 38 DOF humanoid robot with a four DOF head, 2 six DOF legs, and 2 five DOF arms, each with 5 single DOF fingers. Sony has developed intelligent servo actuators, DC servo motors integrated with planetary gear reductions and controllers in one package. The motors provide high strength-to-weight ratios with high backdriveability. Acceleration sensors and force sensors at the feet enable the Quest for Curiosity (QRIO) robot to exhibit a wide range of gaits.

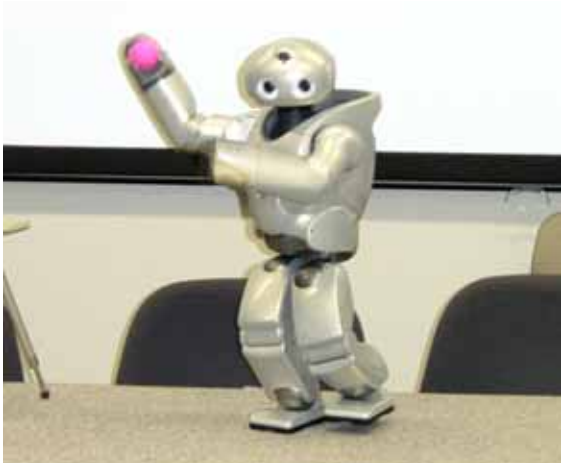

Figure B.34. The Sony QRIO: Pitching a baseball demonstration.

Table B.2
History of Robotics at Sony

Year	Development
1982	High speed assembly robot SRX
1990	Feasibility study on a personal robot
1994	AIBO project started
1996	P2 Humanoid announced by Honda
1997	SDR project started, SDR-1 developed - small biped entertainment robot
1998	SDR 2
1999	SDR 3 - AIBO ERS 110 on sale (first AIBO)
2000	SDR 3X
2002	SDR 4X
2003	SDR 4X (QRIO[1]) - AIBO ERS 7 on sale

QRIO is the culmination of a project that started with Mr. Kuroki heading a two-man team. The project grew 20–30 people over the seven-year span.

QRIO DEVELOPMENT

Motion Creating System

The motion-creating system consists of a motion editor that allows timeline-based motion creation and editing. Forward and inverse kinematics analysis is used to create and modify poses. Gait patterns are

[1] Sony views QRIO (pronounced curio) as a “goodwill ambassador” for the company.

automatically produced by a gait pattern generator. The system allows the user to synchronize motion segments with music.

Motion Control System

The philosophy of motion control is to achieve artistic expression in an entertaining manner. This group addresses motion-based entertainment, which complements communication-based entertainment done by other groups.

The Real-time Integrated Adaptive Motion Control effort (dating back to 2002) focuses on real-time stabilization and gait generation, adaptive controllers for terrain adaptation, and adaptation to external forces and disturbances. Error-recovery functions, such as recovering from falls, rising after falling down, and general posture recovery, have been implemented. More recent research addresses combining running and jumping gaits (2003) and walking with edge contact (unlike most flat-footed gaits), leading to more natural gait control (2004). The Guinness Book of World Records lists the QRIO as the fastest humanoid at 14 m/min in a running gait. Key to the successful performance is a new stabilization criterion, which is a generalization of the zero moment point (ZMP) stability criterion.

In addition to the real-time control software, the team has also developed simulation software that allows a developer or programmer to experiment with a virtual QRIO. The software incorporates rigid body dynamics with impulse calculations including an efficient, O(N) forward dynamics algorithm.

Intelligent Systems Research

Dr. Stefan-Guttman presented impressive research results with stereo-vision algorithms running on two-color charge-coupled device (CCD) cameras (352 x 288) using field programmable gate array (FPGA) modules for processing stereo images (which allow computation of disparity maps in hardware). He presented results on recognition of faces, the use of stereo range data for plane extraction, and real-time computation of ego-centric occupancy grids. The group plans to incorporate simultaneous localization and mapping (SLAM) algorithms for locomotion in 2.5D. Some SLAM-like algorithms are already used in demonstrations.

The group has worked on stair climbing, a particularly challenging task for humanoids, with impressive results. The extraction and segmentation of planes is used for stair recognition and the stair climbing algorithm is a finite-state machine that combines searching, aligning, and looking with posture control behaviors. Currently QRIO can climb stairs with a maximum height of 4.0 cm. The vision system (with a 12.5 frames per second update rate) is essential for this and other tasks.

The group has also addressed path planning in an occupancy grid with a primitive belief state. They use A* planning in a 4x4 position grid with eight orientations. The combination of 3D occupancy grid and 2D floor height map provides the environment map, and the A* algorithm allows the robot to walk on different floor levels.

SONY INTELLIGENCE DYNAMICS LABORATORY

Presentation by Hideki Shimomura

Sony established a new company called Sony Intelligence Dynamics Laboratories, Inc. on July 28th, 2004, with Toshi T. Doi as president. The company was founded to address three issues. First, Sony perceives the lack of robustness in unknown environments as a significant obstacle to entertainment robotics. Second, they recognize the immense amount of developer's time and intuition required to make robots work. Third, they believe that current technology does not provide the required interaction capability to attract customers. The goal of this new company is to explore the possibility of creating an intelligent robot that can develop its intelligence on its own.

Shimora is evaluating many approaches, including emergent intelligence (Kuniyoshi, Tokyo), cognitive development robotics (Asada, Osaka), embodied cognitive science (Pfiefer, Zürich), and cognitive science based on a dynamic systems approach (Tani, RIKEN)

The intelligence model has three levels. At the lowest level it is necessary to processor sensory information and signals for grasping and interaction with the human. At a slightly higher level, it incorporates mechanisms to acquire and learn tasks, including forms of reinforcement learning, teaching and imitation. At the highest level, cognition, emotion and motivation are important.

A key aspect of this work is the emphasis on "overwhelming computational power." A PC cluster system connected with QRIO via wireless network enables the necessary computations. The 1.12 Tflop/s cluster is the 202nd in the world in terms of speed and the fastest among private Japanese companies. This may be the first attempt to use clusters for real-time processing for robot control.

SUMMARY

The panel was very impressed by the high caliber of applied research presented by Sony researchers. It compares favorably with the best research being conducted by U.S. academic and government laboratories. It was refreshing to see Sony's mission-oriented approach being compatible with innovative robotics research.

Site: **Sungkyunkwan University**
Intelligent Systems Research Center
300 Chunchun-dong, Jangan-gu,
Suwon, Kyungki-do, 440-746, Korea
http://isrc.skku.ac.kr

Date Visited: October 11, 2004

WTEC Attendees: A. Sanderson (Report author), G. Bekey, Y.T. Chien, L. Weber

Host: Dr. Sukhan Lee, Professor, Director, Intelligent Systems Research Center,
Email: lsh@ece.skku.ac.kr
Seung-Min Baek (Ph.D.), Research Professor, Intelligent Systems Research Center,
Tel: +82-31-299-6475, Fax: +82-31-299-6478, Email:smbaek@ece.skku.ac.kr

OVERVIEW OF THE VISIT

The visit was hosted by Dr. Sukhan Lee, Director of the Intelligent Systems Research Center (ISRC) at Sungkyunkwan University (SKK). Dr. Lee has in the past held positions in the research laboratories of Samsung Corporation. He has also played an active role in developing Korean national initiatives for technology development. As background to the discussion, Dr. Lee provided an overview of these initiatives. He then presented an overview of the programs and directions of the Intelligent Systems Research Center that he has established over the past 18 months. A brief tour of ISRC laboratories and presentations by several researchers were also provided.

Background—National Initiative on Intelligent Robotics

Over the past two years, the Korean government has conducted a strategic planning process that resulted in the National Technology Roadmap (NTRM) with the theme: "Toward the Society of Information-Knowledge-Intelligence." Three major strategic themes are defined in this roadmap:

1. Ubiquitous computing and communication
2. Innovation in content and service
3. Ambient intelligence

Within these strategic themes, the roadmap envisions a transition of emphasis from "information" to "intelligence," and this theme is consistent with the integration of new intelligent robotics technologies into an infrastructure that would support:

- Intelligent manufacturing
- Intelligent appliances
- Intelligent transportation systems
- Intelligent personal assistants
- Intelligent healthcare systems
- Intelligent home/room/office/building

Specific types of integrated robotic systems as part of "Ubiquitous Robotic Service to Humans" would be based on the concept of "Robot Inside." These fundamental robotic technologies would be integrated into the home network, sensor network, ubiquitous network, machine-embedded and humanoid robots in support of robotic personal assistants, edutainment and intelligent robots, intelligent vehicles, intelligent buildings, and home robots.

The strategic goals of the NTRM initiative would be:

- Driving engine for future economic growth
- Broader scope of intelligent robotics
  - Service robotics for consumer markets
  - Intelligent robotic functions as component technologies
  - Service and solution from integration with networks
- Fourth generation of R&D: Integrating R&D and market creation

Overview of Intelligent Systems Research Center

The ISRC at Sungkyunkwan University was designated by the Ministry of Science and Technology (MOST) under the 21st Century Frontier Program in November, 2003, and has since been extended with a second year contract. Additional sponsors include the Gyeongi Provincial government, the Ministry of Information and Communications (MIC) and Sungkyunkwan University.

The Center is directed by Professor Sukhan Lee, and includes 14 core faculty members, four research faculty, 10 center researchers, and 40 student researchers. The participating institutes, in addition to Sungkyunkwon, include Korean Institute of Science and Technology (KIST), Hanyang University, Seogang University, Seoul National University, Seoul City University, and Soongsil University. The Center has also worked to develop international collaborations in the U.S. and Europe. The collaborative partners currently include University of Southern California (USC) and Carnegie Mellon University (CMU) in the U.S., and l'Institut National de Recherche en Informatique et en Automatique/Le Laboratoire des Sciences et Matériaux pour l'Electronique et d'Automatique (INRIA/LASMEA), Fraunhofer Institute, and Royal Institute of Technology (KTH) in Europe.

The ISRC will focus on fundamental research on intelligence technologies and on the development of enabling infrastructure for novel network-based robotics including standardization and business models. Key applications will include cleaning, security, rescue, and advanced manufacturing robotic systems. The Center's strategic R&D goals are:

1. Robot intelligence as component technologies: system-on-chip (SoC), middleware
2. Integration of robotics and computer science
3. Hardware and software co-design
4. Real-time and robust robot intelligence; robotic dependability
5. Integration of innovation and entrepreneurship
6. Globalization of R&D

Overview of Major ISRC Research Programs

A. Perception and Reasoning
  - 3D Perception, modeling and planning
    - 3D infrared (IR) camera
    - Fusion and filtering/simultaneous localization and mapping (SLAM)
    - 3D environmental modeling
    - Object recognition and tracking
    - Contextual understanding of a scene

B. Natural Human-Robot Interaction
  - Face and gesture recognition
  - Caller identification
  - Infotainment content generation

C. System Approach to Robotic Dependability
  - Cognitive robotic engine
  - Self-healing/application/growth
  - Intelligent systems on a chip

Future Challenges

- Technical Challenges
  - Breakthrough in perception
    - Fast and robust 3D visions
    - From recognition to contextual understanding
  - Natural human-robot interaction
    - Mental and emotional exchange as a companion
  - Dependability in task execution
    - Dexterity
    - Self-repair/adaptation/growth
  - Co-working and living with human in home environment
    - Safe and soft robot
- Issues in Commercialization and Industrialization
  - Service robotics in commercial sector
  - Value creation by integrating innovation, technologies, market
  - Open and modularized robotic architecture; standardization
  - Expanded business model to include service and solution
  - Industry standards for safety and evaluation

OBSERVATIONS

The SKK visit was very well organized and was very helpful in discussing overall national strategic themes and how they relate to specific technical programs being undertaken at Korean laboratories. The ISRC has clearly defined goals and programs with an emphasis on systems and integration of fundamental results and infrastructure. There is recognition that reliable components will be needed to created reliable and successful robotic systems. There is also a commitment to actively pursue paths to commercialization and industrial cooperation consistent with the strategic goals of Federal investment.

Site: **Tokyo Institute of Technology**
Hirose-Yoneda Robotics Lab
2-12-1 Ookayama, Meguro-ku,
Tokyo 152-8552
http://www-robot.mes.titech.ac.jp/home_e.html

Date Visited: October 4, 2004

WTEC Attendees: B. Wilcox (Report author), R. Ambrose, Y.T. Chien

Host: Dr. Shigeo Hirose, Professor, Department of Mechanical and Aerospace Engineering, Tel/Fax: +81-3-5734-3177, Email: hirose@mes.titech.ac.jp

OVERVIEW

Professor Hirose gave an overview of the research in his laboratory at the Tokyo Institute of Technology. First, he discussed snake robots. The motivation for working with a snake robot is that they are both a leg and hand in one, and that they inspire a huge number of novel applications (e.g. smart rope, smart hoses).

He first described the ACM-R3. It is composed of rectangular segments, to which are attached free wheels that are not driven. It has an actuator capable of delivering 10 Nm of torque between adjacent segments. The vehicle moves with undulating motion by applying force on each segment in such a way that the wheels roll. This vehicle was later demonstrated in the lab. A new model is under development with active wheels. It will have a sidewinder motion that is more efficient, with no slippage.

Professor Hirose next described HELIX, a swimming snake-like robot that employs something similar to the rotary motion of certain flagella. Such flagella represent the only continuously rotating joints found in nature. In HELIX, the snake-like robot has vanes (fins) that are not helical, but instead are parallel to the body. This was found by computer simulation to be the most efficient configuration. The balance of momentum is very important since there is no body, as in the case of the flagella, to react against. He drew a figure showing an undulating swimming snake with forces peaking only along short portions at the locations allowing the maximum angle to the direction of swimming. In contrast to this, a spiraling snake can get almost uniform thrust along its length. The original concept for the "Spirochete" was to have twined axons along its body. By changing the lengths of these axons, the spiral shape would propagate down the body. However, this was found not to be workable. Instead, a two-axis U-joint was developed for each link.

Turning away from snake-like robots, Professor Hirose next described the Titan series of walking robots. The Titan III and IV are four-legged vehicles each with whiskers on their feet for sensing. As statically-stable quadrapeds they move one leg at a time. Each upper leg is a parallelogram that maintains the orientation of the lower leg as the upper leg moves, and also makes it easier to apply the high torques needed for walking mobility.

The TITAN VII is able to climb steep slopes by way of rappelling, with two wires to move along the face. This is for use in construction. It currently uses pulleys at the top and winches at the bottom, but they are now developing a unit with winches on the body. A five- to seven-ton machine for steep slope construction, Titan VIII, has been commercialized.

Leg-wheel hybrids were discussed next. The "roller walker" combines the idea of a quadraped walker with the idea of "roller skating." Each leg has a free-swiveling footpad, which only slightly diminishes the degree of freedom (DOF) for each leg and yet allows walking without scuffing. The wrist and elbow are coupled to remain parallel. It has no brakes.

Other miscellaneous robots were then described briefly. The Titrus "dinosaur" robot uses its tail for balance and as a third leg for parking. The TAQT vehicle is a tracked vehicle capable of stair climbing. The four tracks are arranged as two pairs that can articulate to form a "V" shape as required. The payload carrier

(which can carry a person in a seat) runs over the back of the vehicle along a circular rail so that the payload can always remain horizontal, and also maximizes the center-of-gravity (CG) stability on stairs. It has been commercialized, but it is very expensive and hasn't sold well. It moves into the V-shaped posture to skid steer, with the inner parts of the four tracks making contact with the floor for max width/length contact ratio. Developed in response to a 2002 nuclear accident, the Japanese government paid for it, and Mitsubishi licensed the patent to manufacture it.

Other robots developed by Hirose's lab include a Mars rover shown at Rover roundup in Santa Monica (January, 1997). It was in the shape of a three-wheel equilateral planform. The SMC robot has a parent and children-type rover. It is a six-wheeled vehicle, but each of the wheels can separate from the host vehicle and become one-wheeled "tail draggers." The tails can be used for manipulation when the wheels lie flat on their outer face.

In manipulation mode they are strictly teleoperated. Current research is to integrate it with stereo vision and an automated control system.

The Gunryu I robot has four tracks linked by a separable elbow that allows it to become two different robots. The elbow has a two-link arm to each of the track pairs. The elbow has no actuators presently, but they are planning to add them. The purpose of this robot is to demonstrate cooperative, extremely high mobility. When one of the robots gets into a situation where it has inadequate mobility, it can link up with the other one and keep moving. In this way the pair has higher performance than either one separately (e.g. the combined system can do more than the sum of its parts). It currently operates by dead reckoning, landmarks, and global positioning system (GPS). One use of these systems is cooperative positioning systems, where more than two robots move one at a time. The stationary robots form a temporary coordinate measurement reference frame using laser striping and laser time of flight ranging sensors (0.3 mm accuracy at 400 m) such as used by civil engineers. Professor Hirose discussed briefly a system that uses small robots that only have corner cubes for a three-rover navigation team, where only one of the rovers has the full suite of laser sensors.

Several robots for humanitarian demining have been developed in Hirose's lab. Japan has a joint project with Afghanistan to develop such a system. The complete system has many levels: Level 1 is an aerial survey with a blimp or helicopter; Level 2 uses a large earthmoving machine, but it is so big that it cannot eliminate all the mines. Level 3 currently uses a human with a dog and a metal detector. One key point is that demining is now an important source of jobs that pay better than other work available, so the objective is not to eliminate these jobs, but rather to make demining safer. Hirose's lab has developed a vehicle with an arm on one side of the vehicle to reach into a minefield from a marked safe zone. The vehicle can traverse along the line of demarcation, and the arm can reach over the uncleared zone with sensors. Robert Ambrose made the point that many roboticists assume that manipulators should be placed on the front of a vehicle, but in fact anthropological studies have shown that arms are best placed where there is side-to-side freedom in the vehicle (that a human achieves with torso movements). Hirose's vehicle must commute from the base station to the work site each day to prevent theft, even though it is a relatively low-cost buggy ($700). He uses a counterweighted arm so that the vehicle performance doesn't change depending on the arm position. The gasoline motor on the buggy is used to drive an electric generator that operates all the demining equipment. One means for setting off small anti-personnel mines is with a spinning "rototiller" that chews up the top few centimeters of soil. Later, during the lab tour, we were shown a very simple demining device that is basically a long pole with a direct-drive teleoperated end-effector and a transparent blast shield. The human can lie on the ground and probe and manipulate with the long pole, protected by the blast shield.

Hirose has also developed an improved screw-jack for rescue operation (the "Gareking") that delivers >1 ton lift using a scissors action with unique side lift (so that convenient access under the load point is not needed, since in rescue it is usually unavailable). Professor Hirose reiterated that solving the problem is the objective, not building a robot. He tries to keep everything "as simple as possible." He pointed out, for example, that using human power is a reasonable alternative in rescue operations. It is possible to get 10–20 watts for about two hours from a human for powering machines in rescue operations, such as powering a pump for an inflatable bag which is used to lift enormous weight.

The Souryu series of robots includes the Souryu I “snake-like” vehicle, which has six tracks. This vehicle consists of three articulated cabs, each with two tank-like tracks. The center cab has parallel tracks, but each of the two end cabs has non-parallel tracks that form tapered ends for penetrating clutter. The Souryu III is a “super step climbing” robot that has found most use in under-floor inspection.

Professor Hirose's lab has developed a robot with a launchable tether with gripper that can grapple onto small cylindrical holdfasts such as tree limbs. The gripper is passive in the sense that it latches closed on impact, but then a ratchet memory mechanism releases after two pulls on the rope.

In a final Q&A session Professor Hirose said that, at this time, his lab is not part of the Selene project to send a robot to the moon.

Site: **University of Tokyo – Department of Mechano Informatics**
Inaba-Inamura Laboratory – Humanoid Robotics
Jouhou System Kogaku Laboratory
Faculty of Engineering, University of Tokyo
7-3-1, Hongo, Bukyo-ku, Tokyo, Japan
http://www.jsk.t.u-tokyo.ac.jp

Date Visited: October 8, 2004

WTEC Attendees: A. Sanderson (Report author), J. Yuh

Hosts: Dr. Masayuki Inaba, Professor, Research Laboratory Director, Tel: +81-03-5841-6345, Email: inaba@jsk.t.u-tokyo.ac.jp
Dr. Tetsunari Inamura, Assistant Professor, Department of Mechano Informatics, Faculty of Engineering, University of Tokyo

BACKGROUND

The Inaba Laboratory at the University of Tokyo has a long and distinguished history of research and contribution in the area of humanoid robotics. Earlier research in the laboratory also included active collaboration with Professor Inoue, particularly in the use of hardware-based vision and image-processing capabilities. Many students from the Inaba laboratory have gone on to successful research and engineering careers in both university and industrial research on humanoid systems in Japan.

Overview of the Visit

Professor Inaba hosted our visit. He provided an extensive overview of the development of humanoid robots over the past fifteen years. Many of these systems were demonstrated by students and research staff in the laboratories.

HUMANOID ROBOTICS RESEARCH

Research on humanoid robotics began at the University of Tokyo in 1990 with the study of eye-hand cooperation. The relation of perception to action was viewed as fundamental to advanced robotics, and research projects were developed to improve real-time image processing as a basis for real-time perception-action systems. These programs studied manipulation, grasping, teaching by showing, and task recognition as a base for more intelligent robot behaviors.

These early experiments provided the motivation to consider "whole body" robots as the next step in development. However, at that time, it was very difficult to integrate adequate computational capability into the robot body in order to control motion and sensing. Therefore, in 1992, the strategy of "Remote Brain Robots" was initiated to build whole body systems tethered to computational systems. These experiments used the remote tether to achieve body control, and a number of different body configurations were developed and studied. Based on the need observed in these experiments, a significant effort has been put into the development of 2D/3D tracking capability, optical flow analysis, depth maps and stereo capabilities. This generation of remote brain humanoids included 8–12 motors with off-board visual processing.

During the period 1993–1997, the complexity of these whole body systems was increased by 16–35 motors. More sophisticated vision-based guidance was introduced, and additional sensor capabilities included load cells, force sensors, accelerometers, and tactile and skin sensitivity. More complex tasks were demonstrated, such as the ability of a humanoid to stand from a fallen position, climb a ladder, and sumo wrestle.

From 1996 to 1998, the program moved from the development of small humanoids to large humanoids, based on the same software and architecture as previous systems. These larger humanoids offered features

that included advanced autobalancing capability. It was noted that one of the principal students who worked on this generation of humanoids went on to make major contributions to more recent research developments at Sony.

In more recent work, a series of humanoids (called H6 and H7) have been developed with increasing capability. An online step generator is used to support more advanced walking capability. An on-body dual-processor PC supports these systems, and a gyroscope and a binocular camera are integrated. A commercial version of the H7 humanoid is now available and is typically rented to universities and research institutes as a platform for humanoid research. It is primarily used for educational purposes involving students that develop software programs.

Current Research Issues

The focus of current research is on:

1. Open architectures for humanoid robotics
   - Providing standard environments for programming complex humanoids and allowing more emphasis on behaviors and human interactions.
2. More flexibility in the body
   - New designs for structural components including flexible elements of humanoid skeletal parts. Three dimensional computer-aided design and stereolithographic methods of fabrication are being used to develop complex shapes from plastic materials. These components are intended to provide more natural compliance and flexibility in body motions and interactions.
3. More adaptive sensing and mechanisms
   - Binocular eyes are driven to achieve more natural eye movements.
   - The neck is driven by six wires to achieve more natural motion with compliant spinal components.
   - Stiffness and posture control are being developed in the spinal column.
4. More sophisticated and adaptive human interactions
   - Self-body image by continuous learning from interactions.
   - Whole body compliance control.
   - Autonomous adaptive bodies—changing shapes and tools.

Future Directions

Professor Inaba is planning continuing growth in the mother and brain computer with emphasis on

- Planning
- Visual processing – human motion description
- Human interaction
  - Resolving ambiguous communications
- Motion planning and prediction
  - Inference
  - Task-level planning
- Vision-based motion planner

The vision for these systems is to provide an integrated software approach that would support “reactive autonomy,” with capability for reliable and efficient prototyping and experimentation, in order to develop systems that could be used in practical applications.

Potential applications include home robots as helpers and servers in healthcare and entertainment. The learning capability of these systems is important to be useful and to be accepted in normal environments.

Professor Inaba commented on the importance of Japanese government investments in robotics research. He emphasized that the need for continuity of support in the university is very important for the development of these technologies. He feels that long-term designs and strategies will be required to achieve research goals. These technical research directions must include a system-oriented approach, experience with robots in daily life activities, and dramatic improvements in perception.

OBSERVATIONS

The Inaba laboratory has been a leader in humanoid robot research in Japan, and has had success in demonstrating a series of generations of functional capabilities. This laboratory has maintained a focus on humanoid capabilities, and brings an important perspective on requirements for continuity of research and the need for reliable and programmable components in order to develop these systems.

Site: **University of Tokyo – Underwater Technology Research Center**
Institute of Industrial Science (IIS)
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http://underwater.iis.u-tokyo.ac.jp/Welcome-e.html

Date Visited: October 9, 2004

WTEC Attendees: R. Ambrose (Report author), J. Yuh, B. Wilcox, D. Lavery

Hosts: Tamaki Ura, Professor, Tel/Fax: +81-3-5452-6489, Email: ura@iis.u-tokyo.ac.jp
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UNIVERSITY OF TOKYO (TAMAKI URA)

Tamaki Ura has a very focused research program centered on the development and sea testing of underwater robots. His lab has developed a series of systems with an increasing degree of capability. During the 1980s, the lab developed the PTEROA-150, which was able to dive to waters 2,000 m deep, and cruise at 2 knots for one hour. The success of the PTEROA Project led to a string of new systems under the R-One Project, including PW45, Twin-Burger 1, Twin-Burger 2, the R-one Robot, Manta-Ceresia, Tri-Dog 1 and Tantan. Ura's most recent projects have been the Nakhodka Robot and the Dam-Survey Robot.

Work on the design of the R-Two Robot is based on the lessons learned from these robot developments. The R-One had a mass of 5 tons, and a 12-hour run time. Its large radius and other problems led to the smaller diameter of the R-Two. The R-Two will be a research system able to dive down to 4000 m, have a 1.6 ton mass and an eight-hour run time.

Professor Ura took the panel on a tour of his lab, and demonstrated the Tri-Dog system operating in a custom water tank. The system was able to use sonar and a laser system to maneuver and follow trajectories. We were also shown the high pressure tank for testing equipment design for deep operations, and two smaller robots that will soon be sea-tested.

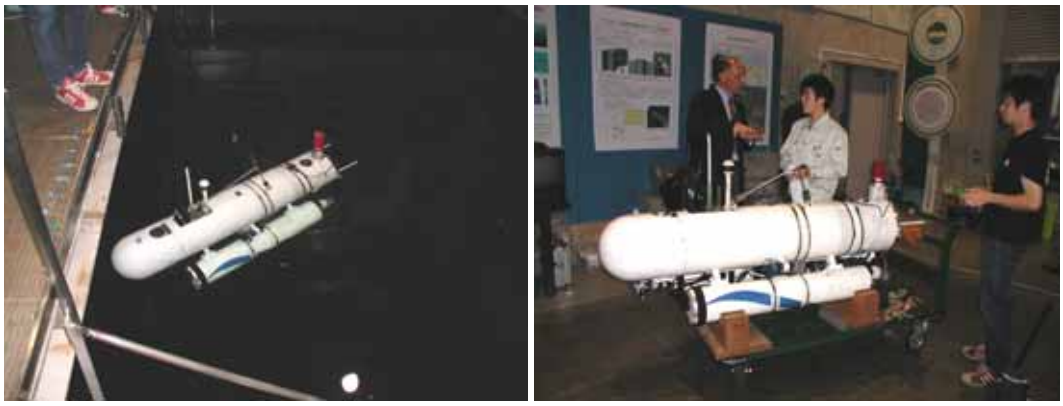

Figure B.35. Photos of robot in and out of Tokyo's water tank.

UNIVERSITY OF TOKYO (HASHIMOTO)

Hideki Hashimoto's lab has a wide range of research topics, with a primary focus on intelligent spaces. The technologies required for intelligent spaces use a mix of cameras and other sensors to track humans using a mass-spring-damper model of attention. Hashimoto's approach uses an array of sensors in a room mounted

on pan-tilt units, and uses color as a tracking tool. Hashimoto et al. have also developed a monocular vision system called the Distributed Intelligent Network Devices (DIND) approach that uses appearance-based tracking. Hashimoto's lab has also developed Gain Scheduling Middleware (GSM) for the stable control of mobile robots that operate around humans within the intelligent space.

Hashimoto's lab included a mix of other technology projects. Hashimoto has a long history of work in haptic devices, and showed the panel multiple generations of arm-level and hand-level force-reflecting masters that he has custom developed. His most recent work in haptics was demonstrated to the panel, using a PHANToM-like device to teleoperate a micromanipulation system (inverted six degrees-of-freedom (DOF) platform) fitted with a six-axis force/moment sensor.

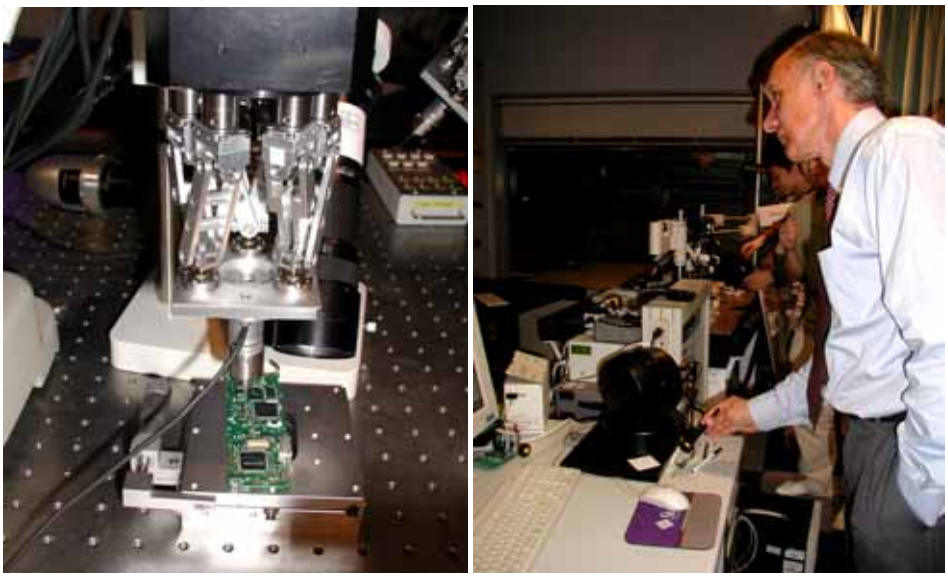

Figure B.36. Photos of the micromanipulation system and haptic interface.

UNIVERSITY OF TOKYO (KATSUSHI IKEUCHI)

This was a well supported lab with a beautiful amphitheater for virtual reality (VR) projection. The VR was based on a mix of geometry, photometry and environment knowledge. The geometric data was acquired using a CYRAx2500 laser range tool, with 1.5 m accuracy over a 50 m range. Cutting through the lab's work was a cultural theme. In the case of the ranger it was a Bali temple that was recorded with fine detail.

Figure B.37. Tokyo van with mapping sensors on roof.

The second Ikeuchi lab had a mix of manipulators and learning work. Techniques for learning from the motion capture of a human were being used to teach a humanoid. Again, the cultural element was present with the motion choice of a Japanese dance. Motion segmentation was done using zero velocity points in the joint space motion of the human motion data. This was found to be inadequate, and so the musical beat was added as a second source for segmenting the motion into quanta. The target for the work was a Honda P-series humanoid whose speed was too low to demonstrate tracking. The video was sped up, and the comparison to the human motion was quite good. The lab had a dual arm torso with Mitsubishi PA/10 manipulators that may be the in-house target for future work.

Ikeuchi also had an outdoor lab with a van whose roof was full of sensors for doing geometric mapping. The project has used the van to drive through an urban environment and build geometric maps of buildings.

Site: **University of Tsukuba**
Graduate School of Systems and Information Engineering
Intelligent Robot Labs, Cybernics Lab and Bio-medical Lab
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Ibaraki-ken 305-8573, Japan
http://www.roboken.esys.tsukuba.ac.jp/english/index.html
http://sanlab.kz.tsukuba.ac.jp/indexE.html
http://www.kz.tsukuba.ac.jp/~hoshino/

Date Visited: October 9, 2004

WTEC Attendees: R. Ambrose (Report author), G. Bekey, B. Wilcox, D. Lavery, J. Yuh

Hosts: Professor Shin'ichi Yuta, Vice President for Research, Tel: +81-298-2005, Email: yuta@esys.tsukuba.ac.jp
Professor Yoshiyuki Sankai, Email: sankai@kz.tsukuba.ac.jp
Associate Professor Takashi Tsubouchi, Email: tsubo@roboken.esys.tsukuba.ac.jp
Associate Professor Kiyoshi Hoshino, Email: hoshino@esys.tsukuba.ac.jp

UNIVERSITY OVERVIEW (SHIN'ICHI YUTA)

Professor Yuta gave the panel an overview of the University of Tsukuba's philosophy in research. It has a U.S.-style organization, where each professor is independent, unlike most Japanese universities where professors work together as a team. The university is private, and each student pays his own way. External funding is for equipment, which is often used to attract students to a lab's efforts. He noted that there is a shortage of Ph.D. students, while MS candidates are more abundant.

CYBORGS (YOSHIYUKI SANKAI)

Professor Sankai showed us videos and a presentation describing his work in technology for incorporation into and onto humans. He has worked on technology for the human heart, lung, kidney, eyes and legs. His primary work seems to be in the latter, having developed a Hybrid Assistive Limb (HAL). This is a four degree-of-freedom (DOF) exoskeleton that a person wears on his legs, allowing him to carry large loads. The exoskeleton uses harmonic drives and direct current (DC) servo motors at the knee and hip, with outboard structure. The connections to the body include a custom shoe with a linkage integrated at the heel, flex straps at the shin and femur, and a belt-like interface holding it to the torso. The key sensors are force sensors in the shoe, angular position sensors in the joints and electromyographic (EMG) sensors placed on the skin of the thigh. The use of EMG seems to be the real innovation, compared to U.S. systems, like at the Defense Advanced Research Projects Agency (DARPA), which use force or position displacements between the human limb and machine. The EMG data intercepts the human intent at a high order, instead of waiting for a large error to integrate in position, velocity or force that must then be handled in a feedback loop. This benefit was achieved with effort, requiring careful signal conditioning and likely some heuristic iteration.

The results seem to be better than U.S. systems. While the U.S. electronics and mechanical designs are superior in craftsmanship, the use of EMG and overall simplicity of Sankai's system are excellent. He showed videos of operations that are better than (advertised) results at Berkeley and Sarcos. He also showed early failed attempts that highlighted his effort in improving the EMG signal. Sankai's work has captured the imagination of the public, and is also well funded. He has started a company with students called Cyberdyne to produce and sell the "cyber suit."

Figure B.38. Cybersuit in use (left) and the labeled major subsystems (right).

INTELLIGENT ROBOT LABS

Shin'ichi Yuta and Takashi Tsubouchi's Lab

This lab had the remarkable goal of over one robot per student. Our walkthrough of their lab showed that they had more than met their goal. The lab was clean, organized, and very full of robots. At the time of our visit, the robots outnumbered the students. This was also one of the few Japanese labs heavily focused on mobile, wheeled robots.

Figure B.39. Photos of two mobile robots in this lab.

Kiyoshi Hoshino's Lab

Several technologies were demonstrated in this small lab, which was also very full of robots. The first demonstration was a small, prosthetics-like hand developed with three generations. The second generation hand was quite good, with eight DOF (4x1 per finger knuckle, one couple yaw of three fingers, and three for the thumb). The third generation hand was described as having 13 DOF, but this unit was not seen. The hand used MicroMo motors with axial placement, and a final bevel gear at the joint. Cables/belts were used to couple distal joints. The joints appeared to drift, but were easily back driven by the student for calibration with a 22 sensor cyberglove.

Figure B.40. Photo of hand and limb prototypes.

Other robots in the lab included a pneumatic-powered humanoid system using SMC cylinders (not demonstrated), an arm that appeared to use air muscles (not demonstrated) and a visual tracking system to estimate the pose of a hand using monocular vision and prior experience/models of a hand.

Site: **Waseda University**
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http://www.wabot-house.waseda.ac.jp/

Date Visited: October 7, 2004

Attendees: Y. Zheng (Report author), G. Bekey, R. Ambrose, V. Kumar, A. Sanderson, B. Wilcox, J. Yuh, H. Miyahara

Host: Dr. Shuji Hashimoto, Professor, Humanoid Research Institute, Tel: +81-3-5286-3257, Email: shuji@waseda.jp
Dr. Shigeki Sugano, Professor, Humanoid Research Institute, Email: sugano@waseda.jp
Dr. Atsuo Takanishi, Professor, Email: contact@takanishi.mech.waseda.ac.jp

BACKGROUND

The assessment team chose Waseda University to visit because it has a long history in robotics research, and is especially well known for its humanoid biped walking robots. In 1973, the first full-size humanoid robot was developed at Waseda University by the late Professor Kato. In 1984, Waseda University developed the famous musician robot which could play piano automatically. In 1992 the Humanoid Project began by developing a series of humanoid robots including Hadaly-1 in 1995, Hadaly-2 in 1997, WABIAN in 1997, and Wendy in 1999. In recent years, the institution has continued and expanded its research activities in robotics and established the Humanoid Robotics Institute. The director of the Institute, Professor Shuji Hashimoto, hosted our visit.

THE ACTIVITIES OF ROBOTICS RESEARCH AT WASEDA

Waseda University has eight laboratories in different departments, which are led by ten faculty members plus six research associates and three visiting professors. The university has nine advisory members from outside the university and has forty different topics under the study. The eight laboratories involve sixty graduate students. Research activities at Waseda are supported by companies, the Ministry of Education, New Energy and Industrial Technology Development Organization (NEDO) of the Ministry of Economy, Trade and Industry (METI), and Waseda University.

Waseda University has three themes regarding their activities of robotics research: “From Factory to Home,” “From Superman to Human,” “From GUI to Post-GUI,” and “From Virtual to Real.” For the first theme, Waseda considers a humanoid like a human-friendly robot suitable for working with humans in a human living environment. For the second, a humanoid is considered like a human simulator with a sensor complex to evaluate living environments for the aged and disabled. For the third, a humanoid is considered a multimodal communication terminal connected with computer networks. For the fourth, a humanoid is considered as media with a virtual space and real world. Recent activities at Waseda include the Third Phase of the Key Technology Research, which has developed twenty robots used in individual studies.

Dr. Hashimoto spoke about the individual research topics of the eight faculty members at Waseda University, which are shown below.

A. Harmonized Human Machine Environment—Professor Shuji Hashimoto
   - Research activities include: artificial creatures, auditory and visual scene understanding, multimodal advanced interface, media fusion, multimodal platform humanoid robot.

B. Telerobotics—Professor Seinosuke Narita
   - Research activities include: telerobotics systems, virtual humanoid, and analysis of space structure from image.

C. Meta Communication—Professor Katsuhiko Shirai
   - Research activities include non-verbal communication, facial pose and eye-gaze detection, and motion recognition of the human face.

D. Perceptual Computing—Professor Tetsunori Kobayashi
   - Research activities include: speech and image processing for man-machine communication, group communication, and multimodal interaction.

E. Integrated Mind-body Mechanism—Professor Atsuo Takanishi
   - Research activities include: Bipedal Humanoid Robot, Mouth Opening and Closing Training Robot, Food Texture Measurement Robot, Anthropomorphic Flutist Robot, Emotion Expression Robot, Talking Robot, and Rat Robot.

F. Intelligent Machine—Professor Shigeki Sugano
   - Research activities include: safety mechanism and control, human-robot tactile communication, dexterous manipulation, physical and emotional communication between humans and robots, motion creation based on KANSEI, and mind mechanism in machine systems.

G. Medical Robotics—Professors Fujie, Umeze and Takanishi
   - Research activities include medical and welfare robots.

Professor Hashimoto also introduced the RoboCasa, an Italy-Japan joint laboratory whose mission is research, dissemination, and industrial application for humanoid robotics. Another project which Professor Hashimoto introduced is the Wabot-House co-sponsored by Waseda University and Gifu Prefecture government. Wabot-House is a five-year project with the goal of establishing a new institute at Gifu Techno Plaza. The objective of the institute is:

a. Perform research in a robot community which leads to co-creation among robots, human and various environments.
b. Perform research on co-creative coordination technology for developing the robotics industries in the regional society.

Waseda University also has the 21st Century Center of Excellence (COE) program, which is directed by Professor Fujie. The program aims at innovative research on symbiosis technologies for humans and robots in an elderly dominated society.

The Research Laboratories

Waseda University is well-known for its design and development of various robotic systems. We were impressed by the large number of robots and robotics laboratories spread around the campus. The robots we observed included the WE-4RII in RoboCasa as shown in Figure B.41. The robot has visual, tactile, auditory, and olfactory sensing capabilities. The robot can also express its emotions and moods by using facial expressions and tones as well as arm and waist motions. The RoboCasa program appears to be successful.

Figure B.41. The WE-4RII robot sees and follows the red ball.

We also saw a number of Italian researchers working in the laboratory. Another robot we saw is the WOJ-1RII robot, which is a mastication robot with sufficient muscle function to generate contract force. Another interesting robot was the WM-6 robot which can interact with (and move as fast as) a rat. The purpose of the robot is to investigate the factors which are necessary for a robot to interact with a creature.

Another robot is the WF-4 flutist robot which can play the flute at a respectable level, and is able to collaborate with a human flutist. The robot has very complicated mechanical structure, and as usual, Japanese researchers managed to design and implement it very well. (Figure B.42).

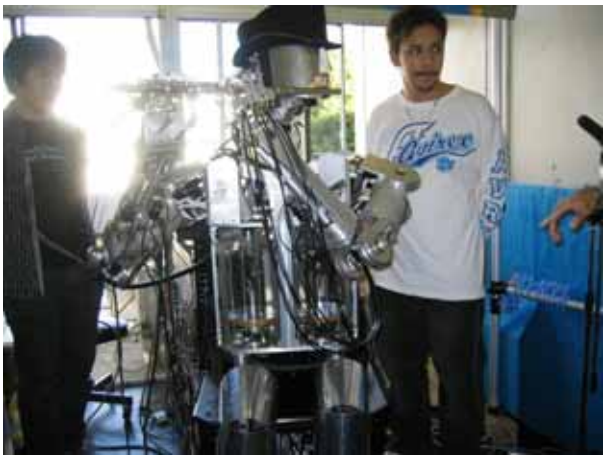

Figure B.42. The WF-4 Flutist robot.

Waseda University is involved in welfare robots and medical robots as well. The welfare program is in cooperation with the Metropolitan Center of the Mentally and Physically Handicapped, a part of the 21st Century COE program. Dr. Fujie is particularly responsible for the efforts here. His research efforts include the development of a motion analysis room which is equipped with a 3D optical motion capturing system using an infrared ray, a walking assisting device which is equipped with force sensors to sense the pushing force on the right and left arms, respectively. The device can also alternate floor tire resistances to adapt different levels of gait disorders (Figure 6.6). We also saw a number of medical robots developed by Dr. Fujie and his students.

Another interesting robot we saw is the Wendy robot by Dr. Shigeki Sugano (Figure B.43). The Wendy robot was designed for research to develop a social system and technological design principles for the future when

robots become an integrated aspect of our life. Wendy can perform various physical interactions with humans. For example, Wendy is equipped with sensors to calculate appropriate motion when it makes contact with a person. The Wendy robot is a part of the so-called robot community, which aims to foster co-creation among robots, human and various environments. The research is also a part of the activities carried on at the WABOT-HOUSE Institute of the Waseda University, which is led by Dr. Sugano.

Figure B.43. The Wendy robot.

As mentioned earlier, Waseda University is well known for its development of biped walking robots, which have recently started being developed as humanoid robots worldwide. We saw quite a few humanoid robots including WABAIN-RV, WABIAN-2, and WL-16, as shown in Figure B.44. Some robots are as big as a real man, and others are smaller. The WL-16 robot has a parallel structure in its legs and can carry a man.

SUMMARY

Waseda University is a pioneer institution in the research of biped walking robots. The first biped robot was developed in 1973 when little robotic effort was carried on by the rest of the world. While the University continues the humanoid robot program, many new areas of research have been developed to reach a primary goal, i.e., achieving effective human-robot interactions. That is evidenced by many new robots such as the emotion expression robot, the Wendy robot, the walking assistant machine, the flutist robot, and the rat-like WM-6 robot. The new Humanoid Robotics Institute, the WABOT-HOUSE Laboratory, and the 21st Century COE program are all for that purpose.

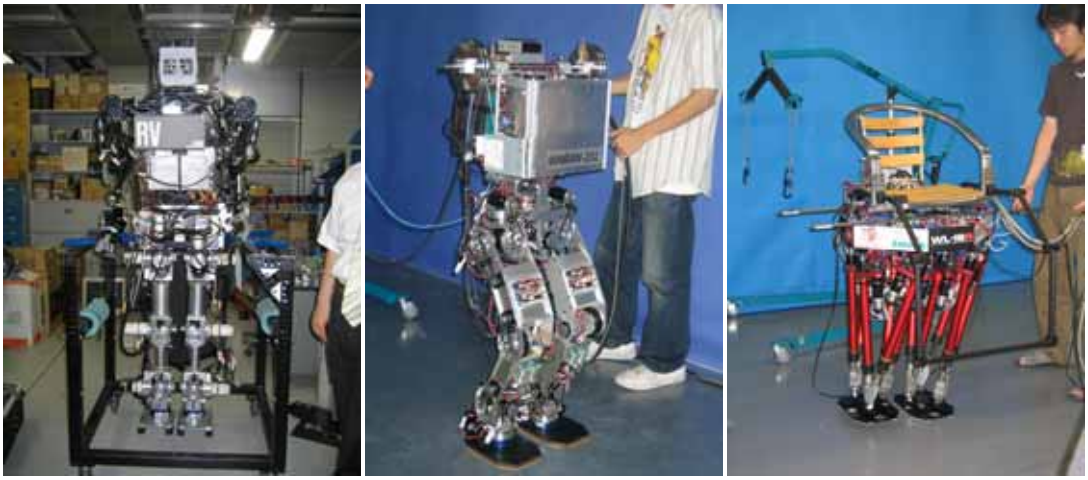

Figure B.44. Waseda humanoid robots: WABIAN-RV (L), WABIAN-2 (M), and WL-16 (R)

APPENDIX C. SITE REPORTS—EUROPE

Site: **ABB Laboratory**
Corporate Research Center
Forskargränd 8
SE 72178 Västerås, Sweden
Tel +46-21-32 30 00, Fax: +46-21-32 32 12

Date Visited: April 29, 2005

WTEC Attendees: B. Wilcox (Report author), G. Bekey, V. Kumar, R. Ambrose, Y. T. Chien

Hosts: Chun-Yuan Gu, Program Manager, Mechatronics and Robot Automation, ABB Corporate Research Center, Email: chun-yuan.gu@se.abb.com
Tomas Lagerberg, Manager, Automation Technologies, ABB Corporate Research Center,
Anders Nylander, President, Business Area Unit for Robotics and Manufacturing of ABB Automation Technologies

BACKGROUND

The morning session at ABB was led by Program Manager Chun-Yuan Gu (Mechatronics and Robot Automation) and Manager Tomas Lagerberg (Automation Technologies) from the ABB Corporate Research center. In the afternoon session, we were joined by President Anders Nylander of the Business Area Unit for Robotics and Manufacturing of ABB Automation Technologies AB.

ABB employs about 100,000 people—45,000 in power systems (grid control, transformers, high voltage AC and DC transmission up to 800 KV, etc.) and 55,000 people in automation (motors, contactors, soft starters, speed controllers, frequency converters for up to 50 MW machines), instruments for temperature, pressure, pH, etc., and control systems (input/output (I/O), software (SW) for process control).

They showed a demonstration of two robots performing coordinated motion (simulated adhesive bead laydown on bond line), using one controller for the two robots. To specify waypoints, it takes perhaps one hour to define a bond line on a computer-aided design (CAD) part. An important point is that many customers don't have CAD models. For example, automotive manufacturers don't release their CAD models to their piecepart suppliers. Instead they supply a master copy of a part. Small robots are repeatable to within 0.1 mm, and it is possible to get to 0.02 by iterative learning, although this requires substantial thermal stability. Large robots are repeatable to about 0.1 mm.

There are nine research programs at the ABB research center: SW technology, Advanced Industrial Communications, Manufacturing Technology, Power T&D, Mechatronics and Robotics Automation, Nanotechnology Applications, Power Electronics, and Power Device Technology.

ABB does not really do basic research—that is done at universities. ABB collaborates with universities; it has agreements with the Massachusetts Insitute of Technology (MIT), Carnegie-Mellon University (CMU), Stanford, Cambridge, Imperial College, and Swiss Federal Institute of Technology (ETH) in Switzerland.

The nine R&D programs represent different areas on the Enterprise/Products/Solutions chart.

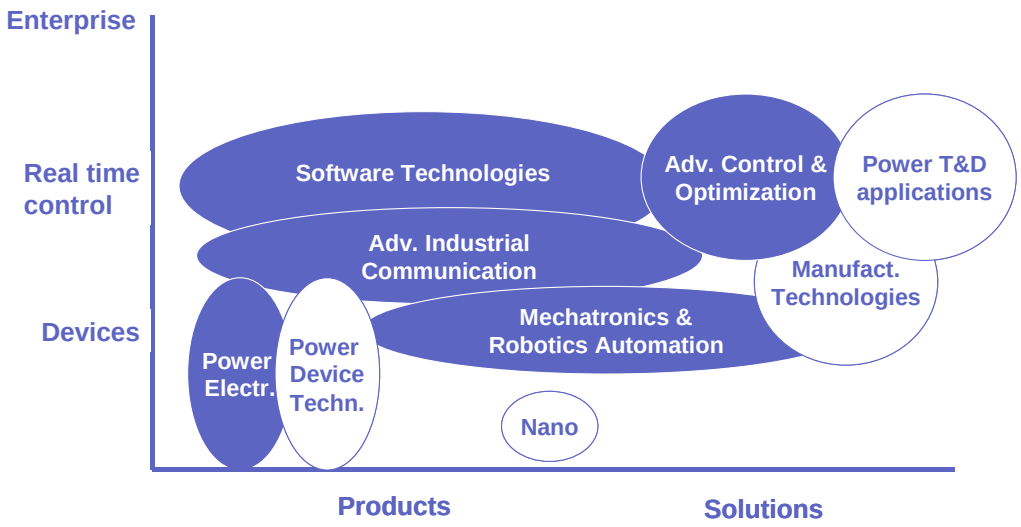

Figure C.1. The nine R&D programs at ABB.

The mechatronics and robot automation research effort focuses on advanced robot design and integration.

In 1974, ABB introduced the world's first microcomputer-controlled electric robot: IRB6. In 1982 they introduced joystick programming of robots. In 1986 they introduced the AC drive on robot motors. In 2002 they were the first to reach a cumulative sales total of 100,000 robots.

They have introduced a product "RobotStudio" simulation tool for easy programming.

At present, the unit cost of hard automation crosses over with robots between manufacturing volumes of 100,000 to 1 million units. With manual labor there is an essentially constant unit cost, independent of the number of units. So there is a "robot zone" where robotics can be competitive with both manual labor and hard automation. The key to future use of robotics is to expand this zone.

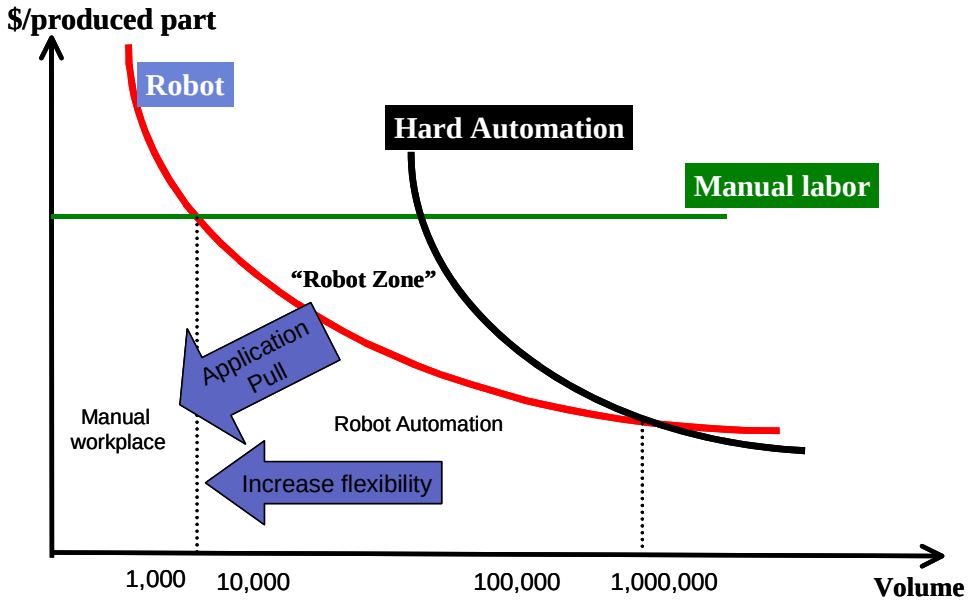

Figure C.2. Economic region where robotics is competitive.

Next, the WTEC team met with President Anders Nylander of the ABB Business Area Unit for Robotics and Manufacturing.

There is 5–7% annual growth in robotics worldwide. The automotive industry is the key driver for robotics. The definition of robotics is restricted to systems with five or more degrees of freedom (DOF), so many of the SCARA robots commonly used for electronics assembly do not qualify as robots under this definition. Also, computerized numerical control (CNC) machines (e.g. computerized milling machine, even those with more than five axes) do not qualify as robots. Major markets include foundry operations, spot and arc welding, etc. There has been substantial price erosion in recent years.

They are working on "virtual robot" software, which allows planning, programming, commissioning, operations, and production statistics. The automotive industry wants to use as little space as possible, and robots now are cheaper than hard automation and more flexible. The automotive industry is still relatively labor intensive. It strives for common standards, needing simplicity and reliability.

Next, Christer Norström presented the concept of "Robot Dalen (Valley)." Norström is professor at Mälardalen University, which has 15,000 students, 225 grad students, 57 professors, and $120 million in U.S. research funding per year.

There is a concept from the U.S. called "Triple-Helix" that says there is a need to stimulate BOTH research and business in a healthy business climate. The concept of the Robot Dalen started from industry and research (Mälardalen University and Stockholm are in the same valley). There are 15,000 people in the valley now working in the area of automation. This includes industrial robotics as well as grippers, system integrators, field robotics, robotics for healthcare, and Volvo Heavy Equipment (who, along with Caterpillar and Komatsu are the "Big Three" in worldwide heavy equipment). The Robot Valley concept is to create an efficient system for developing ideas and fostering innovation.

An example is for elder and healthcare—what can we do in rehabilitation? Measuring the degree of rehabilitation is closely related to athletic training equipment. In Sweden there is a fundamental economic problem that all hospitals are under government control, and they do collective procurement. So there is no way to get into the market in an incremental way.

Another example is education in the widest sense. The Lego robotics competition is an example that requires teachers to take robotics classes.

Support for innovation is difficult. Their goal is to have 40 start-up companies per year founded by students. Industrial robots are now a commodity product with high volume and low margins. Agricultural robots are just taking off. Healthcare robots are in their infancy. Every president of a company wants to move all manufacturing to a "low-cost labor" country. But the Robot Valley team has done a survey and found that 9 of 14 will have a better return on investment if they "robotize" rather than moving. The Robot Valley team helps with competence - they induce students in the universities in the valley to take a course in automation in their senior year. They establish mentor groups, with two students, a product leader, a professor, and a system integrator. They are doing this now with 50 companies within a 70 km radius.

The key challenges they face are:

- It is perceived as too expensive to install a robot (people in companies should be able to install it themselves)
- The time it takes to change products is too long
- The utilization of robots is too low
- The environment is not as deterministic as assumed for most robots
- There is little support for human-robot cohabitation
- Management fears "what if they buy a robot and it doesn't work?" How can they intervene so that work continues even though a robot is not working? How can they do "incremental robotization?"

A study was recently done in Sweden that shows that big factories such as Volve are at the state-of-the-art (SOA). But small companies are not SOA, and in many cases are far behind. But the large companies depend on the small feeder companies.

Site: **Charite Hospital**
Campus Virchow-Klinikum
Clinic for Maxillo Facial Sugery-Clinical Navigation and Robotics
Berlin, Germany

Date Visited: April 28, 2005

WTEC Attendees: R. Ambrose (Report author), M. Dastoor, Y.T. Chien, B. Wilcox, D. Lavery

Hosts: Prof. Tim C. Lüth, Email: tim.lueth@ipk.fraunhofer.de
Juergen Bier, Email: juergen.bier@charite.de

BACKGROUND FROM REMARKS BY PROF LÜTH

We again met up with Prof. Lüth at Charite, where we were initially shown the applications of his research at Fraunhofer Institute, Production Systems and Design Technology (IPK). This dual role for Prof. Lüth is an excellent example for other countries wanting to find a path for integrating technology and research into applications. Prof. Lüth's involvement at both sites is deep and has yielded great results.

Lab tours

The facility 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 the research, founded at IPK, is not matched in the U.S.

The study team was taken through a series of labs with multiple generations of navigation systems developed in-house. The latest generation has reduced the required inter-ocular baseline to a small distance (~0.4 m) and is mounted on a small roller mount that takes up only a small amount of floor space. The optical markers are significantly smaller than their competition, are tracked with a well-tested software product now in wide distribution.

Figure C.3. NC Machining Center in prototyping lab.

Figure C.4. Second generation optical tracking system (over David Lavery's head) (left), first generation optical tracking system (right).

Figure C.5. Third generation optical tracking and cranial mounts (left), Dr. Lüth demonstrates use of registration software (right).

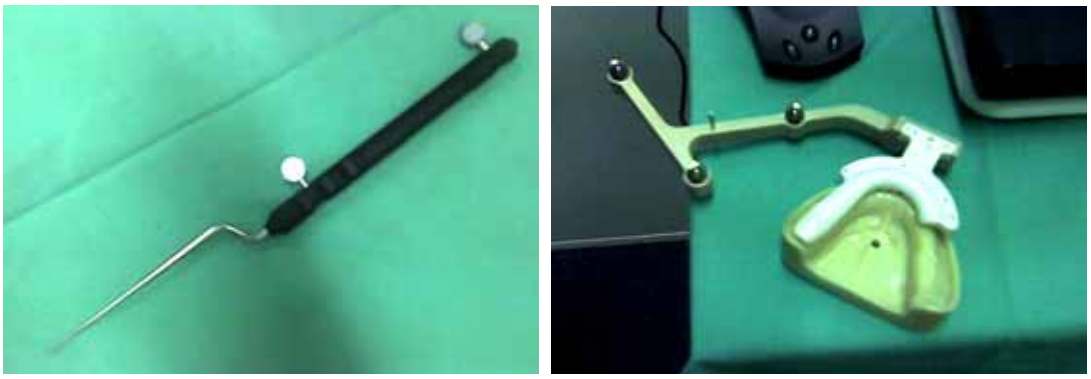

Figure C.6. Registration probe (left), registration trackers on dental mount (right).

Figure C.7. Lower extremity fixture and motion tracking system.

Figure C.8. Close-up of registration software interface.

Site: **CNES**
Centre National d'Etudes Spatiales de Toulouse
18 Avenue Edouard Belin
31 401 Toulouse, Cedex 4, France

Date Visited: April 25, 2005

WTEC Attendees: B. Wilcox (Report author), R. Ambrose, Y. T. Chien, M. Dastoor

Hosts: Michel Maurette, Robotics expert, Laboratory Centre Spatial de Toulouse,
Tel: +33 5 61 27 44 77, Fax: +33 05 61 28 17 48,
Email: michel.maurette@cnes.fr
Guy Laborde, Head of System Testbeds service, CNES, Tel: +33 5 61 28 26 27,
Email guy.laborde@cnes.fr

BACKGROUND

On the way from the visitor center to the lab, we were taken by Michel Maurette to a Mars-like test area, about 30 x 50 m. It is in a shallow depression so that mast cameras don't see other terrain outside the nominal test area. There is a small lab building nearby for test support. There were no tests in progress at that time. They have 10 cm ground truth topography for this site.

From there we went to the robotics lab. We first visited a room in the back with a very complete and sophisticated stereo calibration and test area, including stereo camera heads being developed for flight. There was very careful attention to maintaining mechanical rigidity and alignment during the fabrication of these heads. Originally, they started with 20 cm stereo camera separation, but now are using 12 cm separation, and may go down to 10 cm as camera resolution continues to improve. They are using the same 1024 x 1024 pixel cameras that are used on the Rosetta comet mission (and on the Space Station). They are using a "stacked chip" packaging technology they have qualified thermally from -120°C to +20°C and also through the Ariane-5 launch vibration spectrum. On one side of the room is a large collimator used to project identical spots as seen from infinity into both cameras of the stereo head for calibration. On the other side of the lab is a ~3 x 4 meter test area with brick-red gravel glued to regular geometric shapes (e.g. rectangular and triangular prisms) to validate the performance of stereo cameras mounted on motion stage. They calibrate each camera to a fifth of a pixel, and use a ~50 x 50 lookup table plus interpolation to do ortho-rectification. They expect to do visual odometry every 10 to 50 cm of vehicle motion, and to perform stereo correlation and path planning every two meters.

Next, we moved to the adjacent software development area, where we were shown a simulation of a Mars rover in computer-generated terrain. The claim is that the algorithm they are developing is superior to the Mars Exploration Rover (MER) in that it plans paths that are more complex than simple arcs, and this is needed if the terrain is very difficult. In the example shown, as the terrain map is built up using simulated stereo data, it becomes clear that there is no passable way out, it is only possible after a complex path is planned out through the last possible opening. At the end, new stereo range data shows (as the vehicle approaches it) that the final exit is not passable.

All software is in ANSI "C" and ground support is in Motif/Open-GL (X11). They are transitioning to the compact-peripheral component interface (PCI) bus on their research rover Illustrateur Autonome de Robotique mobile pour l'Exploration Spatiale (IARES) (most existing equipment is VME). All code works on Intel or PowerPC processors with same source code.

There was much discussion around a Russian rover chassis used in IARES that has many degrees of freedom (DOF). The chassis has six-wheel drive, with turning cylinders on the undercarriage to prevent high-centering. It has six-wheel drive and steering, two speeds with a brake on each, and has an "inchworm" peristaltic mode for use in very soft terrain. It takes 1 W to release the brakes.

We were joined by Guy Laborde, the "Chef de Service of the Bancs and Simulateurs Systeme." There was some discussion of the proposed European Space Agency (ESA) Exo-Mars mission, planned for 2011 or 2013. Pre-phase A for that mission is done, and it is now in Phase B. The rover under consideration is a 6-wheel machine with single body (as driven mostly by the mass limitation), similar to the rocker bogie used for Sojourner and MER. Stereo vision is the baseline for hazard avoidance, since it is light and involves no moving parts. A laser rangefinder has also been studied. The planned landing will occur within ±45 degrees of latitude and below 2 km (Mars Orbital Laser Altimeter (MOLA)-grid) altitude (as generally required for parachute-assisted landing).

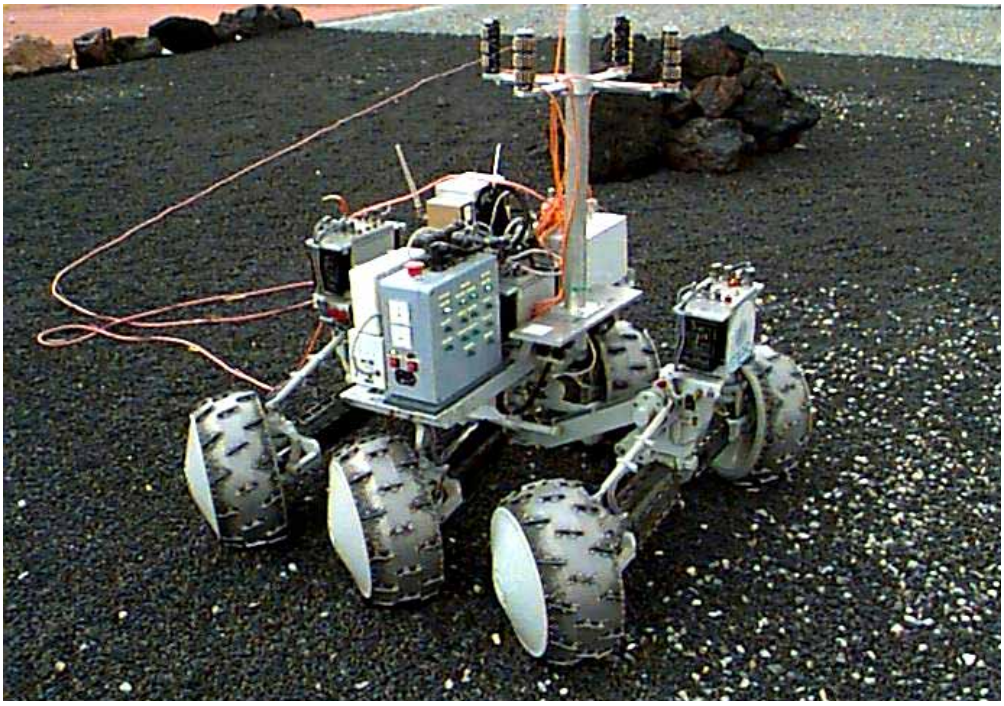

Figure C.9. CNES Mars Rover test vehicle IARES.

The test vehicle IARES has a passive roll axis front and back, and a powered roll on the center cab. The no-load speed is 50 cm/s in high gear, 10 cm/s in low gear. Typical loaded speeds are half that.

Their view is that CNES will develop the software, and the Russians will participate in developing the hardware. CNES has made extensive use of the Marsokhod rovers in the past. In particular, the Russians (VNIItransmash) have optimized the kinematics for the Exo-Mars mission chassis.

For hazard avoidance, the threshold to declare an object an obstacle is the step height based on the footprint of wheel and slope for axle (in many different rover positions)—they save the worst number. The path planner is not like MER in that the planner uses a two-stage pyramidal algorithm in which the first step consists of an "A" algorithm, the result of which is used for A* optimal path finding. The previous perceptions are merged with the current one and used for path planning. Their inertial measurement unit (IMU) is a concern because its mass is 10 kg, and it requires frequent recalibrations. They believe that visual odometry is better. They currently do sun sensing on every stereo cycle. They are considering use of landmarks as well as regular localization from orbiter.

There were a few people in the lab doing software development. There was a hardware development area nearby, including a small machine shop.

Site: **Cybernétix**
Offshore Division
Technopole de Chateau-Gombert, BP 94
13382 Marseille Cedex 13, France
http://www.cybernétix.fr

Date Visited: April 27, 2005

WTEC Attendees: A. Sanderson (Report author), Y. Zheng, J. Yuh, H. Ali

Hosts: Peter Weiss, Coordinator of European Programs, Offshore Branch,
Email: peter.weiss@cybernétix.fr

BACKGROUND

Cybernétix is a small company specializing in robotics and automation systems. Cybernétix has programs that focus on:

- Increasing productivity of production lines
- Improving product quality
- Replacing human intervention for difficult, dangerous, painful and unrewarding tasks

Cybernétix optimizes the design and the manufacturing of products, processes, equipment and systems through a global approach of automation and advanced robotics, and studies project feasibility and develops prototypes.

The Offshore Branch is focused on systems for ships and underwater applications including inspection, maintenance, and repair of deepwater facilities.

Overview of the Visit

Our visit to Cybernétix was hosted by Peter Weiss, the coordinator of European Programs, Offshore Branch. The visit included an overview of programs and a visit to laboratories and instrumentation at the Marseille laboratory.

OVERVIEW OF CURRENT ROBOTICS RESEARCH

Cybernétix activities in technology development include four major areas:

Deepwater Intervention

Recent and current programs include: deepwater intervention, inspection and maintenance, construction assistance, and monitoring.

Crawlers

SPIDER is a crawler for deep and shallow deployment with particular application to pipeline inspection and surveys. The adjustable weight and configuration makes it suitable for shallow, high current areas where traditional remotely operated vehicles (ROVs) are difficult to implement. The vehicle is 4.3 meters in length, 1.7 meters in width, and 2.3 meters in height, and weighs 1,800 kg with a remote power supply. The operating depth extends to 1,500 meters. The crawler supports sensor systems for visual, sonar and other inspections, and includes a telescopic zoom with pan and tilt camera.

Figure C.10. SPIDER crawler.

The PMS Pilot mining system for the recovery of polymetallic nodules works in waters 6,000 meters deep. The remote operated crawler is equipped with a pumping system to collect the nodules at the seabed, crush them and send the mixture to the surface. The PMS was developed in cooperation with the China Institute of Mining Systems (CIMR).

Figure C.11. PMS Pilot Mining System for subsea mining.

Figure C.12. Mining tool of PMS.

AUVs

SWIMMER is a hybrid system concept that includes an autonomous carrier vehicle, which is able to transport a standard ROV to a subsea docking station. Once docked to the station, the ROV can be controlled from the surface. The SWIMMER vehicle is 6.1 meters by 2.5 meters by 2.5 meters, and weighs 4,785 kg. The SWIMMER shuttle is operated like an AUV and moves toward a predefined approach point using an acoustic telemetry link to monitor and control the vehicle. The shuttle stabilizes 20–30 meters above the target location, and vertically lands onto the docking station with the help of a short-range positioning system. The shuttle locks onto the docking station and connectors are mated enabling the ROV to be powered and controlled through the umbilical. The ROV is then released from the shuttle and operated from the surface as an ROV.

Figure C.13. SWIMMER hybrid system concept.

ALIVE is an intervention autonomous underwater vehicle (AUV) able to execute telemanipulation tasks on subsea structures. This project is conducted jointly with Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER) and Heriot-Watt University.

Figure C.14. ALIVE vehicle.

Figure C.15. ALIVE vehicle with its hydraulic manipulator arm SAMM.

Typical applications of the ALIVE vehicle will include:

- Carrying out emergency inspection/intervention in case of environmental disaster (e.g. sunk tanker)
- Helping in rescue and salvage operations where the vehicle could be mobilized extremely rapidly (e.g. by helicopter) as opposed to divers or ROVs which need surface support
- Contributing to cleaning operations such as debris removal from protected sites without having to mobilize costly diving vessels where scuba diving is not possible (below 50 m)
- Carrying out site investigation in areas suspected to be polluted by radioactive materials or chemical weapons (where there is high risk for human divers)
- Recovering seabed samples to control sediment contents without having to operate costly intervention spreads that limit the duration of the campaign
- Operating subsea infrastructures such as a benthic station (to download data for example) or an oil wellhead (to actuate process valves) in a very cost-effective manner and with reduced impact on the environment (smaller surface vessel is used if any, and therefore provides reduced fuel consumption and lower pollution risk)

The ALIVE vehicle is 4 meters long, 2.2 meters wide, and 1.6 meters high, and weighs 3,500 kilograms. The propulsion is provided by five electrical thrusters. The navigation sensors include an inertial navigation system and Doppler velocity log for autonomous navigation and dynamic stabilization. A global positioning system (GPS) is linked to surface long base line (LBL) for underwater positioning. A doppler profiler is used for target approach. The SAMM seven degree-of-freedom (DOF) manipulator includes two hydraulic grippers for docking. The manipulator is preprogrammed for manipulation tasks and operated using a supervisory control mode during missions. Communication is provided by an Ethernet umbilical plus on-deck and high-reliability low data rate (100 bps) bi-directional acoustic communication for mission supervision. A high data rate (5 kbps) acoustic communication link is available for uploading compressed sonar/video images during manipulation tasks. The power is provided by pressure-balanced lead-acid batteries with 240 VDC, 40 kWh for thrusters and hydraulic power, and 24 VDC, 4 kWh for instruments. It is possible for a typical mission to last seven hours.

Figure C.16. Autonomous intervention of ALIVE in the Mediterranean in September 2003.

Figure C.17. ALIVE equipped with a landing SKID and scientific payload for autonomous sampling and monitoring.

ROVs

JUNIOR is a deepwater compact observation ROV rated to a 3,000 meter depth and dynamic positioning (DP) station-keeping capability. The small size of this ROV (0.65 meters by 0.45 meters by 0.33 meters) makes it convenient to deploy and maneuver. The principal application is to provide an observational capability for inspection or for monitoring of another working ROV.

Figure C.18. JUNIOR compact observation ROV rated for 3,000 meters depth.

Inspection and Maintenance

These programs include:

- MHC (Magnetic Hull Crawler) (for Inspection) is a robot that attaches magnetically to a ship's hull and moves over the surface performing inspections.

Figure C.19. MHC for underwater non-destructive testing (NDT) and visual inspections.

- ICARE is a remotely operated anchor chain cleaning and inspection system.

Construction Assistance

These programs include:

- Magnetic Hull Crawler (MHC) (for painting and cleaning) is a version of the magnetic attachment system that supports abrasive cleaning and painting.

Figure C.20. MHC for UHP cleaning of ship hulls.

Figure C.21. MHC for hull painting applications.

- SAPPS is a deepwater pipeline flushing, pigging, and hydrotesting system.

Monitoring

These programs include:

Girassol is a subsea monitoring and data collection system, including stress and strain measurements, riser tower dynamic behavior recording, and temperature recording.

Site: **DLR German Aerospace Center**
Deutsches Zentrum für Luft
Institute of Robotics and Mechatronics
Munich, Germany

Date Visited: April 27, 2005

WTEC Attendees: R. Ambrose (Report author), Y.T. Chien, B. Wilcox, D. Lavery, G. Bekey, V. Kumar

Hosts: Prof. Gerd Hirzinger, Tel: +49-8153-28-2401, Fax: +49-8153-28-1134,
Email: Gerd.Hirzinger@dlr.de

BACKGROUND FROM REMARKS BY PROF HIRZINGER

Prof. Hirzinger gave an overview of the Deutsches Zentrum für Luft (DLR) history and future plans for space robotics. The depth and breadth, quantity and quality of the work are first class. His organization has over 150 people, with a unifying basis:

> *Multi disciplinary virtual design, computer aided optimization and realization of mechatronic systems and man-machine interfaces (towards intelligent mechanisms, which react with their environment and model it).*

Throughout the work, there is attention to the close integration of mechatronics, merging mechanical and electrical engineering design. This is a holistic design and concurrent engineering approach.

PRIOR WORK

Rotex

The DLR's Rotex experiment was a major landmark in space robotics. The flight experiment positioned a small, light and fine arm in an intravehicular activity (IVA) experimental rack aboard the Space Shuttle. This experiment tested a mix of control modes, and demonstrated dexterous manipulation in zero gravity. Particulars of the experiment are:

- Flew in 1993
- Demonstrated ground control
- Flight led to the space ball product
- Five to seven second time delays
- Predictive simulation demonstrated to compensate for delay
- Shared control

The user told it to rotate, the machine felt the screw, and it advanced in helix autonomously.

Getex

DLR's participation in Japan's ETS VII free-flying space robot included advanced forms of teleprogramming and dynamic interaction experiments between the robot and carrier satellite.

OLEV (ORBITAL LIFE EXTENSION VEHICLE) OR CONEEXPRESS

A flight demonstration is now being proposed to rendezvous with a satellite and capture it by means of inserting a specialized end-effector into the nozzle and rigidizing. The overall approach is similar to the Defense Advanced Research Projects Agency (DARPA) Spacecraft for the Unmanned Modification of

Orbits (SUMO) project. A technology presentation was demonstrated the approach. Particulars of the proposed system include:

- Model-based servoing
- One camera feature matching for auto capture, six degrees of freedom (DOF)
- Three dimensional reconstruction with Wei, 1997, using radial basis functions
- Orbital recovery, Dutch space, Kaiser Threde project aiming at the "business case" of servicing in space
- In Phase B

Figure C.22. Industrial robot integrated as 0 g emulation for nozzle capture experiment.

TECSAS

DLR's seven DOF free-flying arm on a carrier satellite is supposed to approach a target satellite and grasp it either autonomously or via telepresence, perform a number of motions in compound state and finally deorbit the target.

DLR's work in dexterous limbs is particularly excellent. The lab has a long evolution of systems, as is almost always the case to achieve such depth. Three generations of hands and arms have been developed, with the following particulars:

Hands

- I, 1998, tendons,
- II, 2002, 13 DOF with good thumb, only 12 lines coming out
- 3 kg finger tip grasp
- 2005 DLR/HIT hand, a slightly simplified version of Hand II (1 kg fingertip) now to be commercialized by the company Schunk

Arms

- LWR II 1999 17 kg
- LWR III 2003 13 kg/20 kg load capability, high motion speed
- Dual access to joint avionics with end caps for maintenance
- Kuka will fabricate the arm

Prof. Hirzinger told us that the next generation will be an integrated forearm/hand with a modular upper arm. Motor design is a key part of this work, optimized for very high dynamics, but with low speed and single pole windings. Hand design has focused on fast motion, and has gone away from tendons and back to double differential bevel gears. The first hand with spindle cables was very high maintenance. Each finger has a six-axis load cell on the tip. DLR has formed an agreement with Schunk, which will come out with 20 new hands, at a cost of maybe €25,000.

Figure C.23. Lightweight, dexterous arm and hand.

Figure C.24. Close up of dexterous limb (left), dexterous arm being backdriven by hand (right).

Figure C.25. Latest generation dexterous arm and hand (left), dexterous hand being guided by vision to grasp objects (right).

ROKVISS

Robots have been given a too-high burden for manned space flight. DLR was able to prove its two joints would not be a thermal problem. Proved event upset proof design. The system has two black and white cameras. On reboost it was on the wrong side, and an antenna was blocked temporarily. This and other problems were overcome with extravehicular activity (EVA). Particulars include:

Tasks

- Part mating
- Contour following
- Experiments with artificial delay
- Educational program with students commuting fly over and aiming camera at the city

Figure C.26. Demonstration of on-orbit system, demonstrating force control in contact (left), Prof. Hirzinger and ground control demonstration (right).

Figure C.27. Tool making contact and sliding along edge.

The lab visit ended with a demonstration of mobile manipulation. An earlier version of the lightweight arm and hand were mounted on a mobile, wheeled base. The robot positioned itself in front of a door, and placed its hand on the door handle. The handle was a bar style handle, where the lever must be rotated from a horizontal axis downward to the vertical axis. As the arm pushed on the handle, the force control reacted to

the rotation, finding the axis of rotation and complying. This concluded a set of six real-time demonstrations, which is unusual. The fact that the six systems were of such a high caliber should be noted.

Figure C.28. Dexterous arm on mobile base, opening door (left), robot passing through doorway (right).

Site: **EPFL**
École Polytechnique Fédérale de Lausanne
Swiss Federal Polytechnic University at Lausanne
http://www.epfl.ch

Date Visited: April 26, 2005

WTEC Attendees: Vijay Kumar (Report author), G. Bekey

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Pierre Bureau, K-Team, Bluebotics, Email: pierre.bureau@k-team.com

OVERVIEW

The activity in mobile robotics at École Polytechnique Fédérale de Lausanne (EPFL) was started by Professor Jean-Daniel Nicoud. He was a pioneer in robotics, the developer of the Khepera robot and one of the founders of K-Team, the spin-off company that manufactures the Khepera and the larger Koala robots. The robotics effort at EPFL spans across three schools: Engineering Sciences, Information Sciences, and Life Sciences and involves four different laboratories, the first three in engineering sciences and the fourth in computer science.

Labs in the School of Engineering Science—These include the Laboratory of Intelligent Systems of Prof. Dario Floreano, the Laboratory of Autonomous Systems of Prof. Roland Siegwart and Dr. Aude Billard, and the Laboratory of Robotic Systems of Prof. Reymond Clavel.

Labs in the School of Informatics—These labs include the Non-linear Complex Systems Laboratory where Dr. Alcherio Martinoli is addressing sensor networks and collective robotics, and the Laboratory of Logic Systems where Dr. Auke Ijspeert carries out work on biologically inspired robots.

Labs in the School of Science—These include laboratories on neuroscience and genetics, brain prosthetics, and neuromuscular coordination. The effort in life sciences involves research in neural basis of sensorimotor coordination and applications to brain prosthetics, and as such, is not directly integrated with the other groups, although there are plans for integration in the future. A strength in this area is Henry Markram, who has many papers in *Science* and *Nature* on new models for synaptic behavior. This work, in particular, suggests future research directions in robotics and neural networks (instead of connectionist models).

Lab for Intelligent Systems
Director: Prof. Dario Floreano

The major goal of this lab is to develop systems that successfully mimic the ability of biological systems to self-organize and adapt to changing environments. The lab has thrusts in bio-inspired robotics, neuro-morphic control, and adaptive swarm robotics. Prof. Floreano is highly regarded for his work in evolutionary robotics. His book in this field is excellent (Nolfi and Floreano, 2004). In this lab we saw truly remarkable lightweight aircraft, weighing as little as 9 grams (including two 1 g cameras). The wings are covered with what appears to be a thin vinyl film. We saw a video of the aircraft in motion (also shown at ICRA 2005), showing that the vehicles had obstacle avoidance ability and turned as they approached the walls during indoor flight. An experimentation room contained a number of SwarmBots, mobile robots equipped with a grappling arm, developed jointly with Marco Dorigo in Belgium and other labs under an EU grant. The robots wander until they approach one another, and then one of them extends an arm to connect to a rim on the other, ultimately creating a chain or a cluster of robots. Another research activity concerns the evolution of cooperation and division of labor with sugar-cube robots that are required to cooperate in order to cluster objects of different sizes at a station (bottom image of Fig. C.29).

Figure C.29. Lightweight airplanes (left) and swarming robots capable of chaining themselves together (right), and evolution of cooperation and division of labor with sugar-cube robots that are required to cooperate in order to cluster objects of different sizes at a station (bottom).

Lab for Autonomous Systems
Director: Prof. Roland Siegwart; Assistant Prof: Aude Billard; Senior Researcher: Francesco Mondada

Prof. Siegwart is primarily interested in mechatronics: the design and fabrication of robots capable of operating in uncertain dynamic environments, and software for mapping and localization. His lab has been involved in the design and fabrication of a number of robots. One of them is a very small (a cube approximately 2 cm on a side) autonomous vehicle named "Alice." This robot is used in a number of projects at EPFL, including a Robocup team in this lab. Alice communicates with other robots by local infrared (IR); it also has radio frequency (RF) communication with a range of 6 m. The battery life lasts up to 10 hours.

One of the most interesting projects we saw in this lab concerned mixed societies of live insects (cockroaches) and small robots (InsBots) of approximately the size of a cockroach, but with a completely different body shape (basically a parallelopiped). The robots are sprayed with a chemical so that they approximate the smell of the insects. They are then accepted by the cockroach society and can influence the society behavior.

We also saw an "intelligent car," related to the German autonomous car project initiated by E. Dickmanns.

Figure C.30. Rovers being developed by Siegwart (left) and intelligent car (right).

The humanoid group is directed by Aude Billard, who is a Swiss National Science Foundation (SNF)-supported assistant professor. It is also part of the Autonomous Systems Lab. Her focus is on learning by imitation.

Aude Billard was a PhD student of Jean-Daniel Nicoud. Her lab concentrates on robot learning by imitation and other aspects of human-robot interaction. Several of the robots, developed by her several years ago, are dolls about 2 ft in height named Robota. The dolls are equipped with vision and movable arms and legs, which they use to attempt to follow the movements of a teacher. She also has a larger humanoid robot. These robots are intended for educational use with children as well as for therapeutic applications with disabled children.

Figure C.31. Robota (left) and experiments on imitation with the Fujitsu Humanoid for Open Architecture Platform (HOAP) (right).

Laboratory of Robotic Systems—Director: Prof. Raymond Clavel

Prof. Clavel is a highly respected investigator who has published extensively with patents on parallel mechanisms (see below). Unfortunately, because of time constraints, we were not able to speak to him or his co-workers.

Figure C.32. Clavel's Delta Robot.

Laboratory of Non-linear Complex Systems, Group of Sensor Networks and Robotics
Director: Alcherio Martinoli

Dr. Martinoli's interests are in sensor networks and swarm robotics. The students in this lab are involved in a number of interesting projects. A swarm project involved a large number (perhaps 20 of the small Alice robots developed at EPFL in Siegwart's lab), moving randomly in a space that also included 10 or 12 uniformly spaced barriers. When a robot reached a barrier it would follow it to the end, and then move randomly. The study concerned the relation between robot parameters and their ability to find and follow all the barriers in the field while performing inspection. He was interested in bio-inspired behaviors in swarming.

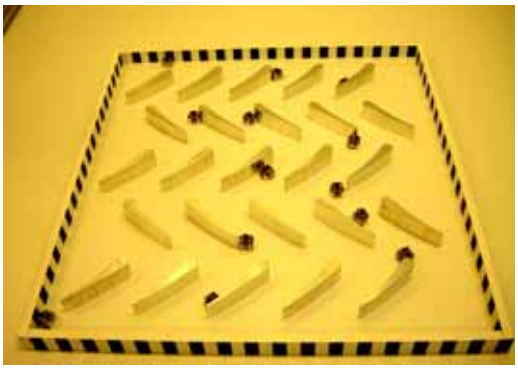

Figure C.33. Alice robots being used to study learning for microinspection.

Laboratory of Logic Systems, Bio-inspired Robotics
Group Director: Auke Ijspeert

Dr. Ijspeert is a Swiss National Science Foundation assistant professor with interests in biologically inspired robotics, at the intersection between computational neuroscience, nonlinear dynamical systems, and adaptive algorithms (optimization and learning algorithms). His focus is on locomotion of modular robots. Unfortunately because of time constraints, we could not visit his lab.

TECHNOLOGY TRANSFER

EPFL has an excellent track record of technology transfer with six successful spin-offs in robotics-related fields over the last ten years. We visited two of the six spin-offs, both addressing mobile robot applications. The first, K-Team, is catering to the needs of the research community and universities, and develops small robots for cooperative robotics and swarm applications. The second, Bluebotics, is developing navigation technology for service robotics applications.

We also saw the products of another spin-off, Cyberbotics, which provides simulation environments for mobile robotics. Their product Webots 4 allows the user to rapidly model, program and simulate mobile robots with physically correct dynamics. To support mobile robotics, they provide libraries of actuators and sensors, the infrastructure to simulate communication, and thus the tools to simulate multiagent systems. Alcherio Martinoli's group uses this software to simulate controllers for automated cars (for example, lane change maneuvers).

EPFL policies appear to be more liberal, faculty friendly, and supportive of technology transfer and new ventures in many ways than other laboratories we visited in Switzerland and Germany.

1. They have a facility on campus to incubate new ventures. Although the rent for this space appears to be higher than what is available off campus, it has the benefit of being close to EPFL labs allowing collaborations during the development of the spin-off.
2. EPFL keeps a much smaller fraction of the royalties or the equity in start-ups compared to U.S. universities. Usually this figure is less than 10%.
3. The overhead rate on grants from industry is usually between 6% and 26%.

Figure C.34. A humanoid platform at Bluebotics.

REFERENCES

Nolfi, S. and D. Floreano. 2004. *Evolutionary Robotics: The Biology, Intelligence, and Technology of Self-Organizing Machines*. Cambridge, MA: MIT Press.

Site: **ETH**
Swiss Federal Institute of Technology, Zürich
Eidgenössische Technische Hochschule (ETH)
Institute for Robotics and Intelligent Systems (IRIS)
Rämistrasse 101
CH-8092 Zürich, Switzerland

Date Visited: April 25, 2005

WTEC Attendees: V. Kumar (Report author), G. Bekey

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BACKGROUND

The Institution

Eidgenössische Technische Hochschule (ETH) was founded in 1855. It is considered one of the 10 strongest universities in engineering in the world. Twenty-one ETH professors have received Nobel Prizes, including Einstein and Rontgen (the discoverer of X-rays). The Zürich campus has 330 professors, divided among 17 departments. It has a total of about 12,000 students (including about 2,000 graduate students); about 500 complete their doctoral thesis each year. An MS program is now being started. The Institute for Robotics and Intelligent Systems (IRIS) is in the Mechanical Engineering and Mechatronics Dept.

IRIS is directed by Prof. Brad Nelson who was recruited from the University of Minnesota over two years ago. As typical in European universities, Brad is only professor in the Institute, and he directs a total staff of 18, including a number of researchers, engineers and a staff person. He received a PhD from Carnegie-Mellon University (CMU) in 1995. He has a very strong research program mainly concerned with microrobotics, biomicrorobotics and nanorobotics.

The IRIS program is divided into three areas:

1. Teaching
2. Microrobotics
3. Nanorobotics

Education

The teaching program currently includes three courses:

1. Intro to robotics and mechatronics (BS level)

   How to control an arm, read encoders, etc. The course is hands-on; students construct a two degree-of-freedom (DOF) manipulator.

2. Theory of robots and mechatronics

   This is a pretty standard course.

3. Advanced robotics and mechatronics

   Competition with mobile robots, emphasizing problem solving with hardware and software. They developed their own mobile platform, but also evaluate ActivMedia and Evolution Robotics.

Microrobotics and Biomicrorobotics

This thrust focuses on developing intelligent machines that operate at the micron and nanometer length scales. Examples of research projects are briefly described.

Microrobotics for handling biological cells involves the use of vision-based manipulation augmented by force sensing and the development of a microelectromechanical systems (MEMS)-based multi-axis force sensor. The force sensor (8 kHz bandwidth, 1 μN accuracy, 1 μN resolution) is unparalleled. An example of a driving application is the study of embryo properties by biologists, and in particular, the mechanical characterization of embryo membranes.

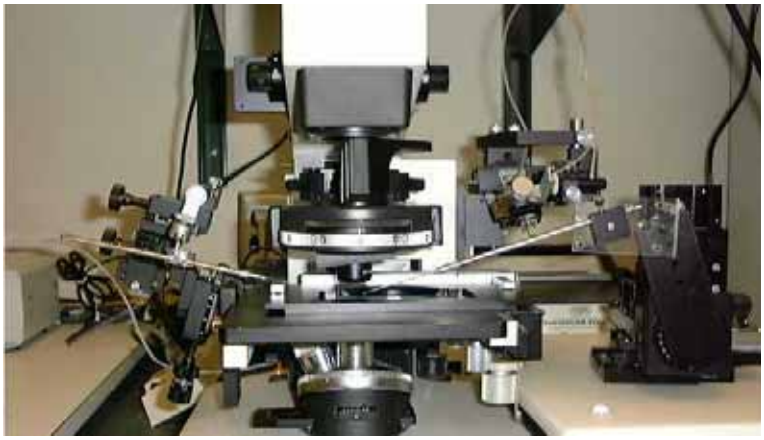

Figure C.35. A probe station with two micromanipulators and a microscope for biological cell handling.

Another project involves the study of fruit flies and the mechanics of flight. Dr. Nelson works with biologists interested in flight muscles of insects, and performs experiments with fruit flies, whose wings beat at 200 Hz. They use MEMS sensors attached directly to the fly's muscles. The fly is approximately 3 mm in length, and wing forces are around 35 μN with a 10 μN weight.

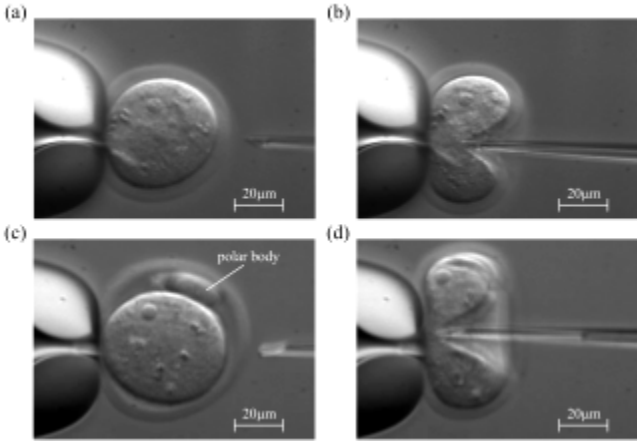

Figure C.36. Investigation of the mechanical properties of the cell embryo

Dr. Nelson is interested in microrobots implanted in the body (e.g., floating in the bloodstream). His lab has developed methods for magnetic steering of microrobots using external power. The microrobots they use are 0.8 mm (800 microns) in length, microassembled. They are exploring ultrasonic sensing for localization of microrobots in the bloodstream.

NANOROBOTICS

A second area of work is nanorobotics. The basic goal is to move microrobot research to the nanometer scale. Dr. Nelson and his co-workers are interested in building actuators and sensors in the range of 1–100 nm. They have active collaborations with the FIRST Center for Micro- and Nanoscience and the Paul Scherrer Institute. The work includes fabrication, control and characterization of telescoping multiwall nanotubes, the study of field emission of telescoping carbon nanotubes (CNTs), and the dielectrophoretic nanoassembly of nanotubes onto nanoelectrodes.

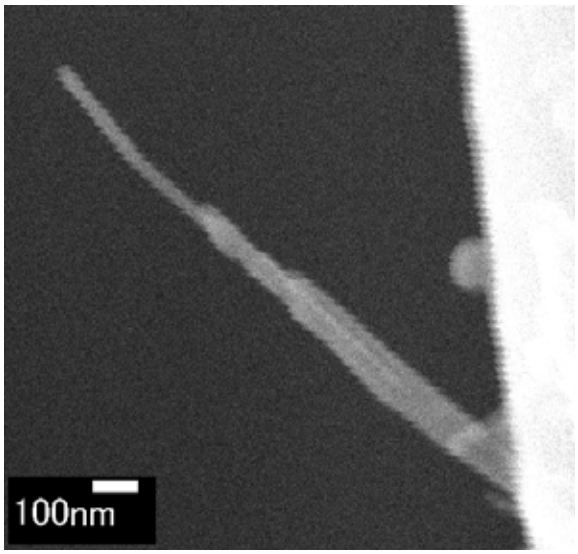

Figure C.37. Telescoping carbon nanotubes.

A particularly impressive project involves the fabrication of nanocoils made of silicon 30 microns long, 20 nm thick. These nanocoils have a little more than 0.02 N/m stiffness for four to five turns (compared to 1 N/m stiffness for a silicon tip).

Dr. Nelson's believes the challenges in this area are truly robotics (and not physics- and chemistry-based) problems. Much of the lab's interests and goals can be viewed as motion planning, integration from multiple sensors, and controlling motion in high-dimensional, unstructured environments.

The Academic Environment

When Dr. Nelson arrived at ETH he was given a start-up package of about $1.5 million and 7½ positions funded by the university (including his own). In addition he receives about 100,000 Swiss Francs annually (about $90,000) for expenses such as travel and supplies. He also has research support from the European Community and from the Swiss National Science Foundation. Salary increases for professors are uniform and independent of performance. If a professor gets industrial support, the university matches it.

The teaching load is very light: a professor only teaches about 2 to 2½ hours per week.

In the introductory course, for example, Dr. Nelson only gives the opening lecture; his assistants do the rest. There is very little pressure on the students. They have no homework or exams. However, each student is given an oral exam at the end of the semester. The students perform very well on these exams because they are highly self-motivated and do not depend on external pressure to study. However, they are not used to the U.S.-style lab courses that require much more work.

Technology Transfer

The group is actively engaged in protecting intellectual property and filing for patents. They are careful about publishing before filing for patents. (Unlike the U.S., researchers do not have a year to file for a patent following disclosure). The patents are owned by ETH if they pay for it, but the researchers can pay for the patenting process and own it.

Dr. Nelson has an extremely talented group, some of whom are U.S. graduate students. In fact, he had an outstanding graduate student at Minnesota who later worked at Honeywell, then could not get a visa to return to the U.S. following a visit to India. That student is now pursuing a PhD at ETH—a big loss for the U.S.

Site: **Fraunhofer Institute – Production Systems and Design Technology**
Fraunhofer Institut Produktionsanlagen und Konstruktionstechnik (IPK)
Pascalstrasse 8-9, Berlin, Germany

Date Visited: April 28, 2005

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BACKGROUND FROM REMARKS BY PROF LÜTH

Dr. Lüth gave the group an overview of the Fraunhofer Institute's operations and his personal background. The Fraunhofer Institutes are intended to complement the basic research underway at the Max Planck institutes. As such, they receive about 25% of their funding from corporate sponsors. The Berlin institute is organized into four groups: Production Systems, Automation Technology, Virtual Product Creation, and the Medical Technology group led by Dr. Lüth. The Automation Technology group built the control system for the Rotex Experiment (described in the DLR site report). The Virtual Products group has a visualization center like the U.S. "caves."

MEDICAL TECHNOLOGIES

The Medical Group was founded in 1986. It has 441 employees, with an operating budget of about €23 million each year. Within this, the Medical Devices team has 25 people, focused on the goal of providing the appropriate functionalities that utilize a common, unchanged sequence of surgical operations. Towards this end, the team has worked towards assistive rather than surrogate systems.

The key technologies being developed by this team are navigation, robot design/mechanisms, and navigated control. The term "navigation" was used in a similar way to the term "real-time registration," providing high-bandwidth data to localize a tool with respect to anatomy, in a coordinate frame that is shared by a 3D model. The 3D model is produced using X-ray or magnetic resonance imaging (MRI) methods, including a fixture that has an attachment for a registration marker.

A unique approach developed by Lüth's group shares control of the tissue removal tool between human and robot. The early work had failed to match the speed goals for surgeons, having used an industrial robot with too low a speed and too much inertia (Mitsubishi PA-10 seen in the lab). A more successful approach has been to allow the human to hold the tool, but only enable its high-speed cutting motor when it is positioned in the 3D zone that has been pre-planned for removal. As the tool leaves this region, the motor is stopped.

Notes for Specific Surgeries

Ear example

- Add facial prosthesis ear
- Install mounts below skin
  - Drill and tap
- Place ear to ±1 mm
- Surgeon moves arm, pushed by hand
- ISO 9000 certified
- World's first robot for head surgery
- Developed for a non-cooperative use (surgeon)

Spine surgery

- Decompression of the vertebrae
- Uses Mitsubishi PA-10
- Arm found to be too slow, needs more power, but that is dangerous
- New idea
  - Replace arm, use instruments on surgeon's arm
  - Power off tool if in bad location

Multi-step Operations

- Photography
- Place markers
- Redundant calibrations
- Displays
  - Glasses cause fatigue (change in focus from hand distance)
  - Went to 4" displays
  - Audio cues as tool approaches dangers
  - Animated tool changes color (green is good)

PHOTOS FROM LAB TOUR

Figure C.38. Integrated manufacturing cell with Kuka robots and NC tools (left), parallel mechanism and integrated seat (right).

Figure C.39. Human motion augmentation system for lifting heavy payloads (left), human offloading and tracking system for motion studies (right).

Figure C.40. Multiple generations of intelligent registration equipment (left), remote center mechanism for 3D imaging (right).

Site: **Università di Genova**
Dipartimento di Informatica Sistemistica e Telematica (DIST)
Via all'Opera Pia, 13
16145 Genova, Italy

Date: April 29, 2005

WTEC Attendees: Y.F. Zheng (Report author), A. Sanderson, J. Yuh, H. Ali

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BACKGROUND

The University of Genova is one of the most active institutions in robotics research in Italy, and one of the two Italian universities that the assessment panel chose to visit. Research activities are primarily concentrated in the Department of Communication, Computer and System Sciences (DIST). Our visit to the institutions consisted of touring five individual laboratories, each led by a faculty member.

Research Activities at University of Genova DIST

The Laboratory for Integrated Advanced Robotics (LIRA) led by Professor Giulio Sandini

The laboratory has several projects going on; three will be described here. The first project studies a robotic arm equipped with a five-finger robotic hand and two robotic eyes. The arm has seven degrees of freedom (DOF), and the eyes have eight. The primary purpose of the project is to study the sensor-motor control scheme of human beings and to implement it on the robotic arm. Questions like, how a human handles the object when he/she sees it, and how a newborn learns to grasp objects, etc., are studied. Research topics also include grasping according to the shape and function of objects. The project is quite new and is sponsored by the Toyota Motor Company of Japan. During the visit, we were not allowed to take pictures. According to the host, an identical robot arm has been installed at a Toyota laboratory in Brussels.

The second project is related to a polarized eye that has a fish eye view. The main feature of the eye is that the central area has a high resolution which goes down along the radial directions. The third project is called MIRROR, which studies the sensor-motor control mechanism of human beings, and applies it to robot manipulators for visual and grasping interaction. For that project, a PUMA arm, equipped with robotic hands and eyes, has learned to grasp objects with different shapes (Fig. C.41).

The Mechatronics and Automatic Control LABoratory (MACLAB) led by Professor Giorgio Cannata

The laboratory focuses on robotic components and mechanisms that improve the performance of robots. The first robotic device is a robotic hand that is equipped with tactile sensors. The sensors are based on silicon-type soft material that can detect the touch to its surfaces. The second robotic device is a pair of robotic eyes each with four DOF (Fig. C.42). The eye design has been driven by the goal of emulating the kinematics and muscle/tender actuations of human eyes. The idea is that human eyes have six muscle/tenders to control the eyes, but four of them play primary roles. The group thus uses four tenders sliding along the eyeball to control the motion of the eyes and to verify that four tenders are sufficient for the motion of the robotic eyes.

Figure C.41. Sensor-motor control of robotic arm.

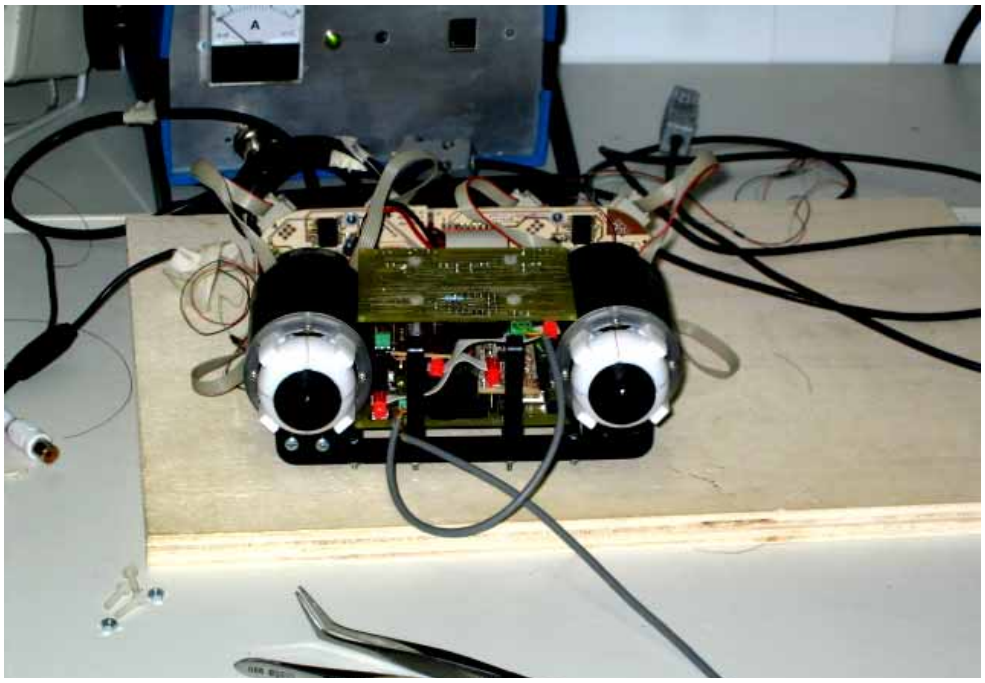

Figure C.42. A pair of robotic eyes.

The Laboratory of Robotics and Automation led by Professor Giuseppe Casalino

The laboratory is the largest among all the five groups and is involved in a number of topics including the following:

a) Coordination of two robot manipulators (Fig. C.43).

b) Fine manipulation planning and control for fragile object grasping using robotic hands.

c) Learning control which improves the performance of robotic hands through repeated executions to reduce errors in motion.

d) Visual servoing and active vision based on stereo-vision for robot to work in unstructured environments.

e) Teleoperation for presence of human operator in a robotic system for optimal performance.

f) Closed loop control of nonholonomic systems for navigation of car-like vehicles and underwater vehicles.

g) Team control of multiple mobile robots for increasing the effectiveness of coordinating robots in performing certain tasks.

Figure C.43. Two coordinating robots.

The Laboratorium led by Professors Pietro Morasso, Renato Zaccaria, Vittorio Sanguineti, and Antonio Sgobissa

The laboratory works on mobile robotics, computational neuroscience, neural control of movement and rehabilitation, and neuroengineering. In the laboratory, we saw a manipulator interacting with human arms with different impedance settings for haptic control. The activity was supervised by Professor Morasso who coordinated with Professor Neville Hogan of MIT. The latter has been in the field of impedance control for a long time.

The research efforts of the Laboratorium have also been on outdoor navigation using vision sensors for localization and mapping. The visiting team saw a video that showed a mobile robot moving autonomously in an outdoor environment. At the time of visit, the robot was to be tested at an airport for the purpose of autonomous ground transportation there.

SUMMARY

The University of Genova has a wide scope of research activities in robotic research. The activities are primarily conducted in the Department of Communication, Computer and System Sciences. Research activities are distributed in five laboratories each led by faculty members. Notable research activities include sensor-motor control; smart robotics devices such as eyes and hands; mobile robots; coordinating robots; human-robot interaction; and sensor and computer vision.

Site: **Universitat de Girona**
Grup de Visió per Computador i Robòtica
Departament d'Electrònica, Informàtica i Automàtica
Institut d'Informàtica i Aplicacions
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Date Visited: April 22, 2005

WTEC Attendees: A. Sanderson (Report author), J. Yuh

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BACKGROUND

The University of Girona was established in 1991 as a regional public university in Catalonia, Spain. The University of Girona has seven major schools: Faculty of Sciences, Faculty of Business and Economic Sciences, Faculty of Education Sciences, Faculty of Law, Faculty of Arts, Advanced Polytechnic School and University School of Nursing, as well as a number of research and educational centers and institutes that run research programs and support doctoral programs. The University includes 18 departments that organize the degree programs. The Department of Electronics, Computer Sciences and Automation includes the faculty that are most involved with robotics research.

Overview of the Visit

Our visit to the University of Girona included a meeting with Dr. Joan Batlle, the rector of the university and former director of the Computer Vision and Robotics group. Professor Batlle was very helpful and provided a perspective on the growth of this research area at the University, as well as the plans for growth of research at the university as a whole. Funded research programs in interdisciplinary areas are a strategic priority of the university. In addition, the province of Catalonia has a priority for growth of modern technologically based industries. A technology incubator is being built near the university campus, and the new underwater robotics laboratory is located at that site.

OVERVIEW OF CURRENT ROBOTICS RESEARCH

The Computer Vision and Robotics group develops real-time computer vision and image processing systems with applications such as object, pattern, color and shape recognition and tracking of mobile objects. Fields of application include underwater robotics, biomedicine and security-related systems. Systems are developed to improve the autonomy and mobility of disabled people, while others are used with autonomous and teleoperated vehicles for industrial and research applications. Garbí is an underwater robot developed in collaboration with the UPC. Garbí is used for underwater observation and to collect samples. The autonomous and teleoperated robots have transport, industrial and security-related applications.

Underwater Robotics Laboratory

In the experimental work of the laboratory, two underwater robots have been developed. The first one, Garbí, was conceived as a remotely operated vehicle (ROV) for inspection purposes. More recently effort has centered on building control architecture for autonomy, converting Garbí to an autonomous underwater

vehicle (AUV). The second prototype, URIS, was designed as an AUV. The URIS robot has very small dimensions permitting experimentation in small water tanks, and therefore, fast testing of the systems. These two platforms are used to investigate several research activities in underwater robotics. The laboratory has its own experimentation center including a swimming pool and an underwater supervision and control room. The main research topics that are currently being studied in the Underwater Robotics lab are: control architectures for autonomous and teleoperated robots; artificial intelligence techniques applied to robot control; robot dynamics and identification; real-time 3D hardware in the loop simulation; simultaneous localization and map building; and mission control.

Figure C.44. Garbí AUV.

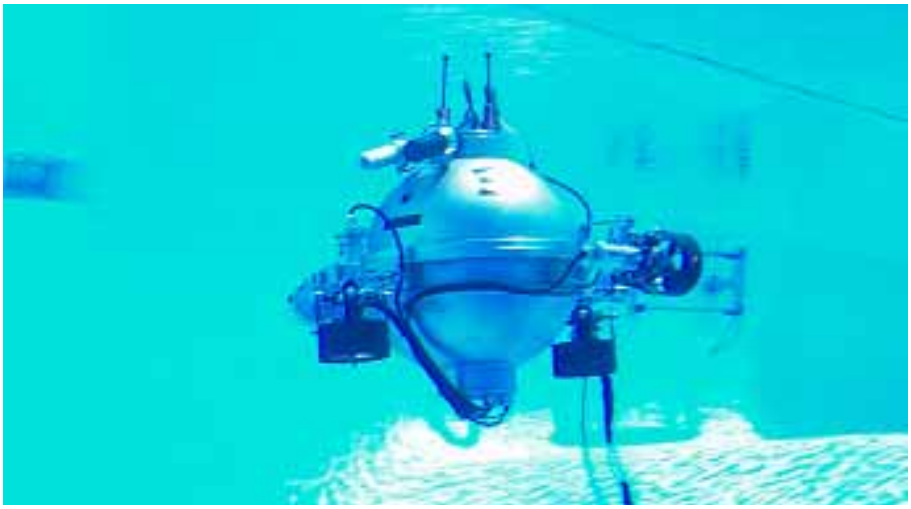

Figure C.45. URIS underwater vehicle at the experimentation center.

One application of this research is the use of an ROV for the inspection of a hydroelectric dam. This is a joint project between the Computer Vision and Robotics Group of the University of Girona (UdG) and the Research, Development and Technological Transfer Center (CIFATT) of IPA Cluj in Romania. The experiments involved the inspection of the hydroelectric dam of Cluj and were carried out during November 2002 with the aim of evaluating the viability of the underwater robotic technology for wall dam inspection. The experiments were used to collect video data about the wall of the dam as well as to study the desired characteristics of an ROV for this kind of application.

The Garbí was first conceived as an ROV for exploration in waters up to 200 meters in depth. Control architecture is being implemented to transform this vehicle into an AUV. Garbí was designed with the aim of building an underwater vehicle using low-cost materials, such as fiberglass and epoxy resins. To solve the problem of resistance to underwater pressure, the vehicle is servo-pressurized to the external pressure by using a compressed air bottle, like those used in scuba diving. Air consumption is required only in the vertical displacements during which the decompression valves release the required amount of air to maintain the vehicle's internal pressure equal to the external. This vehicle can also be equipped with two arms, allowing the vehicle to perform object manipulation tasks through teleoperation. The vehicle incorporates four thrusters: two for performing horizontal movements (yaw motion) and two for vertical movements (Z-axis). Due to the distribution of weight, the vehicle is stable in pitch and roll. For this reason the vertical and horizontal movements are totally independent. The robot has a color camera fixed to the front. The dimensions of Garbí are 1.3 meters in length, 0.9 meters in height and 0.7 meters in width. The vehicle has a maximum speed of 3 knots and its weight is 150 kg.

The URIS is an ROV developed in this laboratory, and is used extensively as a platform for underwater vision experiments. The URIS is 35 cm in diameter and weighs 35 kilograms. The URIS is controlled through an umbilical that provides power, Ethernet communications, and video. It has three degrees of freedom of motion, and supports two video cameras, altimeter, pressure, and differential global positioning system (DGPS) sensors.

Underwater Vision Laboratory

Research is being conducted on the application of computer vision methods to underwater systems. Two different projects, developed under European and Spanish Govt.-supported funding, are focusing on the development of photo mosaics. A mosaic is a composite image that incorporates many individual images into a full visual map. Initially, building photo-mosaics of the ocean floor was initiated in the lab to serve as motion sensor to let the vehicle know how it is moving. This proved to be a very efficient and low-cost sensor to enable station-keeping or local navigation of the vehicle. Simultaneous localization and mapping (SLAM) and sensor fusion techniques are used to integrate measurements from the different available sensors and optimally estimate the trajectory of the robot. The national project aims to simultaneously estimate the vehicle motion and map regions with high relief and topographical variations. On the other hand, the European project aims to build large-scale photo-mosaics for characterizing and monitoring hydrothermal vent environments along the Mid-Atlantic ridge close to the Azores archipelago. The photo-mosaics obtained after the estimation of the vehicle trajectory have proved to allow the geological analysis of the ocean floor structure, obtaining a global viewpoint of the interest site. At the same time, underwater photo-mosaics provide high-quality images of georeferenced areas for the study of biological communities. The lab has developed a library to efficiently handle large-scale mosaics, with more than 40 billion pixels, using a standard computer. Sensor fusion techniques are being developed to combine navigation data, images of the ocean floor, seafloor bathymetry and acoustic imagery.

Mobile Robotics and 3D Perception Laboratory

The main objective of this laboratory is to the study the geometrical relations that allow the perception of the three-dimensional world by means of computer vision. Research on algorithms based on projective calibration theory is one theme of this work.

Basic Research Topics in the Computer Vision and Robotics Group

Simultaneous localization and map building develops and implements spatial localization and mapping in support of the navigation of underwater robots.

Mission Control acts as the interface between the user and the control system. Work in this field is focused on the development of different strategies and the study of the properties of planning and reliability. Future work will include the design and the development of mission control component for robots developed in the laboratory.

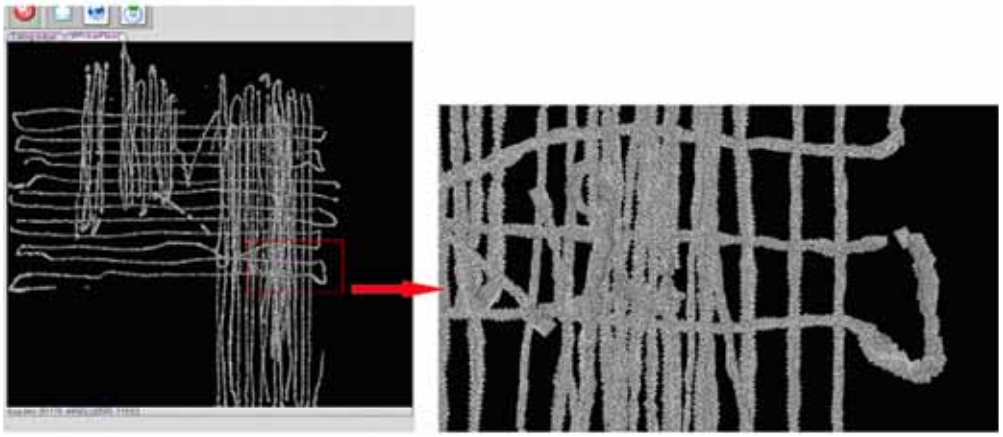

Figure C.46. Georeferenced mosaic of underwater optical images of the Lucky Strike area (Mid-Atlantic Ridge), covering an area of more than 1 sq. kilometer. Source images provided by Woods Hole Oceanographic Institution (WHOI) from the Lucky STRike Exploration 1996 (LUSTRE 96) cruise.

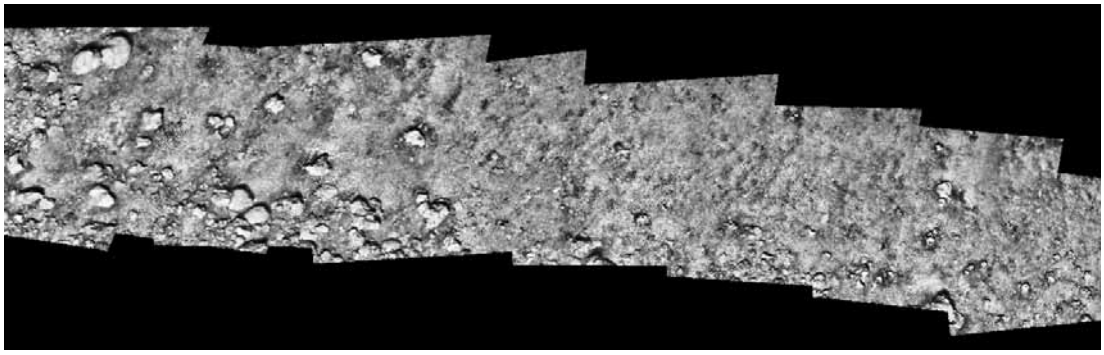

Figure C.47. Detail of the Lucky Strike photo mosaic at a higher resolution.

Multi-AUV 3D Graphical Simulator supports development and programming of AUVs**.** The use of a real-time simulator can help close the gap between off-line simulation and real testing using the already implemented robot. A real-time graphical simulation with a "hardware in the loop" configuration supports the testing of the implemented control system running in the actual robot hardware. This group has designed and implemented NEPTUNE, a multi-vehicle, real-time, graphical simulator based on OpenGL that allows hardware in the loop simulations.

Artificial Intelligence techniques are applied to robot control in support of guidance behaviors for the robots. These methods were initially manually implemented using fuzzy logic, and now use machine learning techniques for the online, automatic learning of the sense-action mapping used to implement the robot behaviors. Reinforcement learning (RL)-based behaviors support the Semi-Online Neural-Q learning algorithm (SONQL). In this algorithm a neural network is used to solve the generalization problem, and a learning sample database is included in order to avoid the interference problem.

The study of the *hydrodynamic equations of motion* describes the underwater movement of the robot and forms the basis for control. Thrusters have been modeled using an affine model and take into account the interaction with the robot hull. For the identification of the Garbí and URIS models, several uncoupled experiments were carried out. Then, the main dynamic parameters for each degree of freedom, were identified using the uncoupled equation of motion, then were extended to the full hydrodynamic equation.

Site: **Heriot-Watt University**
Ocean Systems Laboratory
Department of Electronic and Computer Engineering
School of Engineering and Physical Sciences
Edinburgh, EH14 4AS,
http://www.ece.eps.hw.ac.uk/research/oceans/

Date Visited: April 25, 2005

WTEC Attendees: A. Sanderson (Report author), Y. Zheng, J. Yuh, H. Ali

Hosts: Dr. David Lane, Professor of Electronic and Computer Engineering,
Email: D.M.Lane@hw.ac.uk

BACKGROUND

Heriot-Watt is the eighth oldest higher education institution in the U.K. It was established in its current form in 1966, but its origins date back to 1821 through the School of Arts of Edinburgh. The programs include research areas in engineering and physical sciences and in management and languages. The University was recently ranked third in Scotland by the *Financial Times*. Major research initiatives are concentrated in focal areas including photonics and new optics-based technologies, business logistics, technical textiles, advanced robotics, nano-science and technology, proteomics and nuitrition microsystems, biomimetics, virtual reality and engineering design. The Edinburgh campus is home to Europe's first research park, which has created 1,000 jobs and has an annual total revenue of £63 million. There are facilities for new business start-up companies at the Edinburgh and Scottish Borders campuses.

Overview of the Visit

The visit was hosted by Professor David Lane, Director of the Ocean Systems Laboratory. An overview of programs and tour of the laboratories provided a comprehensive review of both basic research and key applications under development at the laboratory.

OVERVIEW OF CURRENT ROBOTICS RESEARCH

The Ocean Systems Laboratory (OSL) is a center for research, development and exploitation of acoustic, robotic and video-imaging systems, with particular emphasis on 1, 2 and 3D signal processing, control, architecture and modelling. With a staff of 36, the laboratory works internationally with industry, government and research organizations. It aims to develop novel technology for subsea, defense and other industry applications, and to actively educate students in these areas.

Computer vision, sonar and image processing are major research themes that the laboratory has been actively developing to automate deepwater operations. In recent years, the OSL has been involved in using sonar systems to track and classify objects, to provide reactive path planning and to perform concurrent mapping and localization. In the field of vision the OSL has developed algorithms for reconstructing 3D shapes from 2D image sequences and for underwater robot position control from real-time processing of video data (visual servoing). Image processing techniques have been exploited to automatically recognize interesting seabed features and to fuse sonar and laser range data.

Key projects that were discussed at the site visit included: AMASON, Autotracker and ALIVE.

AMASON

AMASON (Advanced MApping with SONar and Video) supports research, implementation and evaluation of a modular, reconfigurable multi-sonar and video sensor system, with advanced data processing algorithms

implemented within a geographic information system (GIS). The goal is to develop a plug-and-play system that will be readily deployable from remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs).

Figure C.48. Mosaicing of multi-image dataset shows detailed structure on ocean floor.

Major topics of research are rapid object and region characterization, classification and mapping/mosaicing in large concurrent data sets from video, sidescan, parametric sub-bottom and multibeam bathymetric sonars. Fusion of feature and symbolic data will be used to improve confidence in detected events of scientific interest. The feature detection, classification and data fusion algorithms will be implemented within a GIS environment. Raw and refined data will be georeferenced, and legacy data sets could be used to improve scientific monitoring and prediction. The goal is to implement the software suite on portable notebook computers. A modular systems architecture will ensure a scaleable and reconfigurable system.

Scientific validation on trawling impacts, sediment stability and coral carbonate mounds are examples of implementation of this system.

Autotracker

The need for fast communication and transport of energy has resulted in an increasing amount of subsea installations (cables and pipelines). The subsea network is especially developed in certain geographic areas including the European seas (Baltic and North Seas, Atlantic Ocean and Mediterranean Sea), Gulf of Mexico and East Chinese Sea. Several parts of these areas are located in deep water (500–3500 m).

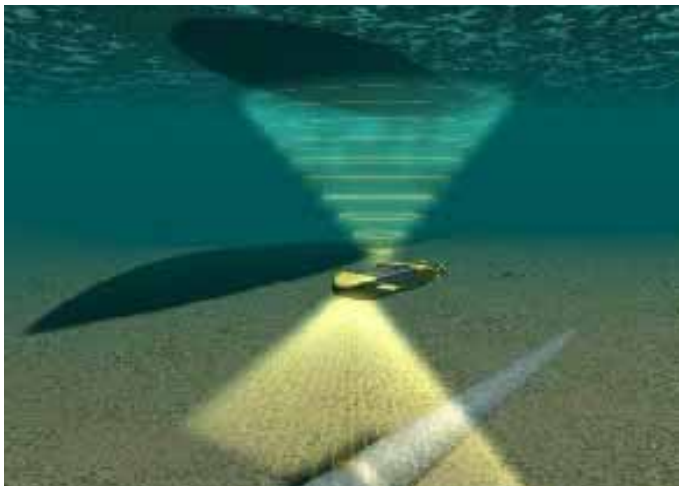

Figure C.49. Simulation display of the Autotracker system, integrating imaging and mapping information to track a pipeline on the ocean floor.

To maintain the installations in safe and reliable condition, preventive maintenance inspections are needed. Current inspection technology deploys shipboard monitoring sensors either from a free-flying surface-towed platform (ROTV), which significantly degrades in quality, or from an ROV, which requires a survey vessel with a large crew. Shipboard inspection technology is not economically effective in water depths greater than 500 m, and with oil exploration and development activity now moving into even deeper areas, an alternative approach is required. The Autotracker system under development would link imaging and mapping, route surveys prior to installation of pipelines and cables, with inspection of the subsea installations during and after the installations.

ALIVE

Underwater interventions below 350 m or in harsh conditions (strong currents for example) are now conventionally performed by ROVs to carry out various tasks such as inspection, maintenance, object collection, etc. Such ROV operations are heavy and costly due to the necessity of having a sophisticated support vessel that has to remain on station above the ROV.

The project is conducted in conjunction with Cybernétix (Marseille, France) and Institut Français de Recherche pour l'Exploitation de la Mer (French National Institute for Marine Science and Technology, IFREMER) (Toulon, France), and a detailed description of the vehicle is included in the Cybernétix site report. This program will develop a light intervention vehicle, autonomous in energy and piloted from the surface through a bi-directional acoustic link, capable of reaching a fixed target on the sea bottom (e.g. wellhead, benthic station, wreck, pipeline, etc.) and supporting a tele-manipulation unit. Typical tasks will be routine inspection and light maintenance, as well as object collection. This vehicle would have no physical link with the surface and could be supported by a light and fast support ship. The OSL contributes to this collaborative program through development of underwater inspection and intervention.

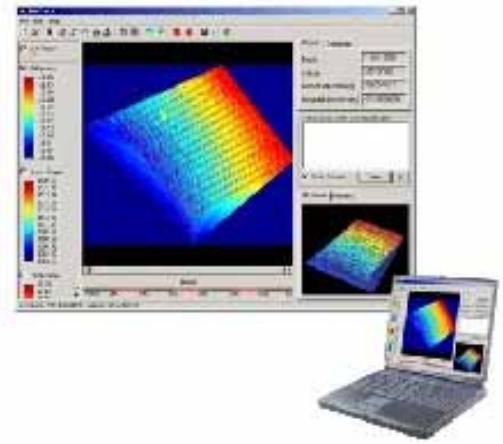

Figure C.50. The SeeTrack system provides a comprehensive applications environment for acquisition and analysis of undersea data.

Commercialization

A commercial company, SEEByte Ltd (http://www.seebyte.com), is a major participant in many of the projects initiated at the OSL at Heriot-Watt.

Key products that have evolved from OSL research and which are provided through SeeByte include:

1. SeeTrack is a post-processing tool for rapid on-site data reduction, analysis and data fusion of sensor data, including sidescan, forward look sonar, imaging sonar and video. It is a modular system and is designed to perform on both notebook and desktop environments. It has been employed during 2000 and 2001 in the U.S. Field Battle Experiments, NATO SACLANTCEN GOATS 2000 trials, Kernel Blitz 2001 and AUV Fest 2001.
2. SeeNav is a navigation tool that can operate in real-time and post-processing modes. It is modular and uses various navigation sensors and the environment to compute the position. It has already been successfully used to produce high-quality and highly accurate geo-referenced sidescan sonar mosaics.
3. RECOVERY is a set of software tools for fault detection and diagnosis in numerous industrial applications, driven by the need to reduce costs, comply with safety and environmental legislation, and maintain company image/profile. Manual diagnosis may be beyond the capabilities of first-level technicians (craftsmen), there may be insufficient time, or the system may be remotely situated.

Site: **IFREMER**
Institut Français de Recherché pour l'Exploitation de la MER
French National Institute for Marine Science and Technology
Z. P. de Bregailllon – B.P. 330
83507 La Seyne-sur-Mer Cedex, France
http://www.ifremer.fr/fleet

Date Visited: April 27, 2005

WTEC Attendees: A. Sanderson (Report author), Y. Zheng, J. Yuh, H. Ali

Hosts: Dr. Vincent Rigaud, Director of the Underwater Systems Department, Direction of Operations, Email: vincent.rigaud@ifremer.fr

BACKGROUND

Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER) is a public institute of the French government established in 1984 under the joint supervision of four ministries: Research, Agriculture and Fisheries, Amenities and Transport, and Ecology and Sustainable Development. Its missions are to conduct and promote basic and applied research, make expert assessment reports, and undertake programs for technological and industrial development. These missions include the development and testing of marine technology.

The IFREMER laboratory in Toulon was established in order to provide a center of research and marine systems support on the Mediterranean. The current facility was constructed at à La Seyne sur Mer, within the industrial port zone of Bregaillon. This site provides geographic access to the Mediterranean and also provides the capability for rapid deployment and efficient testing of new systems and technologies.

Overview of the Visit

The visit to IFREMER included an overview of technologies and research programs followed by an extensive tour of facilities and vehicles in the laboratories.

OVERVIEW OF CURRENT ROBOTICS RESEARCH

Major projects on vehicle development and experimentation include:

Victor 6000

The Victor 6000 is a deepwater remotely operated vehicle (ROV) instrumented for modular support of scientific research including high-quality optical imaging. The working depth is up to 6,000 meters and the maximum speed is 1.5 knots. There are three major camera systems on board as well as sensors for attitude, depth, and sonar. Two manipulators are onboard, one with seven degrees of freedom (DOF) and one with five DOF.

ALIVE

ALIVE (Autonomous Light Intervention VEhicle) is designed (in conjunction with Cybernétix) for performing light interventions on deepwater subsea facilities without the requirement for a dedicated support vehicle. This project is conducted jointly with Cybernétix (Marseille, France) and Herriot-Watt University (Edinburgh, U.K.). A detailed description of the ALIVE vehicle is included in the Cybernétix site report.

Figure C.51. Victor 6000 (left) is a deepwater ROV developed at IFREMER. ALIVE (right) has been developed for manipulation tasks on deepwater subsea facilities.

NAUTILE

NAUTILE is a subsurface habitat for scientific research at depths of up to 6,000 meters. It supports two pilots and one passenger. The planned scientific missions include surveillance, physical measurement and fine bathymetry, support for a large number of different scientific instruments, support for off-shore work, tracking of pipes and cables, and support and assistance for deepwater ROVs and autonomous underwater vehicles (AUVs).

Figure C.52. NAUTILE is a habitat for scientific research at depths of up to 6,000 meters.

ASTER

ASTER is a newly developed AUV that will be used for coastal surveys at depths of up to 3,000 meters. The length is 4.5 meters and weight is 703 kg. The predicted speed is up to 5 knots per hour. The ASTER will be capable of carrying instrumentation appropriate to site surveying, including side scan sonar, multibeam echo sounder, sub-bottom profiler, Conductivity, Temperature and Depth (CTD), Acoustic Doppler Current Profiler (ADCP), fishery sounder, and water sampling devices. The navigation is provided by long range acoustic telemetry, inertial Doppler dead reckoning, and inverse ultra-short baseline (USBL) navigation. Safety considerations include autonomous relocation pinger, acoustic communications modem, radio frequency (RF) beacon, and telescoping mast.

Figure C.53. Photographs of the ASTER AUV in the laboratory. A view of central body hosting instruments and computational capability, (left) view of tail section shows thruster and control surfaces (right).

Site: **INRIA**
Institut National de Recherche en Informatique et en Automatique
2004, Route des Lucioles-B.P. 93-06902
Sophia Antipolis Cedex, France

Date Visited: April 28, 2005

WETC Attendees: Y.F. Zheng (Report author), A. Sanderson, J. Yuh, H. Ali

Host: Dr. Claude Samson, Director of Research Project ICARE, Tel: +33 4 92 38 77 36, Fax: +33 4 92 38 76 43, Email: Claude.Samson@inria.fr

BACKGROUND

The laboratory visited is a part of Institut National de Recherche en Informatique et en Automatique (INRIA), which is a major French national research institute on information and automation. INRIA has a number of regional institutes. The one we visited is located in Sophia-Antipolis, located in southeastern France. Our host Dr. Claude Samson leads the research project Instrumentation, Control and Architecture of Advanced Robots (ICARE). The project is only one of a few which are related in robotics research and conducted at INRIA. Unfortunately, we only had time to visit Dr. Samson's laboratory. The ICARE project, according to its web site, is "dedicated to the study of the problems of command and control in autonomous mechanical systems, with a special but not exclusive focus on robotics. The main target is to develop a methodology for the design and integration of each link in the chain."

RESEARCH ACTIVITIES OF THE ICARE LABORATORY

The ICARE laboratory has four researchers, six PhD students and one assisting engineer. Research activities of the ICARE project focus on: robot and control, control of nonlinear systems, and perception and autonomy. The more detailed areas which the laboratory currently covers include the following:

1977 Robot control
1978 Sensor-based autonomous robots
1979 Robotic devices for enhancing robot performance
1980 Nonlinear control and stabilization for lower-level control of robots
1981 Perception for sensor-based modeling and control
1982 Robot localization, environment modeling and navigation (SLAM)
1983 Simulation and experiments for various control and navigation schemes

The laboratory has two mobile robots for research. One is an indoor mobile robot called ANIS (Fig. C.54) and the other is an outdoor mobile robot called CyCab which is essentially an electric car.

Figure C.54. The ANIS indoor mobile robot.

The most notable feature of the ICARE project is in its navigation scheme of nonholonomic mobile robots in tracking a target vehicle. The scheme is fundamentally different from popular approaches that many laboratories in the world use. These approaches first manage to understand the geometric features of the target using various sensing technologies. Then a path is planned for the mobile robot to follow the target by continuously matching the image acquired by visual sensors with the stored geometric model of the target. In such approaches, conventional control strategies are considered not suitable for the navigation purpose.

The INRIA approach takes a different perspective that does not specify the path of the mobile robot, but instead uses a feedback control scheme. The control scheme always attempts to stabilize inside a neighborhood of zero the difference between the current position and orientation of the mobile robot and the situation of a target frame associated with the target vehicle. The size of this neighborhood is adjustable at will—it is one of the control parameters—and the path is produced in the process of control automatically. A noticeable difference with other feedback control methods is that exact zeroing of the tracking error is not the primary objective. A reason for considering a slightly less ambitious objective is to comply with the inherent impossibility for a nonholonomic vehicle—such as a unicycle-like, or a car-like, mobile robot—to move laterally instantaneously, whereas the (omni-directional) target frame is free to do so. Such an objective is thus coherent with the fact that perfect trajectory tracking by the mobile robot cannot be accomplished in general, and is also coherent with the possibility to automate manoeuvres in a feedback fashion in order to achieve tracking with arbitrary good (but not perfect) precision whatever the motion of the target vehicle. The ICARE project uses a control strategy that is based on the transverse function control approach. The approach establishes a general framework for the design of a control law which yields practical stabilization for nonlinear controllable systems. Estimation of the target's velocity based on visual data is also used for the purpose of target tracking and improvement of the performance of the control scheme. This unique control scheme has been implemented on the unicycle-like mobile robot ANIS and subsequently showed smooth motion in tracking the desired target in laboratory demonstrations.

In addition to the ANIS mobile robot, the host also showed a video that demonstrated the CyCab in tracking another man-driven vehicle by using computer vision to match a desired geometric model posted on the back of the leading cab.

A presentation of ICARE with short videos illustrating the research activities of the group can be found at: ftp://ftp-sop.inria.fr/icare/Outcoming/Icare2004-video_presentation/icare.pdf.

SUMMARY

ICARE studies various topics of robotics research including robot and control, control of nonlinear systems, and perception and autonomy. The project has a unique scheme in the navigation of mobile robots for tracking a moving target. The scheme designs a control law using the transverse function control approach plus estimation of the target's velocity using sensing data in real-time. It can stabilize the mobile robot in tracking a non-feasible trajectory of the target and has been proven effective in laboratory demonstration.

Site: **University of Karlsruhe**
Universitaet Karlsruhe (TH)
Institute of Computer Science and Engineering (CSE)
Forschungszentrum Informatik Karlsruhe (FZI)
Research Center for Information Technologies
http://wwwiaim.ira.uka.de
http://www.fzi.de

Date Visited: April 28, 2005

WTEC Attendees: V. Kumar (Report author), G. Bekey

Hosts: Professor Dr.-Ing. Rüdiger Dillmann, Chair of Industrial Applications of Informatics and Microsystems (IAIM) at CSE, FZI Director,
Email: dillmann@ira.uka.de; dillmann@fzi.de

BACKGROUND

The Research Environment

Professor Dillmann is chair of a large research group within the academic department of computer science (Informatics) at the Universitaet Karlsruhe and the Technology Transfer Center (FZI: Forschungszentrum Informatik). Thus the research stuff is divided into two groups, one at the University (Institute of Computer Science and Engineering (CSE) / Industrial Applications of Informatics and Microsystems (IAIM): chair Prof. Dillmann) and one at FZI. The FZI offers the opportunity to establish spin-off companies (currently there are four companies established in such a way). Each head of an FZI department is also a professor at the University of Karlsuhe.

Dr. Dillmann has established a large network of cooperative research programs with researchers elsewhere in Europe. These include Raja Chatila in France, Henrik Christensen in Sweden, Paolo Dario in Italy, Henrik von Brussel in Belgium, Guilio Sandini in Italy, Roland Siegwart in Switzerland and others. He also collaborates closely with the Fraunhofer Institute for Information and Data Processing in Karlsruhe (http://www.iitb.de) and the Forschungszentrum Karlsruhe (http://www.fzk.de). His other contacts include Advanced Telecommunications Research Institute (ATR) in Kyoto/Japan (Mitsuo Kawato and Gordon Cheng), Chris Atkeson and Jessica Hodgins at Carnegie-Mellon University (CMU), Stefan Schaal at the University of Southern California (USC) and George Lee at Purdue. His work is supported by grants from the European Community, the German government as well as the State of Baden-Wuerttemberg and industry.

MAJOR RESEARCH PROJECTS

Humanoids

Prof. Dillmann has a long-standing interest in various aspects of humanoid robotics. We saw ARMAR, a two-arm robot on a wheeled base in a kitchen environment. The robot has 23 mechanical degrees of freedom (DOF). The robot consists of five subsystems: head, left arm, right arm, torso and a mobile platform. The upper body of ARMAR has been designed to be modular and lightweight, while approximately retaining the size and proportion of an average person. The head has two DOF arranged as pan and tilt and is equipped with a stereo camera system and a stereo microphone system. Each of the arms has seven DOF and is equipped with six DOF force torque sensors on the wrist. The current mobile base of ARMAR consists of a differential wheel pair and two passive supporting wheels. It is equipped with front and rear laser scanner (Laser Measurement System (LMS)). Furthermore, it hosts the power supply and the main part of the computer network.

The robot is being trained to go to the refrigerator and retrieve objects, load dishes into the dishwasher, and place items in the microwave. None of these goals has yet been achieved, but the robot's speech interface is working, and it navigates well on its mobile base. The robot is used as a testbed for the integration of motor, perception and learning components necessary for multimodal human-humanoid interaction in the German humanoid project SFB588. At the moment algorithms for dual-arm motion coordination, recognition, localization and tracking of colored and textured objects are being investigated, implemented and tested. The robot is equipped with five-fingered hands capable of eight DOF motion using hydraulic actuators.

Figure C.55. The humanoid robot ARMAR.

Other Platforms

Dillmann's group has developed several autonomous wheeled platforms capable of navigating hallways with obstacles, some capable of automatically going to charging stations and plugging themselves in.

The lab has developed, in joint cooperation with the company SwissLog Telelift, a low-profile flat-top vehicle capable of sliding under a large container, raising it using an elevator platform and then transporting it. Dillmann's lab has been responsible for the on-board control system including laser scanner based navigation and logistics of a multiple automatic guided vehicles (AGV) installed in hospitals worldwide (e.g. Houston, Los Angeles, Leipzig, Varese, Trondheim, Dessau and Geifswald).

Figure C.56. Mobile robot platforms in Dillman's laboratory. Two SwissLog products are shown on the extreme right.

Pipe Inspection Robots

Prof. Dillmann's lab has developed several articulated, snake-type robots for pipeline inspection. Some are now commercially available and used to inspect water pipes and oil pipelines (including the Alaska pipeline).

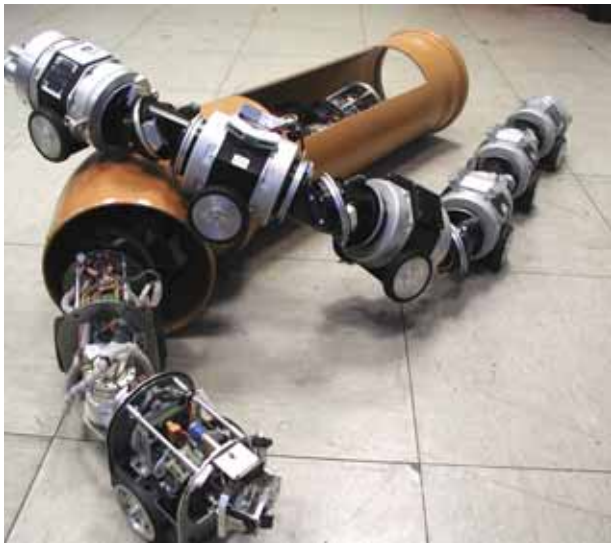

Figure C.57. Inspection robot.

Current work is concentrated on enabling the system to work in an unstructured environment. A multi-articulated system with six links will be used for inspection tasks in sewer pipelines.

Legged Locomotion

There are labs dedicated to the development of control systems for four- and six-legged robots, as well as bipeds. The emphasis appears to be in the application of artificial muscles (McKibben-type muscles with a rubber shield), reduction of size and weight, and joint design. Historically, they have fabricated several of the Lauron-type six-legged machines usually associated with Friedrich Pfeiffer at the Technical University of Munich (TUM). Apparently there has been a long-term cooperative effort between the two labs.

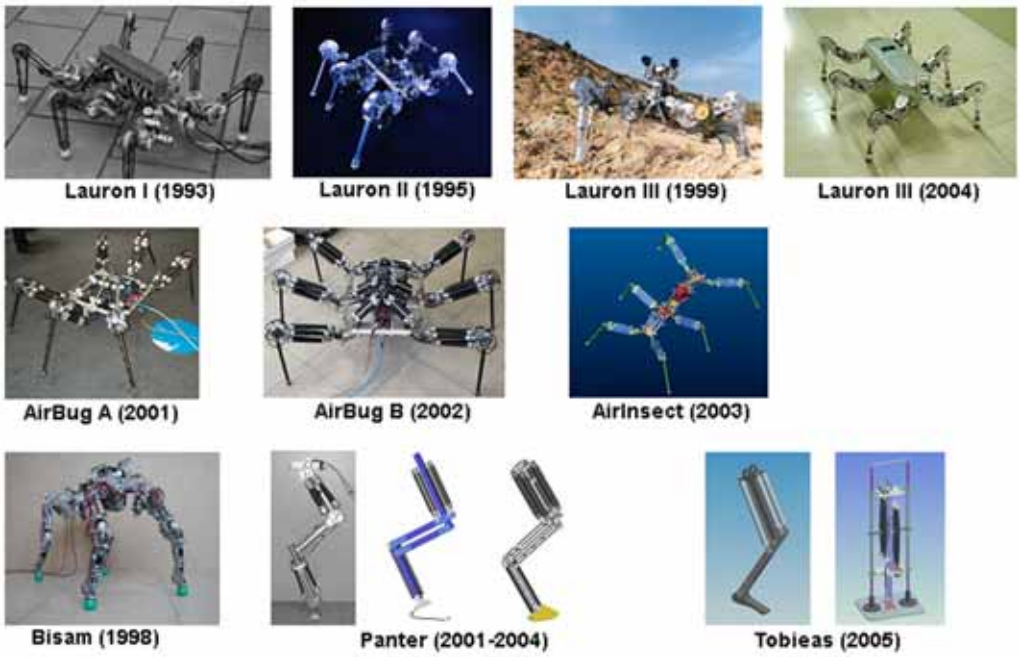

Figure C.58. The walking machines built by Dillmann's group.

Up to now 10 six-legged walking machines have been built and distributed: three to museums and seven to universities or research groups in Germany and Europe.

Medical and Surgical Robotics

Several projects involve cooperation with medical personnel on visual identification of target areas for surgery on the skull, estimation of spine and neck muscle properties to determine the extent of whiplash injuries, and automatic calibration of medical instruments with imagery for image-guided surgery.

COLLABORATIVE PROJECTS

Professor Dillmann has an extensive network of collaborators on many projects. The big projects are:

- Collaborative Research Center on Learning and Cooperating Multimodal Humanoid Robots "SFB588," which was established by the DFG in 2001 and will be run for 12 years (coordinator: Rüdiger Dillmann)
- Cogniron Project (funded by the EU, led by Dr. Raja Chatilla at the Laboratoire d'Analyse et d'Architecture des Systèmes (LAAS), Toulouse)
- PACO-PLUS (funded by the EU, coordinator: Rüdiger Dillmann)

Other collaborative research projects in Germany include:

- Robots in Surgery (SFB 414 in Karlsruhe)
- Telepresence and Teleaction Systems (SFB 453 in Munich)
- Autonomous Dynamic Walking (Munich)
- Situated Artificial Communicators (SFB 360 in Bielefeld)
- Robotic Systems for Handling and Assembly—High Dynamic Parallel Structures with Adaptronic Components (SFB 562 in Braunschweig)
- Spatial Cognition: Reasoning, Action, Interaction (Transregio SFB 6023 in Bremen/Freiburg)
- Cognitive Cars (SFB in Karlsruhe/Munich)

Professor Dillmann also collaborates with other faculty at the University of Karlsruhe and the Fraunhofer Institute.

Prof. Dr.-Ing. H. Wörn, Universitaet Karlsruhe, Institute of Process Control and Robotics

Prof. Wörn worked for many years at Kuka. He now directs a number of robotics projects, including development of robot hands and artificial skin for robots. The skin is a soft material overlaid on a copper skin (piezo-resistive force sensor) that deforms under pressure and locally changes its electrical resistance. Several hundred such sensors are multiplexed for pressure sensing.

Prof. Wörn also collaborates with Prof. Dillmann on studies of robot-aided head surgery. Professor Wörn has also worked on the development of a 3–4 cm sized robot for micromanipulation. He is presently the coordinator of the I-SWARM project, a multi-institution project funded by EU, in which he is working toward the simulation and eventual development of swarms of as many as 1,000 robots (See http://www.iswarms.org).

Dr. Helge Kuntze, Fraunhofer Institute, IITB, Karlsruhe

The major robotic projects at the Fraunhofer IITB are:

- Humanoids (supported by the DFG collaborative project SFB588)
- Neuro-fuzzy-based supervisory robot control architecture
- Pipe inspection—they also work on multisensor pipe inspection systems, while Dillmann concentrates on the mechatronic aspects
- Multisensor homeland security inspection robots for periphery of factories
- Telepresence, nonlinear estimation, localization and tracking, distributed phenomena, recognition of robot intention
- Telepresence—includes motion compression; path transformation; allows human to walk a transformed path while guiding robot motion

OVERALL EVALUATION

There is a very large concentration of robotics researchers in the Karlsruhe region, including Dillmann's lab, the Fraunhofer Institute, a major nuclear research center and various industries. Dillmann clearly believes the robotics is on a growth trajectory in Germany, where the strongest groups include Karlsruhe, Stuttgart (for industrial robotics), Munich and the German Aerospace Center (DLR). Other centers include Aachen, Darmstadt, and Berlin. He also believes that true robot household helpers and medical assistants are only two or three years away.

In our opinion Prof. Dillmann is a very successful entrepreneur, who has succeeded in building a major applied robotics research center. His research activities span a wide range of disciplines such as integrated mechatronics design, autonomous robot systems, service robots, walking machines, humanoids, machine learning, human-robot interaction, robot programming by demonstration, and simulation for medicine applications. The three projects mentioned above (SFB 588, Cogniron and PACO-PLUS) focus on fundamental issues related to the design of highly integrated robotics platforms capable of developing and learning perceptual, behavioral and cognitive skills and communicating with humans and other artificial agents in a human-like way.

Dillmann believes Japan is strongest in humanoids and service robots, while U.S. leads in space and military robotics and Germany is strong in industrial and service robots. Industrial robot companies in Europe (primarily Kuka and ABB) collaborate with universities, while FANUC in Japan does not. This puts German researchers at an advantage.

Site: **KTH**
Kungl Teknisha Hogskolan (KTH), Stockholm
Center of Autonomous Systems (CAS)
SE-100 44 Stockholm, Sweden

Date Visited: April 28, 2005

WTEC Attendees: V. Kumar (Report author), G. Bekey

Hosts: Henrik I. Christensen, Director, Center of Autonomous Systems, Tel: +46 8 790 6792, Fax: +46 8 723 0302, Email: hic@nada.kth.se

OVERVIEW

The Center of Autonomous Systems (CAS) at KTH, Stockholm, was established in 1996 with Professor Henrik Christensen as the director. It brings together four departments: Computer Science, Electrical Engineering, Mathematics, and Mechanical Engineering. It is governed by a board consisting of members from academia and industry, and has an advisory board consisting of distinguished academics from all over the world. CAS aspires to be one of the top five centers in basic research, generating around five to eight PhDs per year. About two-thirds of its funding is shared equally by EU and the Swedish Foundation for Strategic Research (SSF), while the remaining third comes mostly from defense. Only 3% of the funding comes from industry. The group includes six full professors, one associate professor and one assistant professor, with two to four post-doctoral researchers and between 16 to 18 doctoral students.

Research Thrusts

CAS strives to strike a balance between basic research on component technologies and integration of methods into systems. It has three research thrusts: field robotics, service robotics, and technology transfer.

Field Robotics

The interest in field robotics is driven by the strong vehicle industry and related field applications in Sweden. The basic challenges in field robotics are: (a) Robust perception; (b) Long-term autonomy; and (c) Large-scale mapping for large spaces. The CAS has an ongoing project that involves the integration of global positioning system (GPS) information, range from laser range finders, heading from compasses, and odometry measurements, with the goal of mapping large (200 m x 300 m) spaces. They are able to map such spaces with accuracies better than 10 cm.

CAS has two packbots and is working closely with iRobot. They are testing and conducting usability studies on wearable interfaces with soldiers.

Service Robotics

The basic challenges include (a) mapping and navigation; (b) mobile manipulation; (c) user interfaces; (d) autonomy; and (e) architectures for integration.

The work on mapping and navigation, in particular, is innovative. It is formulated as a minimization problem on a graph and is potentially scalable, unlike other competing methods, to large spaces. It should also be noted that the CAS produced the International Conference on Robotics and Automation (ICRA) 2003 best paper award on dynamic modeling and simulation of multifingered grasps.

Technology Transfer

The CAS has many ongoing interactions with industry. The technology transfer examples include the Electrolux Navigation System and the PerMobil Wheelchair Control. They also work closely with ABB, the second largest manufacturer of industrial robots.

EU Activities

The CAS director, Dr. Christensen, is the coordinator of the EU Network of Excellence (EURON), which involves 140 institutions and enables the integration of research and education across institutions and establishes connections to industry. He is also the author for the Robotics Research Roadmap for the EU. Dr. Christensen is also a participant in many EU research projects including:

a. Cogniron: Cognitive robotics for autonomy;

b. Neurobotics: Integration of neuroscience and robotics for assistive devices;

c. CoSy: Cognitive Systems for cognitive assistants

Site: **LAAS-CNRS**
Laboratoire d'Analyse et d'Architecture des Systèmes
Centre National de la Recherche Scientifique
7, avenue du Colonel Roche
31077 Toulouse Cedex 4, France

Date Visited: April 26, 2005

WTEC Attendees: B. Wilcox (Report author), R. Ambrose, Y. T. Chien, D. Lavery, M. Dastoor

Hosts: Raja Chatila, Head, Robotics and Artificial Intelligence Group,
Tel: +33 (0)5 61 33 63 44, Fax: +33 (0)5 61 33 64 55, Email: raja@laas.fr
Malik Ghallab, Director, Programme National Robotique et Entités Artificielles,
Tel: +(33) 561.336.271, Fax: +(33) 561.336.455, Email: Malik.Ghallab@laas.fr
Simon Lacroix, Field Robotics, Planetary Exploration, and Aerial Robotics,
Frederic Lerasle, Cognitive Robotics and Human-Robot Interaction (with Raja Chatila),
Felix Ingrand, Temporal Planning and Control (and demo of Planetary Rover DALA and Mission Planning and Control),
Nic Simeon, Motion Planning and Molecular Motion,
Jean-Paul Laumond, Motion Planning for PLM and Digital Actors,
Sara Fleury, Interactive Robot Rackham and Cognitive Robotics,
Florent Lamiraux, HILARE 2 Robot and Trailer Motion Planning

BACKGROUND

The meeting started with welcome and introductory remarks by Malik Ghallab, the director of the Programme Robotique et Entités Artificielles (ROBEA). Laboratoire d'Analyse et d'Architecture des Systèmes (LAAS) was founded in 1967. Toulouse has the second oldest university of France, after Paris. Centre National de la Recherche Scientifique (CNRS) is the largest scientific organization in Europe, with 1,260 laboratories, 67,000 workers, of which 26,000 are at CNRS. Of those, 11,600 are researchers and 14,000 are engineers, technicians and administrative staff. In all of CNRS, 23,000 are faculty (shared with universities). The rest of the 67,000 (i.e., 18,000) are PhD students, post-docs and visiting scientists. The overall budget is about €2.2 billion per year. LAAS is the largest CNRS laboratory, with about €26 million in funding per year. This lab has 540 researchers and staff associated with three universities, including 200 PhD students. There is no teaching at this site—only some graduate courses and training for research students. They are organized into 14 groups in four main areas: Micro and Nano systems (MINAS), Control Theory, Critical Informatics Systems, and Robots and Autonomous systems (the focus of today's meetings). MINAS is the thrust area in micro/nano, with research emphasis on photonics, optics, microwave communications, power electronics, chemistry, physics, and life sciences. An example of the work in that area is the detection of physical properties from a µm drop of liquid on a cantelever beam. In the Control Theory area, they have an exceptionally strong mathematical group, specializing in control of rockets and turbine engines, working especially with Airbus. The Critical Informatics Systems area emphasis is on quality of service for networks. Raja Chatila is a senior research scientist and head of the Robotics and Artificial Intelligence Group and head of the Robotics and Systems Autonomous area (ROSA).

Raja Chatila briefly described the Robotics and Artificial Intelligence Group. It consists of 21 staff (including 12 researchers, who occasionally teach, and eight professors, with joint appointments with local universities). They have about 30 graduate students at the present time. Also, there are four associate researchers, postdocs, or visiting scientists. Kurt Konolige from SRI International was recently here for three quarters; Ron Arkin from Georgia Tech is coming for 11 months. CNRS labs are always closely tied to universities, hosting neighboring professors. The researchers and professors are civil servants, with salaries covered by the government. The group receives about €600,000 per year from contracts for equipment, scolarships for students, and travel.

An overall long-term objective of the Robotics and Artificial Intelligence group is the creation of an artificial being or entity. This entity should work in a real environment, uncontrolled by an external human. In a complementary view, they also see robotics as a multi-thematic field—a convergence in perception, decision-making foundations, and applications—but not necessarily integration, not necessarily real-time, sometimes covering topics that seem far away from robotics.

Figure C.59. Drone (left) and Karma blimp (right).

Simon Lacroix gave a presentation about field robotics, planetary exploration, and aerial robotics. He stated that environmental perception and modeling are very important for navigation and motion control in natural and artificial environments, whether it is for human motion, robot motion, motion for digital actors, or molecular motion. Planetary exploration research began there with "Adam" in 1993, "Lama" (on a Russian Marsokhod platform) in 1996, "Karma" (a blimp) in 2000, and recently "Dala" (a four-wheel vehicle based on the iRobot ATRV), and the COMETS project with a collection of high lift-to-drag-ratio unmanned aerial vehicles (UAVs) (Figures C.59 and C.60).

Figure C.60. Lama (left), Dala (right).

The overall focus of the work is on integration of perception to action. In the past they have demonstrated an autonomous long-range planetary rover that is able to move several hundred meters without human intervention. That system took about 10 years to develop. They are interested in systems that will behave differently in different environments, e.g. with different navigation modes that are selected according to the environment. In a smooth environment it will use simple models and plans. In a very rough environment it will use complex and accurate models, and sophisticated motion planning. Goals are expressed in Cartesian coordinates. They evaluate different trajectories, in a fashion somewhat similar to the Morphin system developed at Carnegie-Mellon University (CMU). They use visual odometry, perform terrain classification in 2D, and vision-based path tracking. Their inertial and dead-reckoning sensors are a fiber optic gyro plus odometry. With visual motion estimation—2D tracking, stereo correlation, and 3D motion estimation—they have demonstrated 1% accuracy (of distance traveled) over 100 m.

The group started working on 3D Simultaneous Localization and Mapping (SLAM) in 1996 (their earlier work on SLAM dates back to 1985). With this approach, the navigation and mapping over a 60 m loop has been corrected to ~1 cm. They match features directly in the images, not in a Kalman Filter. They are conducting substantial work with panospheric cameras. Image indexing and calibration of panoramic stereovision is a principal focus of this activity.

In the area of motion planning they have "potential" methods that work in easy terrain, but incorporation of rover orientation/motion constraints is very ad-hoc. In the area of motion execution control they showed an example of the Russian Marsokhod chassis that they used for many years going over a very large rock pile, maintaining heading in the process. They don't like the skid steering of the Marsokhod, as it is difficult to control. Current research focuses on remaining issues such as locomotion control, localization, navigation strategies, and dealing with more complex mission scenarios.

Figure C.61. Rackham museum guide.

In the area of flying robots, they are experimenting with bearing-only SLAM that recovers the vehicle position history and some map information only from the bearings to landmarks, without range data. However, they feel that this approach is not relevant to ground robots, which they believe will certainly have stereo vision and thus range data.

At a high level, they are working on the interconnections between and the transition from robotics (e.g. the functional level) to artificial intelligence (e.g. the decisional level).

Phase B is about to start for the ExoMars Project. The relevant European science board has established the need for the mission. They believe it will be necessary to have a rover, of which they have proposed a substantial role in the development. The discussion digressed briefly to the Véhicule Automatique Planétaire (VAP) project that was active from 1989 to 1993, which they described as the "golden age" of robotics sponsorship by CNES (the French Space Agency).

Karma is an autonomous blimp. The good things about a blimp are that it is big, slow, safe, and requires little energy. The bad things are that it is big, slow, sensitive to winds, and needs a hangar. For Karma they created a big stereo optical bench with a camera separation of 3.2 meters that was constructed from carbon fiber composite, but they found that it stayed calibrated for only one day at a time. The stereo vision algorithm they developed specifically for the blimp was fast, but had artifacts.

They presented a taxonomy of autonomy levels (in the context of multi-robot or multi-UAV systems):

- Level 1: No autonomy, robot processes single tasks
- Level 2: Robot processes a sequence of tasks

- Level 3: Level 2 plus the ability to synchronize with other robots
- Level 4: Robot is able to process at the mission level,
- Level 5: Level 4 plus task allocation ability, with all distributed control

As part of the joint COMETS project with Spain, Germany, and Sweden, they are doing a demo in Portugal where an autonomous blimp and helicopter conduct a mission along with a teleoperated helicopter. In this first demo the autonomous system assumes the teleoperator will perform the task, but monitors execution carefully, knowing the task statement.

Raja Chatila and Frederic Lerasle next presented work in the area of cognitive robotics.

Evolution of work in personal robotics has led to the "Cogniron Project"—a European project lead by LAAS to develop a "Cognitive Robot Companion." This robot is conceived to interact with people and understand speech and gestures. An example is the serving of drinks.

Cogniron must behave socially: it must behave in a friendly manner and make people feel comfortable (U. Hertfordshire leads); it must learn: learning skills and tasks, imitation learning (EPFL Lausanne leads); it must understand space: learning space, learning objects (U. Amsterdam and LAAS lead); it must understand what humans are doing (U. Karlsruhe leads): face, expression, gesture and voice recognition; it must communicate: conduct dialog (U. Bielefeld leads), take decisions and express intentions (LAAS leads); it must integrate all activities. There are three key experiments. In the first, a curious robot must discover new objects and try to learn about them. In the second, a home tour robot must learn its environment from a human showing a home. In the third, learning skills and tasks must be integrated (e.g. observing humans and interacting to learn a task like setting a table). The web site for this project is http://www.cogniron.org. In this discussion they did not address the work of the other centers involved in the project.

They are developing a robot that guides visitors in space museum (Figure C.61). The mobile robot uses laser in corridors plus vision-based localization using memorized quadrangles (e.g. posters) with interest points. In another setting, it performs 3D SLAM by matching points detected using the Harris corner detector.

An interesting topic is determining and ensuring acceptable social interaction distances for robots with humans. There is a series of workshops on robot safety in human environments. They believe the burden is on the robot to make it convenient for humans. Any path planning algorithm must take into account that humans might emerge from a doorway, for example, by staying on the opposite side of the corridor.

In object modeling work, they use a distributed system, a neural network where each layer recognizes more and more complex objects and structures. There is specialization in that each neuron does not learn multiple objects. It is not view-based, but rather object-based.

They use three-layer architecture: one for functional and execution, one for validation and execution control, and one for the decision level (planning and supervision).

To accomplish the learning of skills, they use "value function learning." They embed within any visual representations the skill representation as well. When you present an apple to the system while learning a value function, it is modeled by a hierarchical representation (e.g. round, red, with a stalk), the operator concurs to provide a reward to increase the value function. Each component of recognition has no effect on the value function by itself, e.g. a soccer ball is round but not red nor has a stalk, or a red flower is not round but has a stalk. The idea is to associate actions with objects—e.g. a presented apple is for eating.

Frederic Lerasle presented a gesture and face-tracking system. It distinguishes intermittent cues from persistent but ambiguous cues. Shape and color distribution are persistent cues: skin pixel, motion, frontal face detection are intermittent cues. It combines persistent and intermittent cues to maximize robustness with particle filtering. A demonstration tracks faces in and out of full sun to deep shadow, while turning around, etc.

Gestures can be communicative or manipulative. When they are manipulative, the system must use 3D approaches to understand them. When they are communicative, both 2D and 3D approaches plus speech can be used. Their 3D models are based on a chain of truncated quadrics (non-deformable and given, not learned, but they have good properties in projections), with inner degrees of freedom to model articulations. Their 2D tracker knows, for example, the joint limits of a human arm and can create a 3D representation of an arm with single camera view. Among other things, they perform posture tracking of human figures.

Felix Ingrand, who was at SRI, and worked with NASA Ames Research Center, described temporal planning and control. He began with the question, "Why do we need an architecture?" The answer is that robots are complex, and work in real-time with exponential complexity. In the functional level each module deals with one sensor or one functionality (e.g. to manage a camera, another to do stereo, etc.), where algorithms can be broken into pieces. The execution control level sends requests to the functional units. A formal model is needed to prevent runaways, etc. Never do certain things (e.g. correlate stereo without taking images), always do others (e.g. check speeds to make sure they are within bounds). At the decisional level is a temporal task planner (called IxTeT) and a supervisor (IxTeT-eXeC). It has a representation of time and resources, a time-oriented functional representation, and a search mechanism (search in the planning space of partial-order causal links). Flexible plans are more robust to execution errors—based on constraint satisfaction programming (CSP) managers (similar to Europa and Mapgen done at NASA Ames Research Center). They can replan and recover from failures without a total replan, sometimes without even stopping. Parts of the system are distributed as open software. Their web site is http://softs.laas.fr/.

Thierry (Nic) Simeon described motion planning and molecular motion. The original combinatorial explosion recognized for motion planning for robots led eventually to the study of molecular motion. In 1980 Lozano-Perez at MIT formulated the configuration space (C-space) representation. C-space normally is higher dimensional than real space but it is easier to find connected routes from a start point to an end point. In the 1980s there were deterministic methods that featured exponential complexity, and were limited to a few DOF. In the 1990s probabilistic methods emerged that trade a limited amount of completeness for computing efficiency: Probabilistic Roadmaps (PRM, Stanford-Utrecht), visibility roadmaps, Random Trees (RRT, Illinois U.). They showed an example of manipulation task planning—sliding a bar out in many small movements from under fixed obstructions, where the bar cannot be slid out in one motion because of the obstruction of the grasp point.

In molecular motion—proteins are large deformable structures—the folding pattern and flexure patterns must be computed for the function of the molecule to be understood. This problem is of immense practical interest, since a DNA sequence defines the order of amino acids in a protein, but without computing the final 3D shape, the chemical function of an enzyme cannot be understood.

Florent Lamiraux described robot motion planning and control for non-holonomic systems (those with linear velocity constraints—e.g. wheeled vehicles with trailers, etc.).

C-space, decidability, deterministic approaches are described in the book "Robot Motion Planning" by Jean-Claude Latombe (1991). What is required is a locally controllable method where steering methods connect two points in C-space such that points that are close in C-space have a path that stays close to those points. The example they are working with is a robot with a trailer with a hinge point over the front axle. This system is "differentially flat"—by differentiating the motion of the center of the trailer you can reconstruct the configuration of the vehicle—an important concept from control theory.

LAAS was first to propose piecewise-smooth trajectories for these robots. An important issue is planning with uncertainty (due to map errors, robot localization errors, etc.). They use a potential field that pushes away from obstacles, but needs to maintain a solution that satisfies kinematics constraints.

An important practical application of this is the problem of moving Airbus A380 wings over the small country roads from Bordeaux port to Toulouse (where final assembly of the aircraft is performed). Specific examples of solutions from some of the small towns were shown.

Jean-Paul Laumond presented work in "Motion Planning for Product Lifecycle Management," and virtual, natural, and artificial human motion.

In the 1990s they developed the "Move3D" software for generic motion planning, and spun off a startup company called "Kineo". The product is middleware, with a focus on product development to generate long-term company revenues but also a high-value service for short-term revenues. Kineo path planning software for computer-aided manufacturing (CAM) has the automotive industry as the target market. There are only a few providers of CAM software for this large market: Dassault Systèmes, Unigraphics-Tecnomatix, PTC.

The Kineo software addresses assembly path planning problems. It recently solved in two minutes what an expert human took two days to solve; in another case a human could not find a solution, but the computer found a solution in one minute. (Typical cases include planning the motions to install the seats in a car when they don't appear to fit through the door.) It works with path planning clearances as low as 0.1 mm. Kineo is available as a plug-in to Solidworks and other computer-aided design (CAD) systems (this received the IEEE International Federation of Robotics (IFR) Award for Innovation, Barcelona, April 2005).

An example is a real-time video game of an octopus catching a mosquito. AI methods currently used by the video game industry work only in "2 1/2 D," e.g. with only the surface seen at each point modeled. But the octopus/mosquito system is 4 x 7 DOF (this particular "octopus" only has four arms, each with seven DOF). So with AI methods the computing time grows exponentially with 28 DOF, while Kineo is based on a Monte Carlo approach and grows very slowly with the complexity of the problem.

A similar problem is to compose virtual motions for digital actors and mannequins that appear to be natural motions for humans. Human eyes are very sensitive to quality of motions. The observer must understand the emotion and action motions. Motion planning for humanoids must unify obstacle avoidance, kinematics, dynamics, and motion planning.

In lab tours the WTEC team was shown a demonstration of the museum tour guide robot, the nonholonomic tractor trailer path planning robot, and an ATRV chassis performing mission planning and control, SLAM and hazard avoidance.

Site: **Oxford University**
Department of Engineering Science
Parks Road, Oxford OX1 3PJ, United Kingdom

Date: April 26, 2005

WTEC Attendees: Y. Zheng (Report author), A. Sanderson, J. Yuh, H. Ali

Hosts: Dr. Paul M. Newman, Dept. of Engineering Science, Tel: 01865-280950, Fax: 01865-280922, Email: pnewman@robots.ox.ac.uk
Professor Sir Michael Brady, Dept. of Engineering Science

BACKGROUND

The Department of Engineering Science at Oxford University is well known for robotics research in the community. For a long time, research activities were led by Professor Michael Brady who transferred to Oxford University from MIT in 1985. In recent years, robotics research was no longer that active as Dr. Brady shifted his research interests to medical images. In January 2003, Dr. Paul Newman joined the department, and Oxford University became active again. Before joining Oxford, Dr. Newman worked at MIT as a postdoc for two years and received a PhD in Australia under Durrant Whyte at the University of Sydney. Dr. Paul Newman's primary interests are in mobile robots, and his group is called Mobile Robot Group (MRG) within the larger umbrella of Robotics Research Group at the university.

RESEARCH ACTIVITIES AT OXFORD UNIVERSITY

Activities under Michael Brady

The team met with Michael Brady for about one hour. Prof. Brady talked mostly about Guidance Control System (GCS), the company which he formed after he returned from the United States in 1985. The product line of GCS includes:

a. Marine position sensors, which are designed to aid the automatic positioning of vessels in marine applications.
b. Offender monitoring electronics, which are developed for home detention as an effective, non-custodial alternative to prison.
c. Guided vehicle navigation system, which is primarily used for navigation and control of automatic guided vehicles (AGVs).

According to Prof. Brady, the guided vehicle navigation system has been a very successful product, 700 of which have been installed on the AGV manufactured by FMC Technologies of the United States. Prof. Brady believes that mobile robots will have a great future in a broad scope of applications.

Prof. Brady recently formed another company called Mirada which utilizes his medical image processing technologies. His research is focused on three types of medical images: ultrasound, magnetic resonance imaging (MRI), and mammography. The purpose of the research is for diagnosis and prediction of breast cancers.

Activities under Paul Newman

Dr. Newman's main interests are in the area of Simultaneous Localization and Mapping (SLAM) for applications in mobile robots, which is a very active topic of study in the United States as well. The ability to place an autonomous vehicle at an unknown location in an unknown environment, have it build a map, using only relative observations of the environment, and then use this map simultaneously to navigate would indeed make such a robot "autonomous." The SLAM problem has been successfully approached as a

probabilistic problem—inferring position and surroundings from a stream of sensor measurements. A big challenge was in overcoming the scaling problem- how to avoid unbounded growth of computation with map size which prohibits sustainable mobile autonomy. Over the past few years, there has been great progress in this area—mostly by analyzing the underlying inference problem and exploiting its unique structure by application of bespoke estimators.

However the group still does not have SLAM-enabled robots capable of substantive deployments. The problem lies in perception. All the SLAM algorithms require an oracle of some description to associate each measurement with part of the inferred state of the world. If this "Data Association" process goes wrong, terrible things happen. Vehicles get lost, maps get corrupted and new features are mapped when in fact they are re-observing previously seen areas. SLAM algorithms fail catastrophically under poor data associations.

A facet of the research into mobile robotics at Oxford is trying to face the robustness problem head-on. They are combining both sensed geometry, resulting from 2D and 3D laser scanning (see Fig. C.62), and texture information from cameras to extract complex, high-dimensional scene descriptors. They use these rich descriptors to disambiguate the data-association problem, reducing the chances of erroneous measurement-feature pairings and making it easier to solve the "loop closing problem," recognizing when, contrary to internal location estimates, the vehicle has in fact returned to a previously visited location.

Figure C.62. A SLAM-built map of the information engineering building at Oxford. The small triangles mark the path of the robot around the building. The map is built from scratch and develops as the vehicle moves. The same map is used for navigation.

Central to the approach is saliency detection—finding what is interesting and "stands out" in a particular block of 3D laser data or what is remarkable about a given image. Detecting and then later re-detecting saliency in data space (for example by looking at variations in entropy over scale) without recourse to the estimated state (map and vehicle location) offers a substantial increase in robustness.

The research also extends to multiple collaborating millimetre-wave radar sensors for feature detection and multi-spectral SLAM. They are also considering active, high-precision workspace reconstruction using both 3D lasers and cameras for indoor and outdoor settings. A collaboration with the Oxford Department of Linguistics is examining translation between the metric, Euclidian maps of SLAM algorithms and natural language descriptions. This is motivated by the vision of a mobile robot being able to explain and describe its learnt maps to a human user in a natural way. Central to it all is answering "where am I?" Dr Newman says it is a tough question, but one that needs addressing.

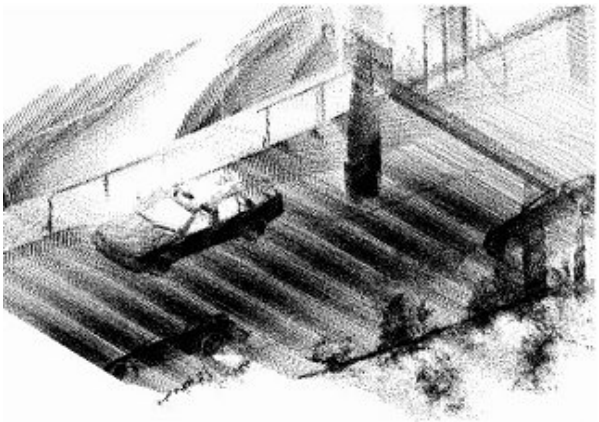

Figure C.63. Section of an outdoor 3D SLAM map created using a 3D scanning laser.

Figure C.64. An Oxford research vehicle showing the scanning laser.

SUMMARY

Oxford University is a reputable organization in robotics research. In recent years, research activities have become more diversified than in the past. Prof. Sir Michael Brady has switched his focus to medical image processing while Dr. Paul Newman, the new academic in mobile robotics research, is focusing on mobile robots with an emphasis on SLAM. In addition to mobile robots, Oxford also studies various topics related to computer graphics, image query, and computer vision. Professor Brady has achieved success in technology transfer, as he has formed two companies. One, called GCS, primarily focuses on sensing and control technologies, and the other is called Mirada, which is in the field of medical images. The latter is relatively new.

Site: **Scuola Superiore Sant'Anna**
Saint Anna School of Advanced Studies
Polo Sant'Anna Valdera,
University of Pisa
Viale Rinaldo Piaggio, 34
56025 Pontedera (PI), Italy

Date: April 29, 2005

WTEC Attendees: Y. Zheng (Report author), A. Sanderson, J. Yuh, H. Ali

Host: Paolo Dario, Director of Polo Sant'Anna Valdera, Tel: +39 050 883400/401, Fax: +39 050 883497/496, Email: dario@sssup.it

BACKGROUND

Polo Sant'Anna Valdera (PSV) is a research park of the Sant'Anna School of Advanced Studies. The school is located in Pisa, Italy, while the research park is located in a suburban area of Pisa called Pontedera. Founded in 2003, the PSV research park 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, which is a collaboration program with Waseda University of Japan, established under the scientific-cultural agreement between Italy and Japan. Dr. Paolo Dario, the director of the research park, was our host and introduced two laboratories: ARTS and CRIM, respectively, which was followed by a visit to the two laboratories by the team.

Overall Activities of ARTS and CRIM

The two laboratories have 90 scientists including 15 PhD students. Research activities cover topics from robotic components to systems, aiming to develop four strategic lines:

a. Surgical robots
b. Mini/micro/nanorobotics
c. Rehabilitation robots
d. Assistive technology for elderly people

Activities in each of the two laboratories are described below.

The ARTS Lab

The ARTS laboratory focuses on basic research of robotics, mechatronics and bioengineering. Research projects currently going on explore biomorphic and anthropomorphic solutions for robotic devices in general, and biomechanics, neurorobotics, 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. C.65)

Figure C.65. Human arm implantable microdevices.

The second project was a so-called humanoid robot, though it was different from humanoid robots that we had seen, a robot equipped with legs and arms, for example. The one in the ARTS laboratory focuses on eye-hand coordination, which is used to study sensor-motor control mechanism of human beings and its application to robotic arms (Fig. C.66).

The third project was a legged microdevice, which could be used as capsular endoscope. The researchers of ARTS study how such a device can automatically move in a tubular, compliant and slippery environment. The potential application is for the diagnosis and therapy of gastrointestinal tract problems of human beings. The fourth topic is an active microendoscope for exploration of the spinal cord. Another topic is related to a mechatronic tool for computer-assisted arthroscopy.

Figure C.66. Sensor-motor control of humanoid robot.

We also saw two robotic hands with five fingers, one made entirely of silicon based materials and the other of metal components. In both cases, each finger had just one degree of freedom.

The CRIM Lab

CRIM focuses on the design and development of micro- and nano-devices, but its strategy is to avoid silicon processing methods popularly used for fabricating integrated circuit (IC) devices which includes many chemical processes such as lithography, itching, diffusion. Instead, CRIM directly cuts materials, plastic, metal or silicon using precision machines. For that purpose, CRIM is provided with a set of machining equipment, such as a Kern HSPC micro computerized numerically controlled (CNC) machine, an electrical discharge machine, a plastic injection molding machine, and a microerosion system. All the equipment is housed in a 100 square meter cleanroom of classes 1,000 and 10,000.

With the above set of equipment, CRIM has developed micro- and nanosensors for different applications including:

a. A novel hybrid silicon three-axial force sensor with a volume less than 7 mm^3
b. Environment-monitoring devices such as a microsensor for atmospheric mercury monitoring and microEMS (Micro Environmental Monitor System) for analyzing heavy metal pollutants in surface and ground water
c. Endoscopy, which was mentioned earlier
d. A mechatronic tool for computer-assisted arthroscopy, which was mentioned earlier

SUMMARY

The PSV research park was one of the largest groups in robotics research that the assessment panel visited. Robotics research activities are primarily conducted in two laboratories, ARTS and CRIM. Current efforts of PSV focus on four strategic lines: surgical robots, mini/micro/nanorobotics, rehabilitation robots, and assistive technology for the elderly. During the research, however, researchers of PSV seek biomorphic and anthropomorphic solutions. PSV has developed quite a few robotic devices and systems while researchers are equally strong in fundamental studies, as many papers have been published by PSV.

Another note is that PSV has an active joint program with the Waseda University in Japan called RoboCasa for which students were exchanged (the WTEC study team saw three Italian students at Waseda University in late 2004).

Site: **Technical University of Berlin (TUB)**
Strasse des 17. Juni 135
10623 Berlin, Germany

Date Visited: April 28, 2005

WTEC Attendees: R. Ambrose (Report author), M. Dastoor, Y.T. Chien, B. Wilcox, D. Lavery

Hosts: Prof. Dr.-Ing Günter Hommel
Faculty of Electrical Engineering and Computer Science
Real Time Systems and Robotics
Tel: +49 30 314-73110
Fax: +49 30 314-21116
Email: hommel@cs.tu-berlin.de

BACKGROUND

Prof. Hommel has been working in robotics for more than 20 years, starting at Technical University Munich (TUM) before coming to Technical University Berlin (TUB). He started in computational kinematics, developing an expert system to find closed form solutions for the inverse kinematic problem. Working with the University of Southern California (USC)/Belgrade dexterous hand led to the development of a sensor glove used for teach-in programming and other applications like gesture recognition. For path planning and collision avoidance (and also for parallel robots), first geometric algorithms were used resulting also in work on geometric assembly planning. Later, motion planning problems were solved using methods from optimization theory. For task planning a knowledge-based real-time planning system was realized using modal logic and scripts for knowledge representation. In the field of object recognition, different sensor systems based on ultrasonic 3D field reconstruction, active stereo vision, and lasers were developed. Service robotics (in close cooperation with Daimler-Chrysler), and medical robotics (in close cooperation with Charite University Hospital in Berlin) were more recent activities. Currently, aerial robotics, exoskeletons, and biologically inspired control architectures for mobile robots are the main foci in the field of robotics.

HELICOPTERS

One of the research directions of the group is focused on autonomous helicopters. A huge amount of work has been performed in helicopter control, development of low-cost sensors for autonomous flight, sensor fusion and algorithms for environment perception. The current and future work in this research area is devoted to cooperation of multiple autonomous helicopters for coordinated execution of different tasks, e.g. perception of the environment with different sensors mounted on different helicopters, transport of a load with multiple coupled helicopters.

Figure C.67. Marvin Mark II in autonomous flight.

The first lab was centered on custom helicopter integration using a commercial gas-powered chassis. These helicopters are meant for autonomous outside flying and have a rotor diameter of approximately 2 meters. The helicopter design is the successor of the Marvin helicopter that won the International Aerial Robotic Competition held in the year 2000 by the Association for Unmanned Vehicle Systems (AUVS). In the last three years these helicopters were part of a European project working on the coordination and cooperation of a fleet of heterogeneous unmanned aerial vehicles (UAVs). The team just came back from the final demonstration in a forest fire scenario, which was held in Portugal (see above). The flying system itself nicely integrates all necessary sensors and computational power for autonomous flight and environment perception, namely a camera on a pan-tilt-platform and a special kind of fire sensor in a custom build case (see below). The systems are reported to do fully autonomous start, land and fly 3D trajectories.

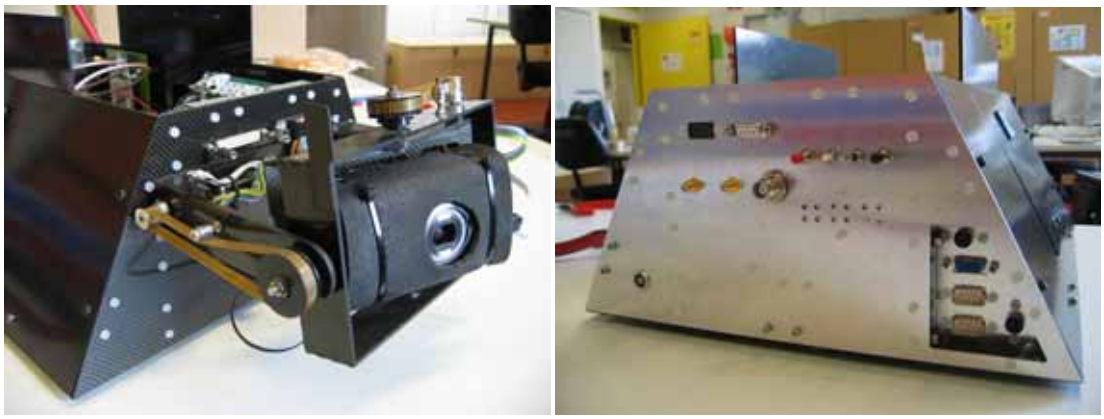

Figure C.68. Marvin's electronic box.

In the second lab an experimental setup based on a free-flying autonomous electrical helicopter was developed. This setup is composed of a commonly used electrical model helicopter equipped with a microcontroller and a small size computer with a real-time OS as well as with an inertial measurement unit. The Cartesian coordinates of the helicopter are provided by mechanical linkage connected to the helicopter and to the ceiling. The team is working on a vision-based system which should replace the linkage. With the experimental setup in this lab, real flight experiments can be performed. This setup has been used for experimental validation of new approaches for helicopter control and for experimental validation of the models for helicopter behaviors, especially for the air dynamical effects on the main rotor.

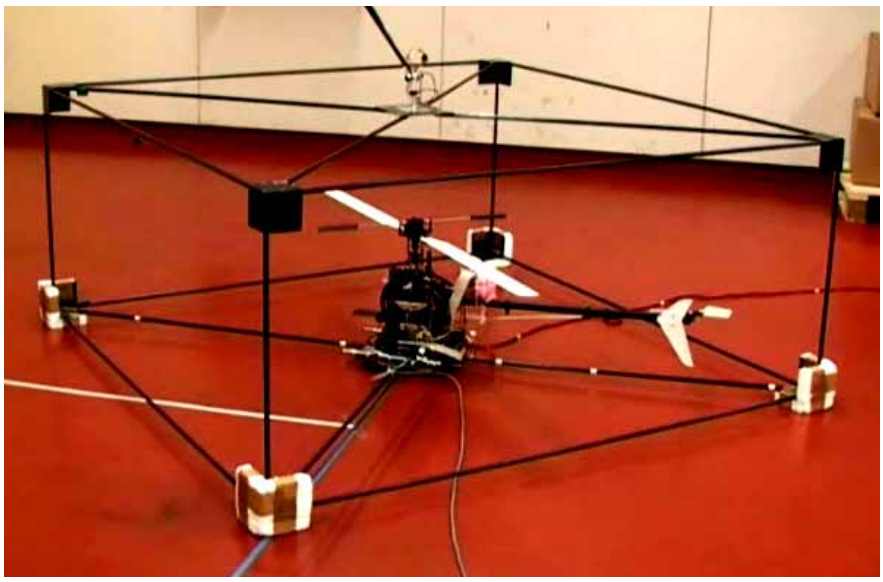

Figure C.69. Autonomous indoor helicopter test-stand.

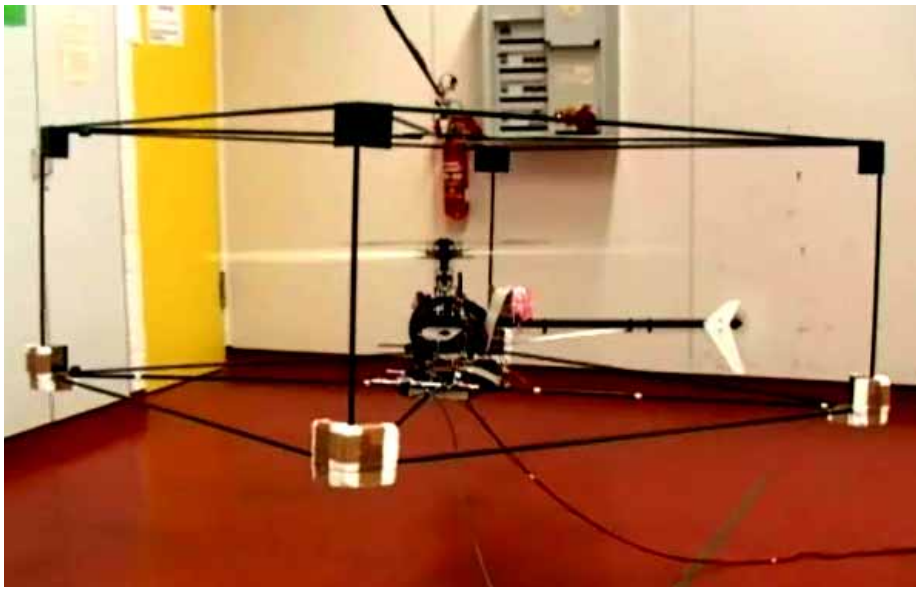

Figure C.70. Indoor helicopter in autonomous flight.

Exoskeletons

The research on exoskeletal devices at the institute is divided into two parts: powered leg orthosis and hand exoskeleton. Whereas the hand exoskeletal work is loosely based on former work of the TUB data glove, the leg orthosis is a completely new project running for almost two years now. The aim of the project is to develop a device that is able to support the leg muscles during common movements like walking, climbing stairs and getting up from a chair—mainly for rehabilitational purposes. With this goal in mind, the main attention is paid to the human-machine-interface that has to be able to recognize the desired motion of the operator to support it properly.

Figure C.71. Powered leg orthosis and motion capturing device.

Two approaches to achieve this are currently investigated: 1) Motion recognition by analyzing electromyographic (EMG) signals of the muscles spanning the actuated joint(s). 2) Analyzing the motion of the so-called “healthy” leg and deriving a suitable motion for the supported leg. Additional attention is paid to implementing new control strategies for the actuator control and to improving sensor data processing to get a precise measurement of the current body state and outer influences like (ground) reaction forces through the sensors embedded in the orthosis.

The hand exoskeleton has been developed with the main focus on rehabilitation and diagnostic support. The work is performed in cooperation with the clinic of Ulm University. The robotic assisted rehabilitation is believed to enhance rehabilitation after surgery or stroke. Currently four degrees of freedom for one finger are actuated by the mechanism but the final exoskeleton will support all fingers. Force is transmitted via pull cables to the joints of the exoskeleton. Sensors of the exoskeleton capture position, force values, and muscle activity. Based upon basic position control, more complex modes including force control are under development.

Figure C.72. Hand exoskeleton with four actuated fingers.

Site: **Technical University of Munich (TUM)**
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Department of Mechanical Engineering
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Sonderforschungsbereich 453
Institute for Real-Time Computer Systems
80290 München
http://www.sfb453.de/

Date: April 27, 2005

WTEC Attendees: B. Wilcox (Report author), R. Ambrose, G. Bekey, V. Kumar, Y. T. Chien, D. Lavery, M. Dastoor

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BACKGROUND

Prof. Dr. Alois Knoll gave a brief introduction to the Technical University of Munich (TUM). The university originally existed as the University of Ingolstadt from 1472. It was moved to the capital of Bavaria, Munich, in the year 1826, by Louis I. Four Nobel Prize winners have been faculty at TUM. TUM has about 20,000 students (both graduate and undergraduate), with 480 professors and 8,500 total employees. It is ranked first in "3rd party" funding in Germany, at about €120 million per year. It has the largest neutron source in Europe (a reactor); it operates the European Southern Observatory in Chile, and has a number of Max Plank Institutes on campus. It is based on three campuses: Garching (with most engineering departments), Freising/Weihenstephan (hosting the "green departments," agriculture, food technology—and the oldest brewery) and the Munich city center (with electrical engineering, economics, architecture). The mechanical engineering area consists of eight parts including mechatronics, machines and vehicles, and medical technology. In the Informatics area they have 19 chairs, 49 professors, 2,223 students (of which 414 are in their first year. Between 5 and 10% continue to the doctorate level beyond the "Diploma" (M.Sc.).

A presentation on robot learning was given by Prof Dr. Jürgen Schmidhuber. The focus of this area is on recurrent neural networks, optimal universal learners, and Gödel machines. In the area of cognitive robotics

they have built the Cogbotlab (see http://www.idsia.ch/~juergen/cogbotlab.html). This work is in collaboration with Istituto Dalle Molle di Studi sull'Intelligenza Artificiale (IDSIA) in Lugano, Switzerland. There was a discussion of the fact that the Haber-Bosch process (the commercial process to make ammonia fertilizer) has been declared the most influential invention of the 20th century, since it enabled the population explosion by allowing agricultural productivity to expand exponentially. By analogy, Prof. Schmidhuber stated that we are on the verge of a robot population explosion that will be enabled by cognitive robots. To make such robots possible we need to address the ultimate learning problem: how to maximize the expected remaining "reward function" until death. The question is how to maximize, and what is optimal?

An example shown was a reactive robot that learns to find a yellow cup while avoiding running into a wall. The robot has no prior programming to help it know how to drive. For the case of Robocup they have developed a feedforward neural network to predict/plan five steps ahead. A recurrent neural network (RNN) uses feedback to provide internal state. Conventional neural networks are essentially statistics (e.g. Bayes' Theorem), while RNNs are not the same (see http://www.idsia.ch/~juergen/rnn.html).

They are also investigating evolution methods. Evolino is a system that evolves hidden units in a neural network. A simulation was shown of cylinder with small surface actuators that "learns" to reduce drag to a minimum. Some key ideas are the Bayesmix predictor (closely related to Occam's razor, see http://www.idsia.ch/~marcus/idsia/nipsws.htm), the work of Solomonoff (see http://world.std.com/~rjs/1964pt1.pdf), Hutter Universal Induction and Decision Theory.

Next was a presentation on High-Fidelity Telepresence and Teleaction by Prof. Dr. Alois Knoll (see http://www.sfb453.de/) This work is collaborative between Professors Ulbrich, Bauernschmitt, Knoll, Zäh/Reinhart, Diepold, Steinbach, Buss, Walter, Färber at TUM and Hirzinger at DLR. The overall principal investigator is Prof. Dr.-Ing G. Färber, treated as "collaborative research units (SFB453)" with long-term funding, selected by Deutsche Forschungsgemeinschaft (DFG). This is the German Research Foundation, equivalent to the U.S. National Science Foundation, see http://www.dfg.de/en/index.html. The purpose is to get the best people working together for a maximum of 12 years. Approximately 10% of proposals are funded, for a total of between 100 and 120 that are now funded. These proposals are peer reviewed, with a very elaborate selection process, but if selected, they have total budgets of €2–3 million per year, funding between one to four institutions per proposal, for substantial multi-year durations.

There was a discussion of the desire of TUM to incubate new companies (they have an incubator on the Garching campus). Spin-off companies can apply for venture capital provided in part by the state of Bavaria under a variety of different funding schemes. The university also provides or arranges capitalization as well as intellectual property licensing in return for their share of ownership. For patents, their policy is that 2/3 of patent revenues go to the university, and a third to the university employee (inventor).

Prof. Dr. Heinz Ulbrich of the Institute for Applied Mechanics discussed active control for detection of contact by the tips of turbine blades and prevention of future contacts or shutdown. Turbine tip clearance strongly affects turbine efficiency, but of course contact is a major cause of failure. He also discussed a high-performance pan-tilt head for the automotive industry (see http://www.abayfor.de/abayfor/English/_media/pdf/publikationen/infoblaetter/abayfor_forbias_GB.pdf), and high-performance inertial sensing.

Next the biped walker "Johnnie" (Figure B.73) was discussed. This humanoid robot has a 40 kg mass, is 1.8 m tall, and is designed to walk at 2 km/h. It uses 20 Maxon motors with harmonic drives for actuation. The ankle joints are actuated via linear ball screws. The objective is to demonstrate autonomous walking and hazard avoidance. It was developed by two people over five years, starting eight years ago, with a smaller budget than most of the comparable Japanese projects with similar scope and accomplishments. It was originally a cooperative project with neurological researchers investigating hemi-paretic walking, where a stroke on one side of human brain makes it so that physical therapists have approximately 8–10 weeks to re-establish walking or the brain walking functions are permanently lost. Originally, they wanted fast walking, which worked great in simulation. It seemed that it should have been possible to make a fast walking machine with then-current motors, etc. However, it was not trivial to make stable walking gaits. It is not based on the quasi-static zero moment point (ZMP) algorithm (used by most Japanese researchers) or anything like it—Johnnie is a non-linear dynamical system that must be stabilized. They have close

collaboration with the harmonic drive vendors—friction is 30% of energy, and models must be accurate to be able to stabilize the system with this much friction. The actuator torque is 200 Nm for the hips and knees. Each three degree-of-freedom (DOF) hip actuator assembly has a mass of 4.3 kg with four motors. They wanted very sophisticated foot dynamics but didn't achieve that. They feel that they need toes, but don't have them at this time. They still have close collaboration with neurobiologists. There is still a significant problem with fast walking: by comparison insect walking is much simpler than human walking; no one yet knows very well how human walking is controlled, and fast walking is not really feasible right now with conventional methods (e.g. multi-I/O Position Integral Derivative (PID) control) with observers for friction and gravity). Humans do fast walking with less effort than slow walking—not like robots. Johnny I has >50 sensors, about 80 sensor inputs, including six DOF Inertial Reference Unit (IRU) (currently about 80 Hz, need 400–600 Hz) but does not have a high-performance military-grade inertial sensor. It is hard to model elasticity to compute the angular position of the body—the angular position must be known quite accurately (e.g. to compute the projection of the gravity force through the foot) and one cannot compute it solely from the kinematics. The new biped, Johnnie-II, under development, will have about 400 Nm of torque in the hip and knees using the same size motors. The actuators will have a mass of 5.6 kg with three DOF (compared to 4.3 kg for three DOF) at 200% of the mechanical output power. A good human athlete can deliver almost 300 Nm of torque at the hips. Sensor data processing is not fast enough now—they need fast analog to digital (A/D) conversion at sensors. The computers are not fast enough, but the new models are much quicker than the old ones. The main problems have been with the sensors (e.g. sensor failures), bus bandwidth (they were using a CAN bus, but now use a parallel bus), processing in general, and action selection.

Figure C.73. Humanoid ‘Johnnie.’

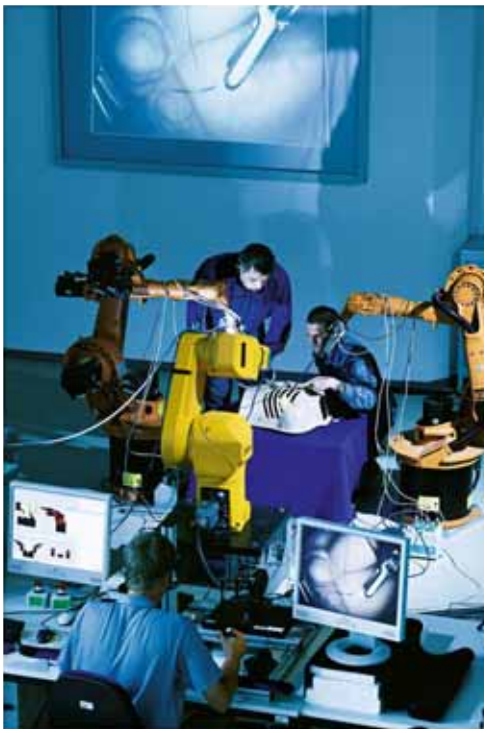

Figure C.74. Integration of force feedback in minimally invasive robotic surgery.

A question from panelist Robert Ambrose was, “One needs to control all the DOF at the same time, but that is difficult. Perhaps it would be good to start with the feet, and then move to more human-like ‘through-the-singularity’ (e.g. partly straight-leg) walking, then to use other DOF to maintain the center of gravity (CG) at constant elevation (as a human does).” The answer is that most Japanese don't have an overall control system, and ZMP doesn't support fast walking. TUM seeks to create an overall control system that solves the control problem “more correctly” (e.g. not using ZMP). Panelist George Bekey asked if they are aware of the research that views fast walking as controlled falling, that uses series-elastic actuators, and incorporates some

of the new high-performance microelectromechanical systems inertial reference units (IRUs). The answer is that they are aware of all of these methods and feel they are doing the right thing within their budgetary constraints.

Autonomy/Automation in Medical Robotics, part of SFB453, was presented by Dr. Knoll. They are developing haptics (feedback of force and touch sensing) for surgery and skill transfer (e.g. an experienced person training an inexperienced person on how the procedure should "feel"). This approach offers tremendous potential for scaling to non-human "sized" situations, improved accessibility, and range of distance, dexterity and speed. An example is minimally-invasive heart surgery—Intuitive Surgical's DaVinci system is already on market, but has no autonomy, no haptic feedback (vision only), and is very fatiguing. TUM is developing its own minimally invasive surgery system (see Figure B.74), and they are currently evaluating haptic feedback and automating complex manipulation sequences. For example, they are attempting to tie knots as seen in textbooks for surgery. The system is force-reflecting in three axes (e.g. the human operator "feels" the force in x, y, and z, but not in roll, pitch, or yaw). The first system they have built uses three industrial robots with force sensors and surgical drapes, a head-mounted display, and force-reflective hand controllers (the commercial "Phantom" devices). They can plot the gripper trajectories in 3D space to record any operation, and can "playback" knots tied by skilled surgeons. Tests have demonstrated reduced forces on tissues as compared to direct operations conducted by typical human surgeons. Most surgeons have preferred 2X amplification of force back to the haptic interface, to give them a better "feel" for what is going on. They want to be able to automate elementary operations by closing the visual serving gap. This means, however, that full visual scene interpretation is needed, including recognition and reconstruction of the fine suture material. Moreover, for transparent support of the surgeon and seamless transfer of control between the semi-autonomous robot and the surgeon, the system must be able to recognize what phase the operation process is in. The overall goal is to move the surgeon up in the hierarchy of controllers, e.g. to initiate "skills" that are done automatically. They now have a system with four instruments and multiple endoscopes—they are exploring when additional arms are useful. They are also developing new scenarios for the operating theatre in which M surgeons control N robots.

Next Thomas Bock of the faculty of architecture spoke about construction robotics. The greatest portion of the work in this field is going on in Japan, since there is no cheap labor available there. Approximately 400 robotic civil engineering systems have been built since the early 1980s. For example, tunnel boring is fully automated (e.g. there are no people "down the hole" during normal boring and lining operations). There are realistic near-term visions of fully automated road construction. Examples were presented of attempts to perform channelizing of lava flows near volcanoes by automated systems. Automated house manufacture has demonstrated the capability to build one house every 2.5 minutes. In Japan, they make houses that are 85% prefabricated off-site and take four to six hours to assemble on-site. Over 5,000 houses per year are built this way from many different sorts of materials (steel, concrete, wood, etc.).

Early robots for construction failed because they copied commercial construction instead of making it robot-friendly. At TUM they now have a 12 x 12 m space that can make any type of pre-formed concrete wall panels, floor panels, girders, beams, etc. In the case of a floor tiling robot, the observation was made that many universities have made the same mistake in that they have tried to do such tasks in the same way that humans do them. Instead they should make everything robot-oriented. Their system is now able to make one floor each week—completely finished. They have also developed MORITZ, a pipe crawling walking machine (see http://www.amm.mw.tum.de/Research/Research/fzagler_e.html).

Site: **University of Zürich**
Artificial Intelligence Laboratory
Dept. of Information Technology
Andreasstrasse 15
CH - 8050 Zürich, Switzerland
http://www.ifi.unizh.ch/groups/ailab/

Date: April 25, 2005

WTEC Attendees: Vijay Kumar (Report author), G. Bekey

Hosts: Professor Rolf Pfeifer, Computer Science Department, Director, AI Lab, Department of Information Technology, Tel: +41-1-635 43 20/53, Fax: 41-1-635 45 07, Email: pfeifer@ifi.unizh.ch
Pascal Kaufmann, Doctoral student, President, Student Research Opportunities Program, ETH, Email: kaufmann@sirop.ethz.ch

OVERVIEW

The University of Zürich Artificial Intelligence (AI) Laboratory is a group of 20–25 PhD students and five postdoctoral fellows directed by Professor Rolf Pfeifer with a mission to understand intelligence, its embodiments and their interactions with the real world. Pascal Kaufmann, a bright young doctoral student, who also happens to be the president of the Student Research Opportunities Program at Swiss Federal Institute of Technology (ETH), represented Professor Pfeifer's group.

GOALS

The AI Lab is strongly based on the work of Rodney Brooks and has three guiding principles:

- Intelligence is derived from organism-environment interactions and is therefore from the need to build physical embodiments and study interactions with the real world
- The body itself can do physical (analog) computation via its interactions with the real world
- Nature and evolution in nature provide basic principles that can be used for intelligent systems

The different projects are derived from two basic premises. First, intelligence emerges through the interaction of the brain, the morphology of the embodiment and its manifestation, and the environment. Second, the laboratory believes in *synthetic methodology*, the methodology in which we gain understanding of complex systems by building and realizing these systems in the real world.

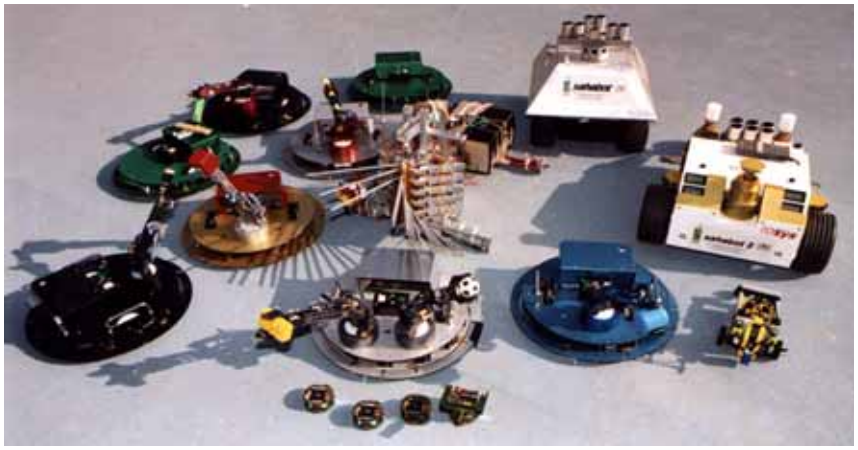

Figure C.75. Examples of embodiments of intelligence in the AI Lab.

PROJECTS

Professor Rolf Pfieffer's laboratory has several funded project areas.

1. Collective intelligence: The organization of robots into flocking and swarming formations by processing simple, local rules based on studies of nature.
2. Self-organization and self-repair of robots: The construction of robots using cellular automata that mimic reaction diffusion systems and simple growth rules for repair.
3. Evolution of artificial cells: The study of the evolution of cells to mimic biological growth.
4. Artificial evolution morphogenesis: The study of animals with different morphologies, and simple rules for organization leading to different morphologies.
5. Neural interfacing: The concurrent study of neurons, pathways in the brain and the perception-action loops in nature and in robotic systems.
6. Humanoid robotics: The design of human-like embodiments of intelligence.
7. Locomotion and orientation, biorobotics: The design of biomimetic locomotion systems and the study of perception-action loops in natural systems.

We were particularly impressed by the commitment to wet lab research (culturing neurons on chips, stimulating neural cells of lamprey fish by laser light) and the coupling of this research to the control of robots. The research includes the use of confocal laser microscopy to understand the mapping of efferent signals to actions in the lamprey brain and the synthesis of a neural network that mimics the lamprey brain.

Figure C.76. Robots with omni-directional cameras used for bio-inspired swarming behaviors

INTERACTIONS WITH OTHER LABS

The lab has a number of collaborative EU projects and an exchange program with Northwestern University. The neural-interfacing work is done in collaboration with the Swiss Federal Institute of Technology at Hönggerberg.

RESEARCH CULTURE

Postdoctoral and doctoral students have a fair degree of autonomy in pursuing their interests and are encouraged to think creatively within the goals and the philosophy established by the director of the research laboratory. Professor Rolf Pfeifer leads an impressive group funded by a wide range of projects and the group's activities are very synergistic. The research agenda for the laboratory is wider in scope and on a significantly longer time scale than that for similar laboratories in the United States.

APPENDIX D. VIRTUAL SITE REPORTS—AUSTRALIA

INTRODUCTION

Research and development in robotics are very active areas in Australia, with support from both government agencies and private industry. Australian researchers have made significant contributions to both the theoretical and practical sides of the field. Unfortunately, budgetary constraints made it impossible for the team to visit Australia. Hence the two site visit reports that follow are virtual: the material was provided by the researchers. The laboratory directors were provided with a set of questions; their replies to the questions are reported here verbatim.

As can be seen from the site reports, both laboratories have been very active in mobile robotics, having developed a variety of advanced ground, underwater and aerial vehicles, as well as mining robots for deployment in mines.

Site: **Australian Centre for Field Robotics (ACFR)**
The Rose Street Building J04
The University of Sydney, NSW 2006, Australia
http://www.acfr.usyd.edu.au/

Date info. Rec'd: December 20, 2005

WTEC reviewers: G. Bekey, V. Kumar, A. Sanderson

Host: Hugh Durrant-Whyte
Director, Australian Centre for Field Robotics
Professor of Mechatronic Engineering
Email: hugh@acfr.usyd.edu.au

BACKGROUND

Robotics at The University of Sydney Australian Centre for Field Robotics (ACFR) is focused on field applications including cargo handling, mining, aerospace, subsea and defense applications. The ACFR is the lead partner in the ARC (Australian equivalent of the NSF) Centre of Excellence in Autonomous Systems, a partner in the Cooperative Research Centre (CRC) in Mining, and is also a DSTO (Defense Science and Technology Organisation) Centre of Expertise in Autonomous and Unmanned Systems.

RESEARCH

The ACFR has four major research themes: Perception, Control, Learning and Systems. These are briefly summarised here:

- **Perception**. Sensor development; especially mm-wave radar, composite radar/EO, inertial/global positioning systems (GPS). Navigation methods; especially simultaneous localization and mapping (SLAM), high-speed navigation, aerospace and subsea navigation systems. Data Fusion: decentralised data fusion methods, statistical approaches to data fusion and mapping.
- **Control**. Platform models; especially for airborne and high-speed land vehicles. Cooperative control; especially for multi-unmanned aerial vehicle (UAV) systems
- **Learning**. Statistical machine learning; especially manifold learning methods as applied to problems in perception and navigation

- **Systems**. System Modelling; especially use of formal methods for specification and verification, mathematical modelling of networked systems. System Design; especially design tools and middleware development.

In addition, the ACFR operates a number of large-scale demonstration systems. These include a fleet of highly capable UAVs, two large unmanned ground vehicles, two submersibles, an unmanned surface vessel, and a dozen other smaller platforms. The ACFR operates a large (20,000 hectare) flight-test and field-test facility. It also has shared access to an island for offshore systems testing.

DEVELOPMENT

The ACFR has close ties with industry in Australia and overseas. It has developed a number of commercially successful systems. Examples of this interaction are:

- The development and realisation of an autonomous 65 ton straddle carrier for cargo handling. Two operational terminals, including one with 18 straddle carriers, is now in commercial use. This system exploits past research in Kalman-filter based navigation and vehicle modeling as well as work in multi-robot systems.
- The development and realisation of a number of robotic mining systems including guidance systems for 250 ton mining haul trucks, and mm-wave radar-based devices for mine imaging and collision avoidance.
- The development of decentralised data fusion methods in defense applications, now used in a growing number of worldwide defense programmes. Substantial funding for this is received from U.K., U.S. and Australia.

FUNDING

The ACFR receives approximately AUD$6m/year in funding, of which 50% comes from industry-funded projects. This supports a group of 120 staff and PhD research students. We consider ourselves to be well-funded by international measures.

It should be noted that at Australian universities, no overhead is paid on monies received from funding agencies. Indeed, researchers typically receive an additional 30% through additional research infrastructure block grants (RIGB). Further, PhD scholarships are separately funded from government/institutional support and not counted in overall funding. Consequently $1 in Australia is worth substantially more than $1 in the United States.

COMPARISONS TO WORK IN EUROPE, ASIA AND THE U.S.

There are a number of areas in robotics where we believe ACFR leads the world, both in research and development:

- **Autonomous Navigation.** The group here is the world leader in localisation and navigation methods. We were the initial developers of Kalman filter-based navigation methods for robotics applications. We have also pursued this further to commercial realisation than any other group. We also invented the term "SLAM" and undertook all the initial development, proof of operation, first implementations, etc. We are probably also the most advanced users of these ideas; in subsea and airborne systems for example. SLAM has become one of the big success stories in robotics; a problem posed and solved.
- **Decentralised Data Fusion.** Over nearly twenty years the group here has developed and demonstrated decentralised probabilistic data fusion methods. Increasingly this work has proved to be world-leading and attracts funding from companies and organisations in the U.S., Europe and Australia. The techniques have increasingly been integrated into major defense programs. This is almost unique technology to ACFR.

- **MM-wave radar.** The ACFR has unique capabilities in design, development and use of mm-wave radar technology for robotics applications. This technology is critical for many ground-vehicle and airborne applications. The ACFR and associated start-up companies produce over 100 radar units a year for robotics applications. No other group, commercial or university, comes close.
- **Commercial application of field robotics.** In the past five years, the ACFR has overtaken CMU to become the leader in commercialising non-defense field-robotic applications. This is particularly true in the number of now fielded systems in areas such as cargo handling and mining. It is our intention to make Australia the world centre of expertise in commercial field robotics systems.

EXAMPLES OF CURRENT RESEARCH

Figure D.1. Autonomous straddle carriers in operation at the Port of Brisbane.

Figure D.2. Guidance system (side and top of vehicle) for large autonomous mining haul truck.

Figure D.3. UAV in Climb-out. Scale of UAV.

Figure D.4. Four different mm-wave radar applications: clockwise from top left; airborne terrain imager, straddle carrier navigation sensor, mining collision detection, terrain profiling for autonomous excavator.

Figure D.5. Deep subsea platform in operation on the Barrier Reef.

Site: **Australian Commonwealth Scientific and Industrial Research Organisation Laboratory (CSIRO)**
Autonomous Systems Laboratory
CSIRO ICT Centre
Technology Court, Pullenvale
Queensland 4069, Australia
http://www.ict.csiro.au

Date info red'd: January 16, 2006

WTEC reviewers: G. Bekey, V. Kumar, A. Sanderson

Host: Peter Corke, Senior Principal Research Scientist, CSIRO Queensland Center for Advanced Technologies (QCAT) Brisbane, Australia,
Email: Peter.Corke@csiro.au

BACKGROUND

The Australian Commonwealth Scientific and Industrial Research Organisation Laboratory (CSIRO) Autonomous Systems lab has a strong focus on reactive control, with a particular emphasis on the use of vision. Dr. Corke was an early pioneer in the area of visual servoing, demonstrating in 1989 a 50 Hz closed-loop system, the fastest at that time. He contributed chapters to early books on the topic and published the first monograph. More recently he has made theoretical contributions related to partitioned systems.

RESEARCH AND DEVELOPMENT

This reactive control philosophy underpins much of the work in mining robotics as well as flying and underwater robots. The control approach fuses fast reactive loops with planners based on very approximate world models, thus sidestepping the problem of map generation and localization. In applications where localization is required, it is seldom required all the time, and this greatly simplifies the problem. This approach is necessitated since mining machines have to work in an environment that cannot be mapped apriori and that is continually changing.

More recently we have taken these ideas and applied them to the control of vehicles. We have developed non-linear control laws for visually servoing a non-holonomic vehicle to a pose, and vision systems for stabilizing vehicles operating in six degrees of freedom (DOF), such as flying and underwater vehicles. Vision is also used for collision detection, odometry, locale and landmark recognition.

FUNDING

Robotics research in Australia is funded by an NSF-like agency (ARC), federal research labs (such as CSIRO) and industry. There is almost zero military funding. In some ways this is a benefit, in that robotic applications that make economic sense are developed. While more funding would always be desirable it may well remove the keen commercial/applications drivers of the work, perhaps leading to more publications but fewer useful robots. Funding for this laboratory is approx AUD$5 million. The staff includes 20 full-time scientists/engineers, plus students and visitors.

COMPARISONS TO WORK IN EUROPE, ASIA AND THE U.S.

We would claim world leadership in the area of mining robotics. Other labs in U.S. (Carnegie-Mellon University-CMU) and Canada (Laurentian, Queens) have largely dropped this area. Our work includes developments in dragline and rope-shovel excavators (such as real-time 3D terrain mapping, path planning, interaction force control), haulage equipment (such as LHDs) and explosive loading.

In the area of vision-based control we would claim equal top with several French groups such as Institut de Recherche en Informatique et Systèmes Aléatoires (IRISA), UNSA-CNRS and LAboratoire des Sciences et Matériaux pour l'Électronique et d'Automatique (LASMEA). The French groups are stronger theoretically, while our group is stronger in diverse applications, such as pose stabilization of ground, underwater and flying vehicles.

EXAMPLES OF CURRENT RESEARCH

Figure D.6. Automated dragline excavator, 3,500 ton machine. Landmark digging trials moved 250,000 tons of material over a two week period in 2003. Performance exceeds that of an “average” human operator.

Figure D.7. Automated load-haul-dump unit (scooptram) used for ore-haulage in underground mines. Capable of autonomous navigation in underground tunnel environment at speeds of 20 km/h with less than 0.5 m clearance on each side. Navigation by means of laser-scanner for free-space detection and topological maps, using reactive navigation with opportunistic localization. Technology licensed to Caterpillar.

Figure D.8. Automated tractor. Small-scale test vehicle for research into visual guidance algorithms such as optical flow and stereo-based obstacle avoidance, visual feature-based navigation, non-holonomic visual servoing.

Figure D.9. Small-scale autonomous helicopter, 60-class gas-powered vehicle with $10,000 avionic system comprising low-cost inertial sensors and stereo vision, no GPS, and all onboard computing. Visually stabilized hover demonstrated with natural image features, no artificial targets.

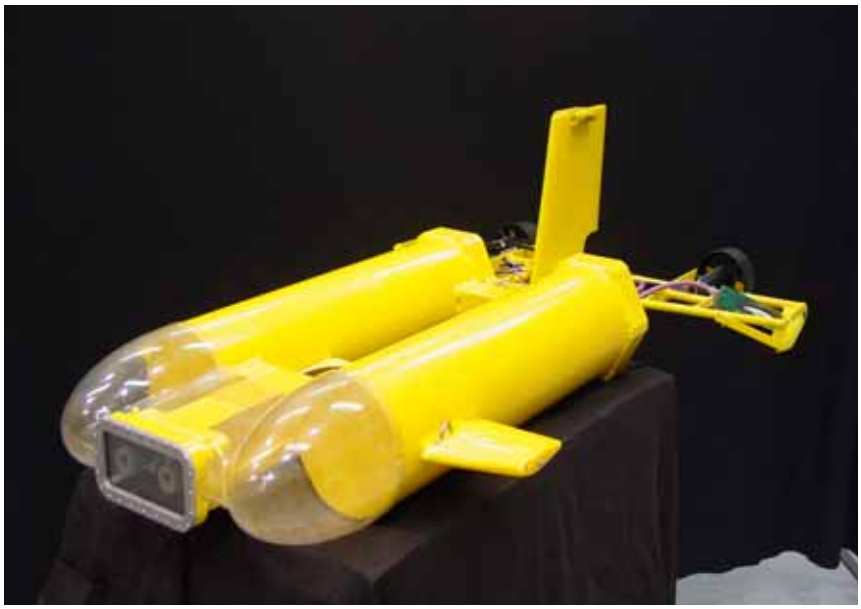

Figure D.10. Hybrid AUV designed for efficient forward motion but with station keeping ability. Tetherless transects over 1 km with terrain following demonstrated. Selected for Antarctic under-ice exploration mission in 2007. Low-cost inertial and stereo vision for terrain following and visual odometry.

APPENDIX E. GLOSSARY

AAAI	American Association for Artificial Intelligence (U.S.)
ACFR	Australian Centre for Field Robotics (Australia)
ADCP	Acoustic doppler current profiler
ADD	Agency for Defense Development (Korea)
AGV	Automated guided vehicle
a priori	From the former or before experience
AI	Artificial intelligence
AIST	National Institute of Advanced Industrial Science and Technology (Japan)
AKI Laboratory	Arimoto-Kawamura-Isaka Laboratory at Ritsumkeikan University (Japan)
ALIVE	Autonomous Light Intervention Vehicle from IFREMER (France)
AMASON	Advanced MApping with SONar and Video at Heriot-Watt University (U.K.)
AOSN	Autonomous Ocean Sampling Network (U.S.)
a priori	Proceeding from a known or assumed cause to a necessarily related effect
ARI	Automation and Systems Research Institute
ARTS Lab	Advanced Robotics Technology and Systems Laboratory at the Polo Sant'Anna Valdera of the Sant'Anna School of Advanced Studies (Italy)
ASME	American Society of Mechanical Engineers (U.S.)
ASRI	Automation and Systems Research Institute at Seoul National University (Korea)
ASTEP	Astrobiology Science and Technology for Exploring Planets (U.S.)
ATR	Advanced Telecommunications Research Institute (Japan)
AUSI	Autonomous Undersea Systems Institute (U.S.)
AUV	Autonomous undersea vehicles
AUVS	Association for Unmanned Vehicle Systems
BcN	Broadband convergence Network
BIO Labs	Biological Laboratories at the Polo Sant'Anna Valdera of the Sant'Anna School of Advanced Studies (Italy)
BKC	Biwako-Kusatsu campus at Ritsumeikan University (Japan)
BT aneurysm	Basilar top aneurysm

CAD	Computer-aided design
CCD	Charge-coupled device
CES	Consumer electronics show
CG	Center of gravity
CIFATT	Research, Development and Technological Transfer Center of IPA Cluj (Romania)
CIMR	China Institute of Mining Systems (China)
CML	Cooperative Mapping and Localization (U.S.)
CMU	Carnegie-Mellon University (U.S.)
CNC	Computerized numerically controlled or computerized numerical control
CNS	Computational Neuroscience Laboratories at ATR (Japan)
CNES	Centre National d'Etudes Spatiales (France)
CNRS	Centre National de la Recherche Scientifique (France)
CNTs	Carbon nanotubes
COE	Center of Excellence (Japan)
CORBA	Common Object Request Broker Architecture
CoRE	Center for Open Robot Experiments
COTS	Commercial-off-the-shelf components
CRASAR	Center for Robot-Assisted Search and Rescue (U.S.)
CRIM	Center for Applied Research in Micro and Nano Engineering at the Polo Sant'Anna Valdera of the Sant'Anna School of Advanced Studies (Italy)
CSP	Constraint satisfaction programming
CT	Computed tomography
CTD	Conductivity, temperature and depth
DARPA	Defense Advanced Research Projects Agency (U.S.)
DC	Direct current
DIND	Distributed Intelligent Network Devices
DIST	Department of Communication, Computer and System Sciences at the University of Genova (Italy)
DKRS	Distributed knowledge representation and reasoning systems

DLR	Deutschen Zentrum für Luft- und Raumfahrt (Germany) German Aerospace Center
DMB	Digital multimedia broadcasting
DoD	Department of Defense (U.S.)
DOF	Degree of freedom
DP	Dynamic positioning
EMATs	Electromagnetic acoustic transducers
EMG sensors	Electromyographic sensors
EPFL	Ecole Polytechnique Fédérale de Lausanne (Switzerland)
ERATO	Exploratory Research for Advanced Technology (Japan)
ESA	European Space Agency
ESRT	Exploration Systems Research and Technology (U.S.)
ETH	Eidgenössische Technische Hochschule Zürich, the Swiss Federal Institute of Technology (Switzerland)
ETS	Engineering Technology Satellites (Japan)
EUROP	European Robotics Platform
EVAs	Extravehicular activities
FPGA	Field programmable gate array
GCS	Guidance Control System (GCS), company formed by Dr. Michael Bradley from Oxford University (U.K.)
GIS	Geographic information system
GPR	Ground penetrating radar
GPS	Global positioning system
GRASP	General Robotics, Automation, Sensing and Perception laboratory at the University of Pennsylvania (U.S.)
GSM	Gain scheduling middleware
GUI	Graphical user interface
HAL	Hybrid Assistive Limb
HOAP	Humanoid for Open Architecture Platform (Japan)
HRI	Human-Robot Interaction
HRP	Humanoid Robotics Project (Japan)

H/W	Hardware
HWRS	Human-friendly Welfare Robot System at KAIST (Korea)
IAIM	Industrial Applications of Informatics and Microsystems at the University of Karlsruhe (Germany)
IARES	Illustrateur Autonome de Robotique mobile pour l'Exploration Spatiale at CNES (France)
IC	Integrated circuit
IDSIA	Istituto Dalle Molle di Studi sull'Intelligenza Artificiale (Italy)
IE	Intelligent environments
IEICE	Institute of Electronic, Information and Communication Engineers
IEEE	Institute of Electrical and Electronics Engineers
IFREMER	Institut Français de Recherche pour l'Exploitation de la Mer (France) French National Institute for Marine Science and Technology
IMU	Inertial measurement unit
INRIA	l'Institut National de Recherche en Informatique et en Automatique (France)
INS	Inertial Navigation System
IN.SAT	Business and Territorial Systems Innovation Laboratory at the Polo Sant'Anna Valdera of the Sant'Anna School of Advanced Studies (Italy)
I/O	Input/output
IPK	Fraunhofer Institute for Production and Design (Germany)
IPSJ	Information Processing Society of Japan (Japan)
IR	Infrared
IRIS	Institute for Robotics and Intelligent Systems at ETH (Switzerland)
IRISA	Institut de Recherche en Informatique et Systèmes Aléatoires (France)
IROS	International Conference on Intelligent Robots and Systems
IRRC	Intelligent Robotic Research Center at KAIST (Korea)
ISH	Intelligent Sweet Home at KAIST (Korea)
ISSAC	Intelligent Sweeping Security Assistant Companion at KIST (Korea)
ISRI	Intelligent Systems Research Institute at AIST (Japan)
IVA	Intravehicular activity
JAMSTEC	Japan Agency for Marine-Earth Science and Technology (Japan)

JARA	Japan Robot Association (Japan)
JEM	Japanese Experiment Module (Japan)
JEMRMS	Japanese Experiment Module Remote Manipulator System (Japan)
JPL	Jet Propulsion Laboratory (U.S.)
JSC	Johnson Space Center (U.S.)
JST	Japan Science and Technology Agency (Japan)
KAIST	Korean Advanced Institute of Science and Technology (Korea)
KIST	Korean Institute of Science and Technology (Korea)
KTH	Royal Institute of Technology (Sweden)
LAAS	Laboratoire d'Analyse et d'Architecture des Systèmes (France)
LASMEA	Le Laboratoire des Sciences et Matériaux pour l'Électronique et d'Automatique (France)
LBL	Long base line
LEO	Low Earth orbit
LIDAR	Light detection and ranging
LIGA	Lithographie (lithography), Galvanoformung (electroplating), Abformung (moulding)
LIRA	Laboratory for Integrated Advanced Robotics at the University of Genova (Italy)
LMS	Laser measurement system
LUSTRE '96	Lucky STRike Exploration 1996 at WHOI (U.S.)
MACLAB	The Mechatronics and Automatic Control LABoratory at the University of Genova (Italy)
MARON	Mobile Agent Robot of the Next Generation (Japan)
MBARI	Monterey Bay Aquarium Research Institute (U.S.)
MBERI	Marine Biotechnology and Environmental Research Institute
MEMS	Microelectromechanical systems
MER	Mars Exploration Rover at NASA (U.S.)
METI	Ministry of Economy, Trade and Industry (Japan)
MEXT	Ministry of Education, Culture, Sports, Science and Technology (Japan)
MFD	Manipulator Flight Demonstration at JAXA (Japan)

MHC	Magnetic Hull Crawler
microEMS	Micro Environmental Monitor System
MIMOT	A bio-mimetic robot from KIST (Korea)
MINAS	Micro and Nano Systems at LAAS (France)
MIT	Massachusetts Institute of Technology (U.S.)
MITI	Ministry of International Trade and Industry (Japan)
MIC	Ministry of Information and Communication (Korea)
MMS	Micro Mechanical System
MOCIE	Ministry of Commerce, Industry and Energy (Korea)
MOLA	Mars Orbital Laser Altimeter from NASA (U.S.)
MOST	Ministry of Science and Technology (Korea)
MR	Magnetic resonance
MRI	Magnetic resonance imaging
MSL	Mars Science Laboratory (U.S.)
MTP	Mars Technology Program at NASA (U.S.)
NASA	National Aeronautics and Space Administration (U.S.)
NASDA	National Space Development Agency, now a part of JAXA (Japan)
NEDO	New Energy and Industrial Technology Development Organization (Japan)
NRF	Network Robot Forum (Japan)
NTRM	National Technology Roadmap (Korea)
ORU	Orbital Replacement Unit at JAXA (Japan)
OSL	Ocean Systems Laboratory at Heriot-Watt University (U.K.)
PAL	Pohang Accelerator Laboratory at PIIR (Korea)
PARO	Knowledge Distributed Robot and the Mental Commit Robot (Japan)
PCI	Peripheral component interface
PEFC	Polymer Electrode Fuel Cell
PERCRO	Perceptual Robotic Laboratory at the Polo Sant'Anna Valdera of the Sant'Anna School of Advanced Studies (Italy)
PHANToM	A haptic device sold by Sensable Technologies
PID	Position, Integral, Derivative

PIIR	Pohang Institute for Intelligent Robots (Korea)
PSV	Polo Sant'Anna Valdera, a research park of the Sant'Anna School of Advanced Studies (Italy)
POSTECH	Pohang Science and Technology University (Korea)
PVDF	Polyvinylidene fluoride
PZT	Lead zirconium titanate
QRIO	Quest for Curiosity robot at Sony (Japan)
RETIS	Real-Time Systems Laboratory at the Polo Sant'Anna Valdera of the Sant'Anna School of Advanced Studies (Italy)
RFID	Radio frequency identification
RIGB	Research infrastructure block grants (Australia)
RIST	Research Institute of Industrial Science & Technology (Korea)
RL	Reinforcement learning
RMS	Remote Manipulator System (Japan)
RNN	Recurrent neural network
ROBEA	Programme Robotique et Entités Artificielles at CNRS (France)
ROTV	Free-flying surface-towed platform
ROV	Remotely operated vehicle
RPI	Rensselaer Polytechnic Institute (U.S.)
RRTs	Rapidly exploring random trees
RT	Robot technology
SCARA	Selective compliant assembly robot arm
SEM	Scanning electron microscope
SFA	Small Fine Arm (Japan)
SIGUBI	SIG on Ubiquitous Computing Systems from IPSJ (Japan)
SJTU	Shanghai Jiao Tong University (China)
SKK	Sungkyunkwan University (Korea)
SLAM	Simultaneous localization and mapping
SLES	Spacecraft Life Extension System (Germany)
SNP	Single nucleotide polymorphism
SNU	Seoul National University (Korea)

SNUUV-1	Seoul National University Underwater Vehicle (Korea)
SoC	System-on-Chip
SONQL	Semi-Online Neural-Q learning algorithm
SPDM	Special Purpose Dexterous Manipulator (Canada)
SSPA	Solid state power amplifier
SUMO	Spacecraft for the Unmanned Modification of Orbits (U.S.)
S/W	Software
TCD	Transcranial Doppler
TEM	Transmission electron microscope
Tflop/s	10^{12} floating point operations per second
TUM	Technical University Munich (Germany)
UAV	Unmanned aerial vehicle
UdG	University of Girona (Italy)
UMASS	University of Massachusetts (U.S.)
UNECE	United Nations Economic Commission for Europe
URC	Ubiquitous Robot Companion (Korea)
URON	Ubiquitous Real-World Oriented Networking at IEICE (Japan)
USBL	Ultra-short baseline
USF	University of South Florida (U.S.)
USC	University of Southern California (U.S.)
USN	u-Sensor Network
VAP	Véhicule Automatique Planétaire project of CNES from 1989 to 1993 (France)
VoIP	Internet telephony
VR	Virtual reality
W-CDMA	Wideband code division multiple access
WHOI	Woods Hole Oceanographic Institution (U.S.)
ZMP	Zero moment point