

Chapter 3

SPACE ROBOTICS

3.1. What is Space Robotics?

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

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

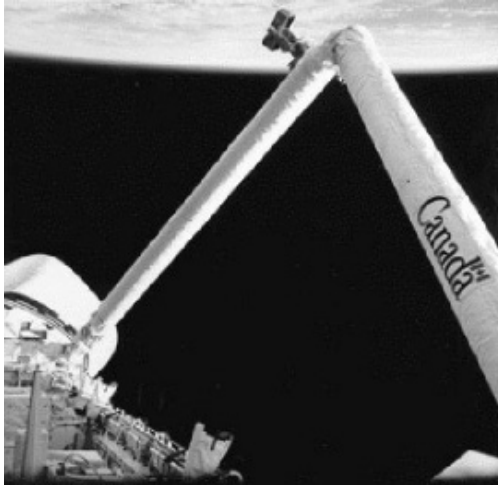


Fig. 3.1. Space Shuttle robot arm developed by Canadian Space Agency.



Fig. 3.2. Mars Exploration Rover.

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



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

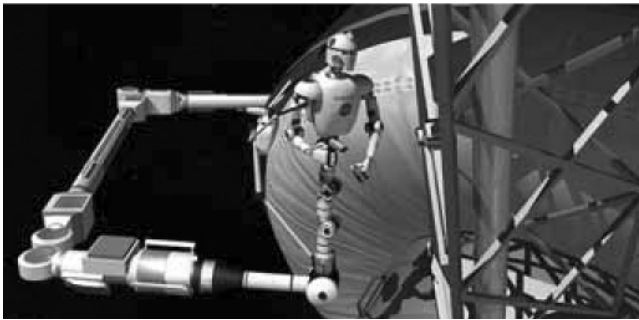


Fig. 3.4. Artist's conception of "Robonaut" (an "astronaut-equivalent" robot) performing space assembly.

3.2. Issues in Space Robotics

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

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

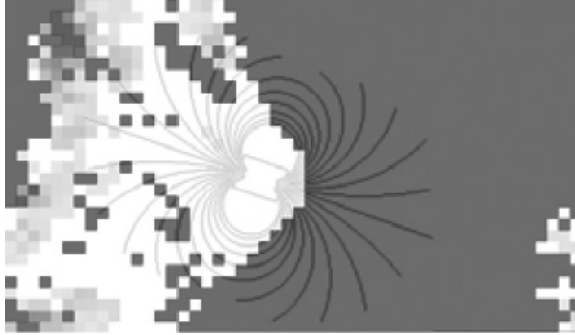


Fig. 3.5. MER path planner evaluates arcs through sensed terrain (gray levels indicate traversability; pattern, unknown terrain).

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

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

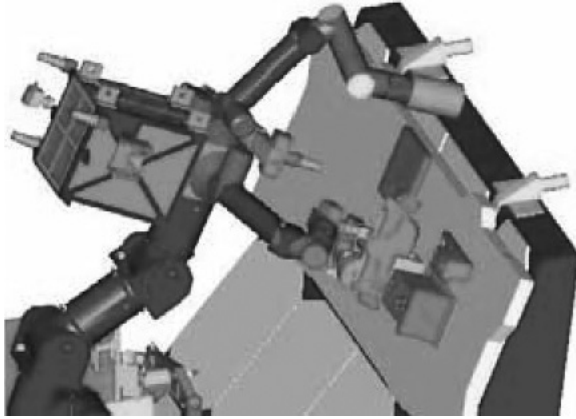


Fig. 3.6. Ranger (U. MD) robot was developed to demonstrate advanced robotics in the space shuttle payload bay.

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

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

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



Fig. 3.7. Robot arm on Mars Exploration Rover.



Fig. 3.8. Robonaut performing dexterous grasp.

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



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



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

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

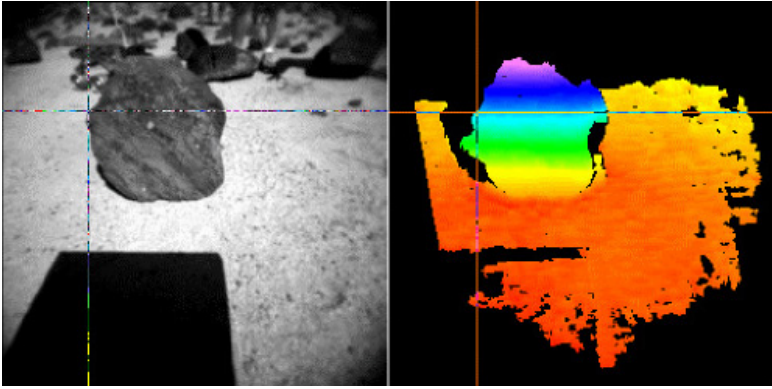


Fig. 3.11. Stereocorrelation example.

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

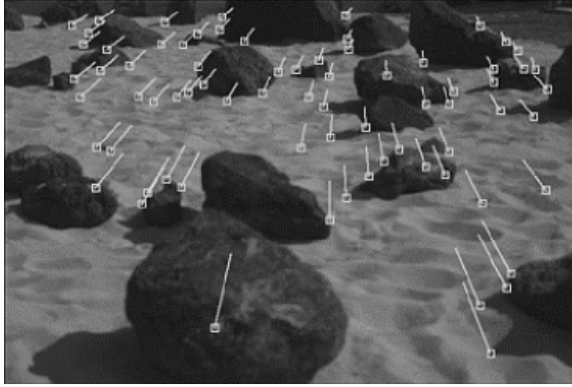


Fig. 3.12. Visual odometry example.

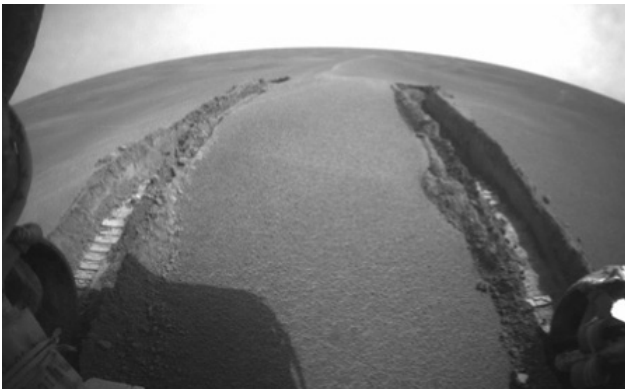


Fig. 3.13. Opportunity Rover image of Purgatory Dune after extraction.

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

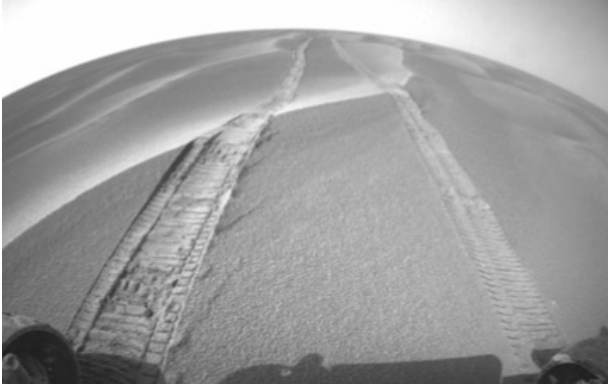


Fig. 3.14. Opportunity image of rover tracks leading into Purgatory Dune.

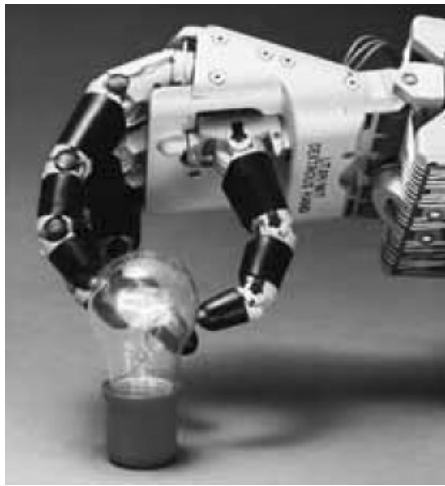


Fig. 3.15. SARCOS dexterous hand capable of force control.

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

Time delay is a particular challenge for manipulation in space robotics. Industries that routinely use teleoperation, such as the nuclear industry, generally use “master–slave” teleoperators that mimic at the “slave” arm

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

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



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



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



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

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

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

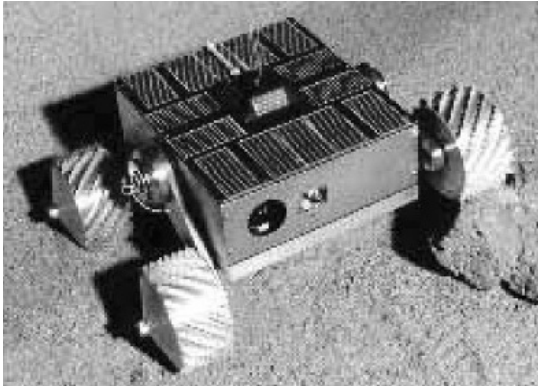


Fig. 3.19. 1.5 kg Nanorover developed by JPL for asteroid or Mars exploration.



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



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



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



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



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

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



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

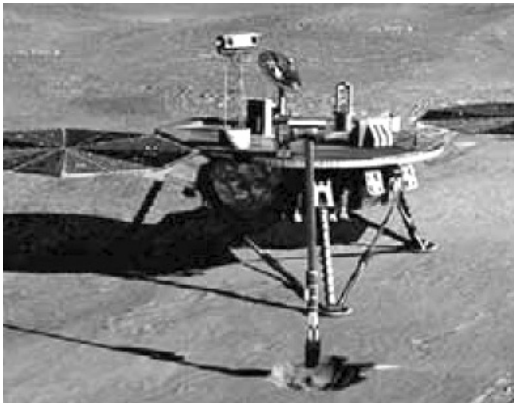


Fig. 3.26. Phoenix arm, built by the Alliance Spacesystems, Inc. for the Phoenix mission led by P. I. Peter Smith of the University of Arizona for use on the lander system developed by Lockheed-Martin of Denver.

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

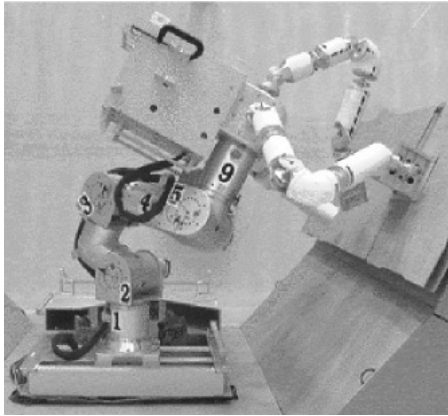


Fig. 3.27. Ranger Manipulator, developed by the University of Maryland, to demonstrate a wide variety of competent manipulation tasks in Earth orbit. Flight hardware was developed in the 1990s for both an expendable launch vehicle and the Space Shuttle, but presently there is no manifest for a flight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



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

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

3.3. International Efforts in Space Robotics

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



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



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

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



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



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

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

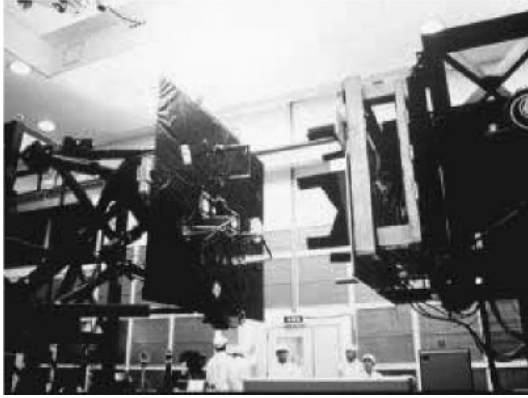


Fig. 3.33. Docking adapter testing for the ETS-VII robotics technology experiment.

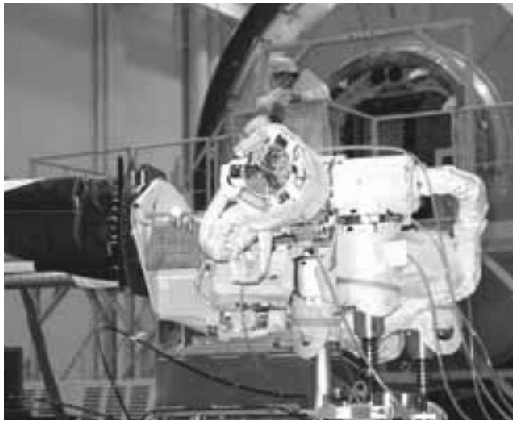


Fig. 3.34. Japanese Small Fine Arm developed for the Japanese Experiment Module awaiting launch to the International Space Station.

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

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

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

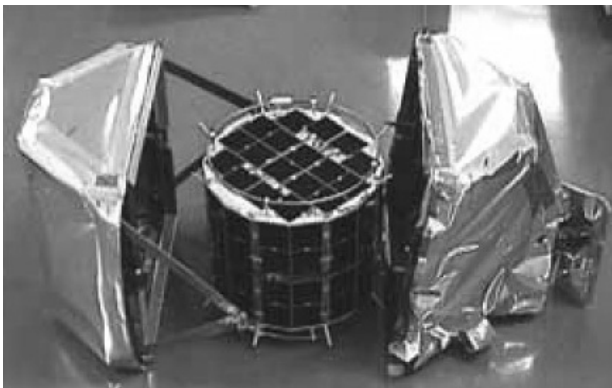


Fig. 3.35. Minerva hopping robot developed in Japan for asteroid mission MUSES-C.

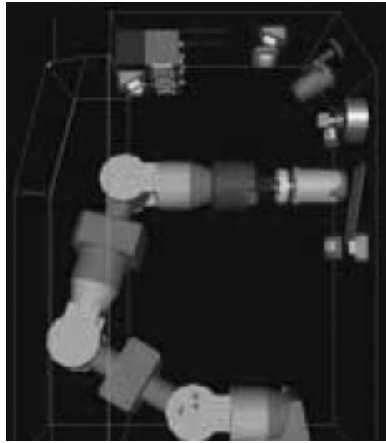


Fig. 3.36. Schematic of German Rotex experiment flown in 1993 with a manipulator and task elements inside a protective cabinet.

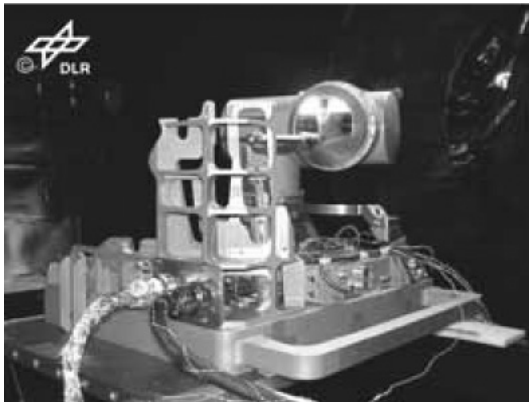


Fig. 3.37. ROKVISS experiment currently flying on International Space Station.

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



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

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

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



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

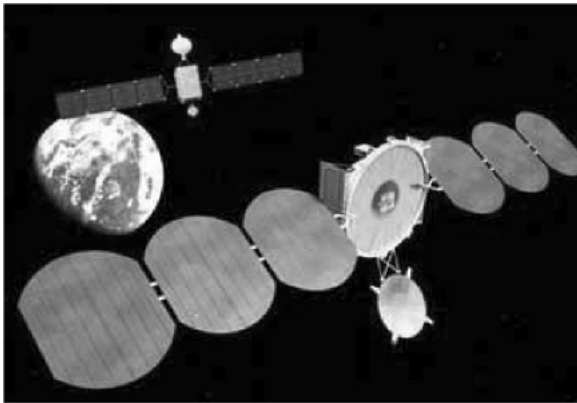


Fig. 3.40. Spacecraft Life Extension System (SLES), which will use a DLR capture mechanism to grapple, stabilize, and refuel commercial communication satellites.

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



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



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

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

3.4. The State of the Art in Space Robotics

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

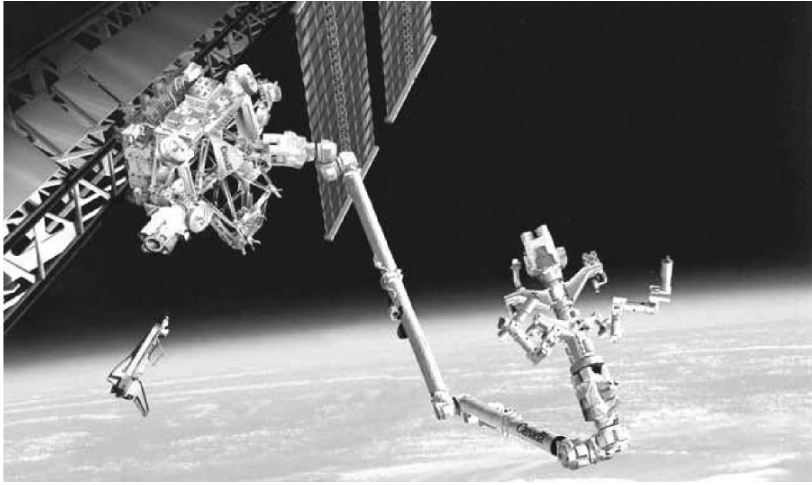


Fig. 3.43. Special Purpose Dexterous Manipulator on the end of the Space Station Remote Manipulator Dextre System, both developed for the Canadian Space Agency. The SSRMS is now in-flight, and the SPDM is awaiting launch.

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

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

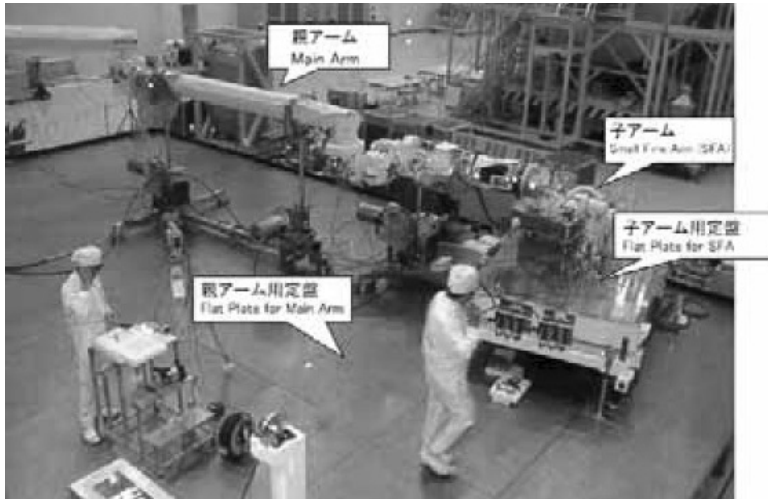


Fig. 3.44. Main Arm and Small Fine Arm undergoing air-bearing tests. Both were developed for the Japan Aerospace Exploration Agency (JAXA), and are awaiting launch to the International Space Station.

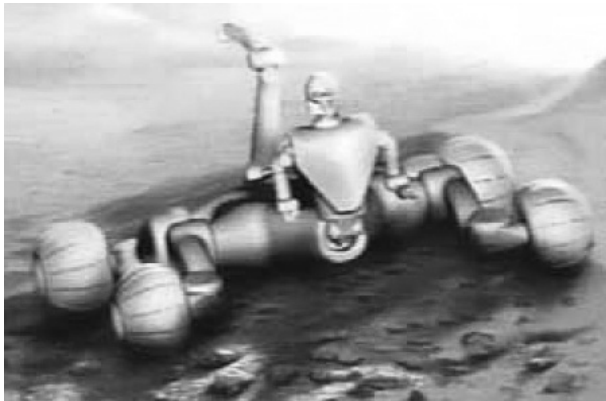


Fig. 3.45. Artist conception of a centaur-like vehicle with a robonaut upper body on a rover lower body for use in Mars operations.

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

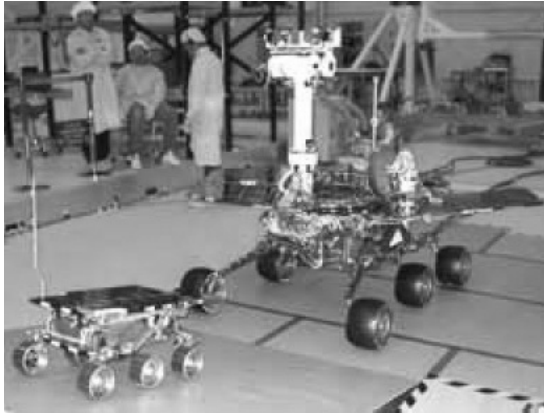


Fig. 3.46. Flight spare of original Sojourner Rover with Mars Exploration Rover “Spirit.”



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

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



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



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

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

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

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

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

References

1. M. Maimone, Y. Cheng and L. Mathies, Two years of visual odometry on the Mars Exploration Rovers: Field reports. *J. Field Robotics* **24**(3) (2007).
2. R. Cowen, Roving on the red planet. *Sci. News* **167** (2005) 344–346.

Chapter 4

HUMANOIDS

4.1. Background

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

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

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



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

4.2. Definitions of the Humanoid System

4.2.1. *Form and function*

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

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



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

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

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

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

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

4.2.2. *How are humanoids built?*

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

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

4.3. Current Challenges in Humanoids

4.3.1. *Design, packaging, and power*

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

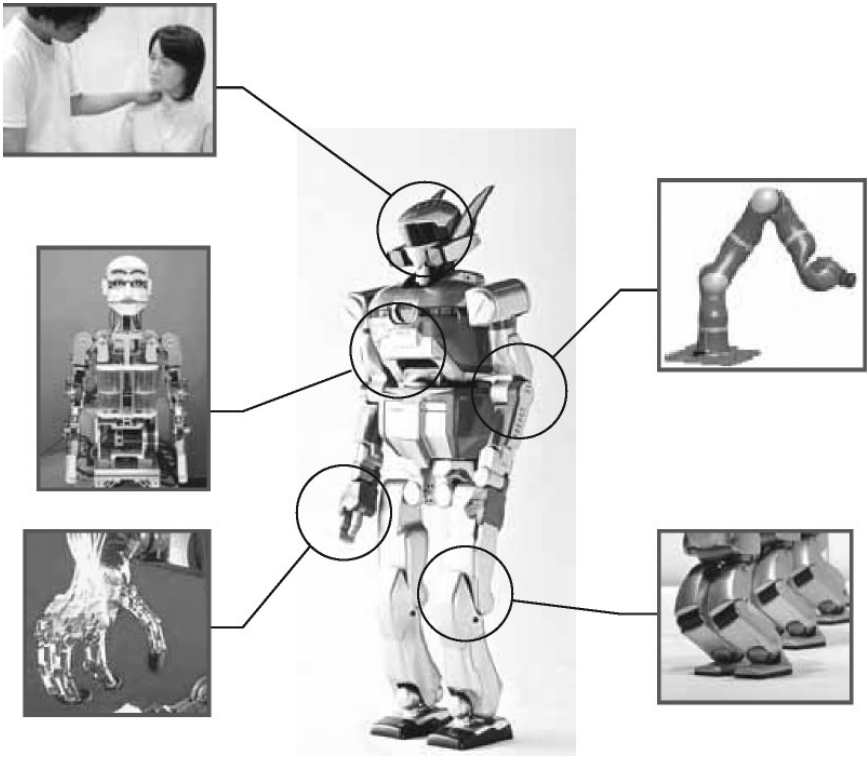


Fig. 4.3. Gross anatomy of the humanoid — heads, torsos, arms, hands, and legs.

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

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

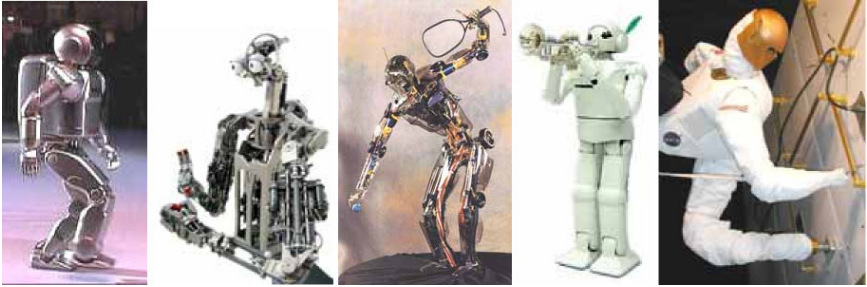


Fig. 4.4. Humanoids from Honda, MIT, Sarcos, Toyota, and NASA.

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

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

4.3.2. *Bipedal walking*

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

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

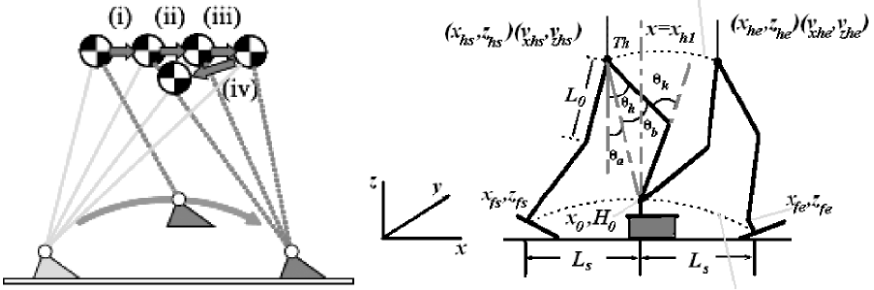


Fig. 4.5. ZMP mechanics.

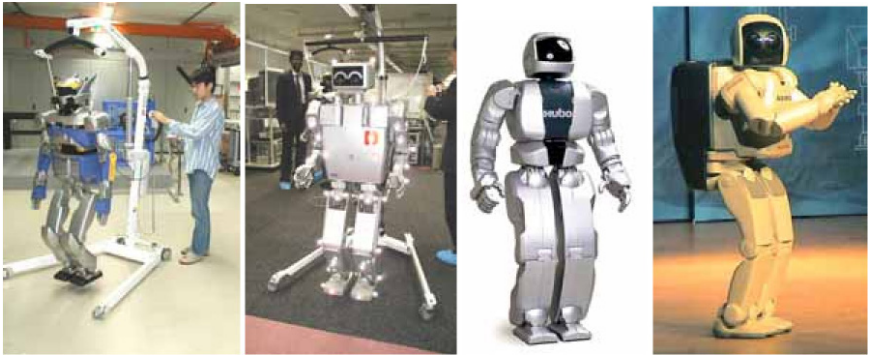


Fig. 4.6. ZMP walkers at AIST Tsukuba, AIST Waterfront, KAIST, and Honda.

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

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

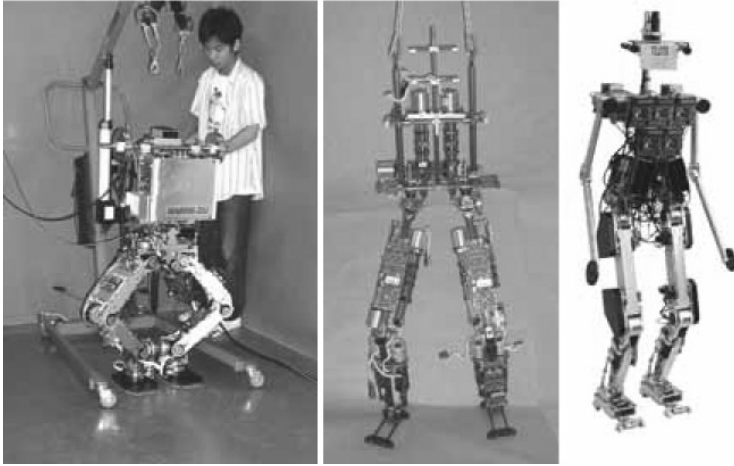


Fig. 4.7. Dynamic Walkers at Waseda, MIT, and TUM.

4.3.3. Wheeled lower bodies

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



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

4.3.4. Dexterous limbs

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

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

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

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

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

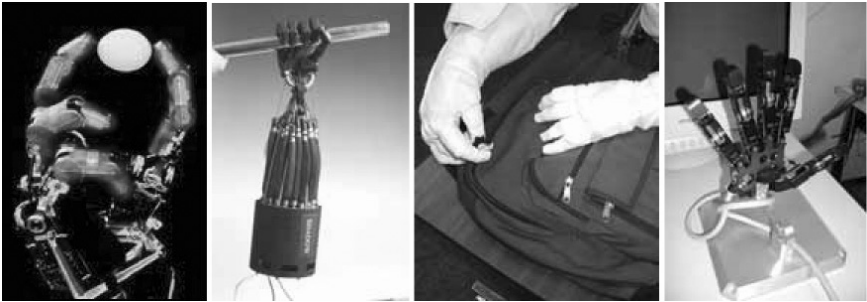


Fig. 4.9. Dexterous hands at DLR, Shadow, NASA, and Tsukuba.



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

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

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

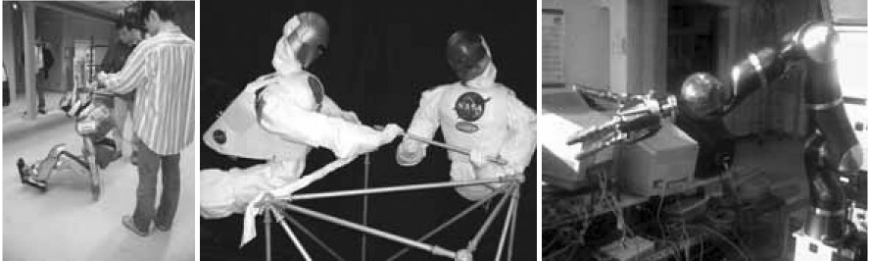


Fig. 4.11. Strong dexterous arms at AIST Tsukuba, NASA, and DLR.

4.3.5. *Mobile manipulation*

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

4.3.6. *Human–robot interaction*

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

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

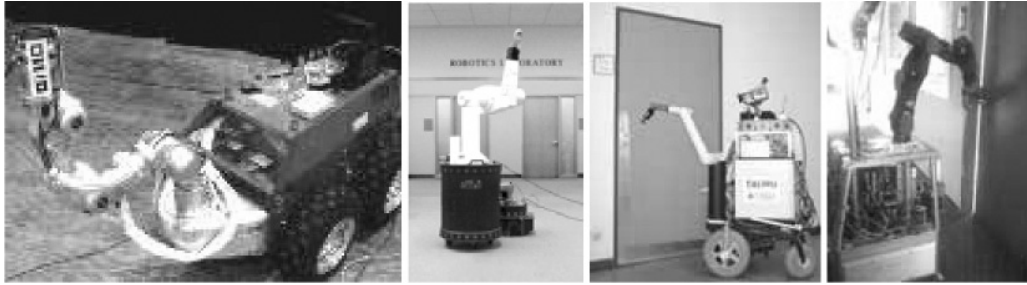


Fig. 4.12. Mobile manipulation at CMU, Stanford, RWTH Aachen, and the DLR.



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



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

1970, where the degree of human-like form and motion in human faces⁵ are found to have a local minimum in reaction. There is a growing but still young body of research in this arena, with many active workshops in HRI, android science, and views on the Uncanny Valley in the past several years (Fig. 4.14).

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

4.4. Key Technologies

Key technologies for humanoid robotics include the following:

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

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

4.5. Fundamental Research Challenges

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

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

4.6. Regions Visited by the Assessment Team

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

4.7. Observations, Applications, and Conclusions

4.7.1. *Quantitative observations*

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

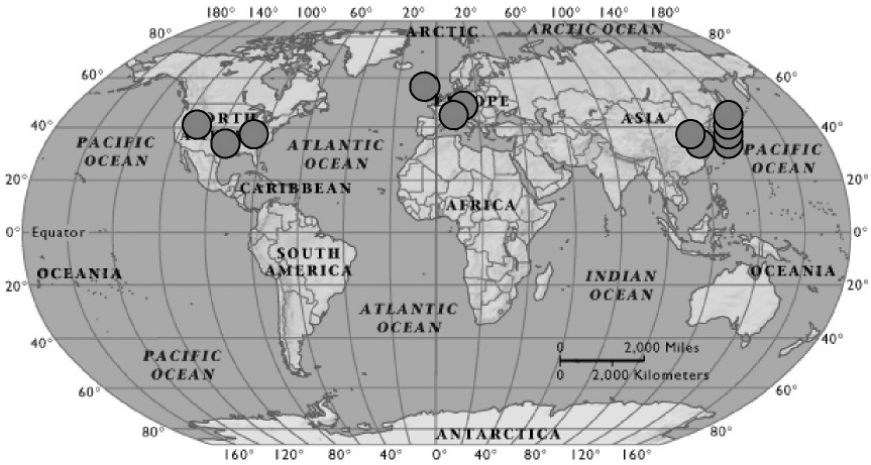


Fig. 4.15. Locations of humanoid systems reviewed.

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

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

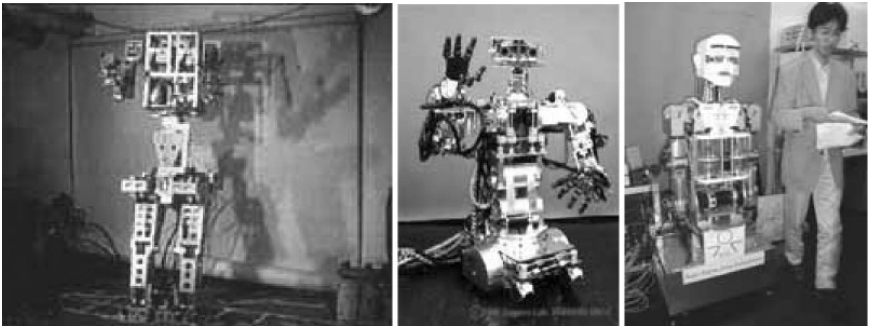


Fig. 4.16. Humanoid systems at Waseda, past and present.

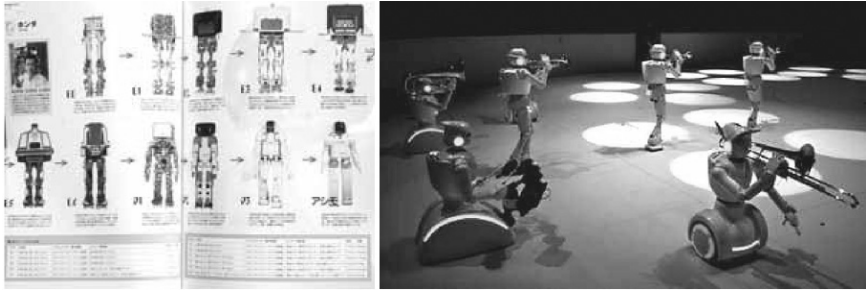


Fig. 4.17. Honda and Toyota humanoids.

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

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

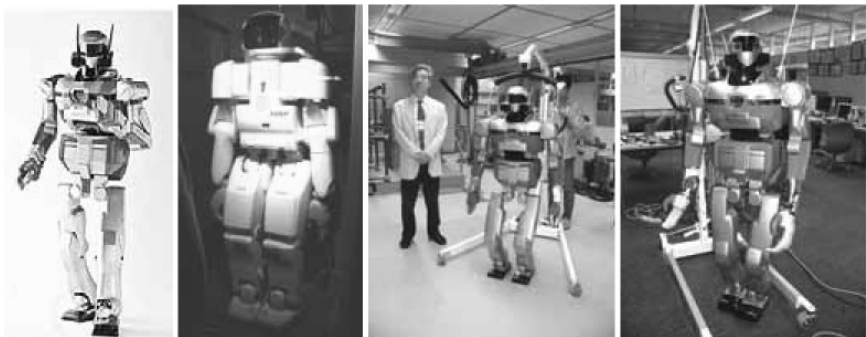


Fig. 4.18. AIST humanoids.

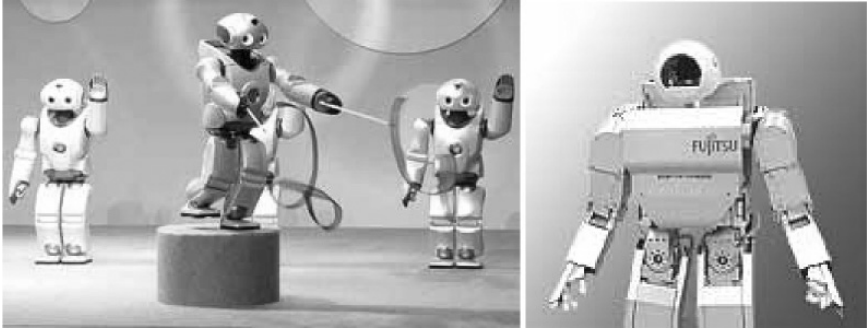


Fig. 4.19. Sony and Fujitsu humanoids.

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

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

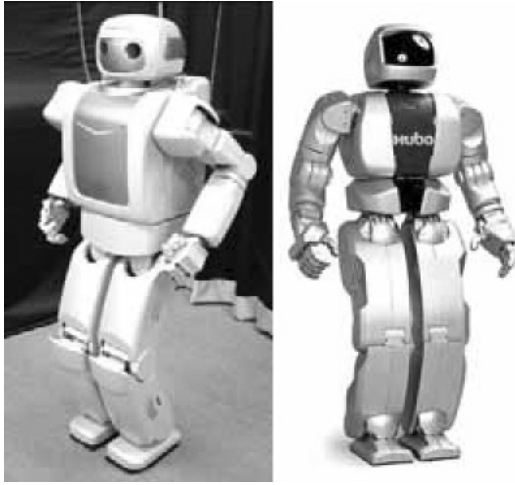


Fig. 4.20. KIST (NBH-1) and KAIST (KHR-3) humanoids.

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

4.7.2. *Qualitative observations*

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

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

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

4.7.3. Applications

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

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

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

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

4.8. Conclusions

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

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

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

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

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

References

1. M. Vukobratovic and A. A. Frank, Legged locomotion studies: On the stability of biped locomotion, *Proceedings 3rd International Symposium on External Control of Human Extremities*, Belgrade, 1969.
2. M. Vukobratovic, A. A. Frank and D. Juricic, On the stability of biped locomotion, *IEEE Transactions on Biomedical Engineering*, **17**(1) (1970) 25–36.

3. J. Pratt, P. Dilworth and G. Pratt, Virtual model control of a bipedal walking robot, *Proceedings of the IEEE International Conference on Robotics and Automations (ICRA)*, Albuquerque, USA.
4. Y. F. Zheng and H. Hemami, Impact effect of biped contact with the environment, *IEEE Transactions of Systems, Man and Cybernetics*, **14**(3) (1984) 437–443.
5. T. Minato, K. F. MacDorman, M. Shimada, S. Itakura, K. Lee and H. Ishiguro, Evaluating humanlikeness by comparing responses elicited by an android and a person, *Proceedings of the Second International Workshop on Man–Machine Symbiotic Systems*, Kyoto, Japan, 23–24 November 2004, pp. 373–383.
6. H. Hirukawa, F. Kanehiro, K. Kaneko, S. Kajita, K. Fujiwara, Y. Kawai, F. Tomita, S. Hirai, K. Tanie, T. Isozumi, K. Akachi, T. Kawasaki, S. Ota, K. Yokoyama, H. Handa, Y. Fukase, J. Maeda, Y. Nakamura, S. Tachi and H. Inoue, Humanoid robotics platforms developed in HRP, *Robotics and Autonomous Systems* **48**(4) (2004) 165–175.
7. Y. Nakamura, H. Hirukawa, K. Yamane, S. Kajita, K. Yokoi, M. Fujie, A. Takanishi, K. Fujiwara, S. Nagashima, Y. Murase, M. Inaba and H. Inoue, The virtual robot platform, *Journal of Robotics Society of Japan* **19**(1) (2001) 28–36.