CHAPTER 3

SPACE ROBOTICS

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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).

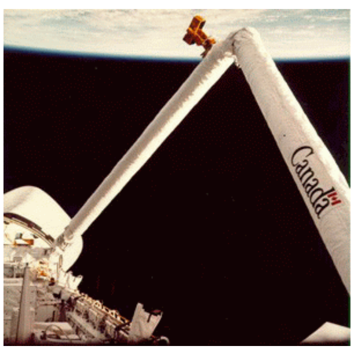

Figure 3.1. Space Shuttle robot arm developed by Canadian Space Agency.

Figure 3.2. Mars Exploration Rover.

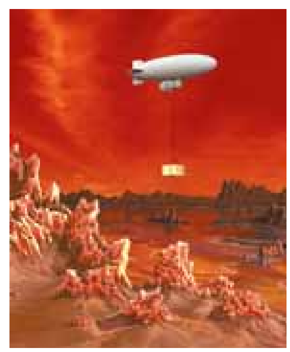

Figure 3.3. Artist's conception of Robot Blimp on Titan.

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.

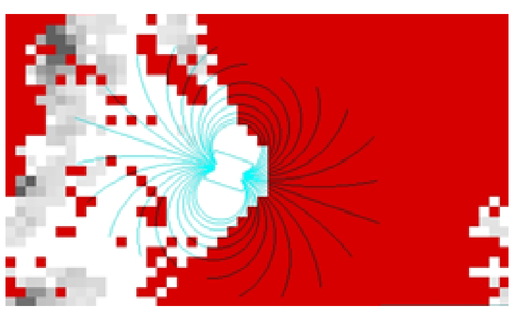

Figure 3.5. MER path planner evaluates arcs through sensed terrain (gray levels indicate traversability; red, unknown terrain).

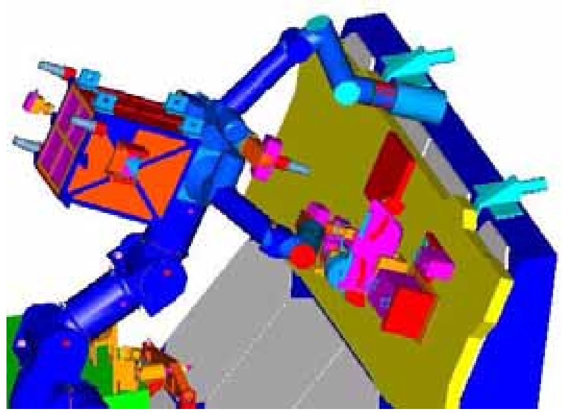

Figure 3.6. Ranger (U. MD) robot was developed to demonstrate advanced robotics in the space shuttle payload bay.

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.

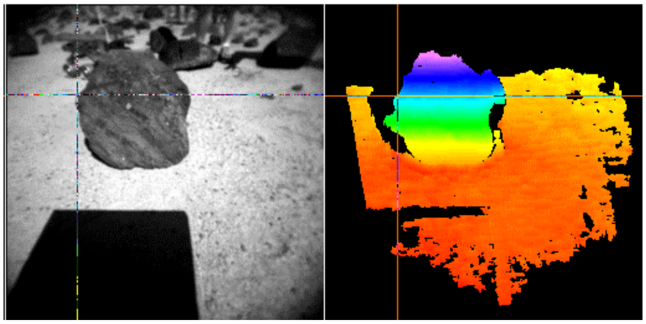

Figure 3.11. Stereo correlation example.

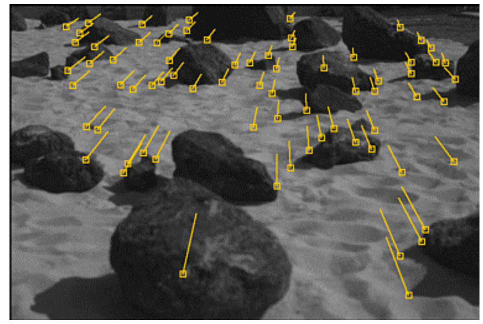

Figure 3.12. Visual odometry example.

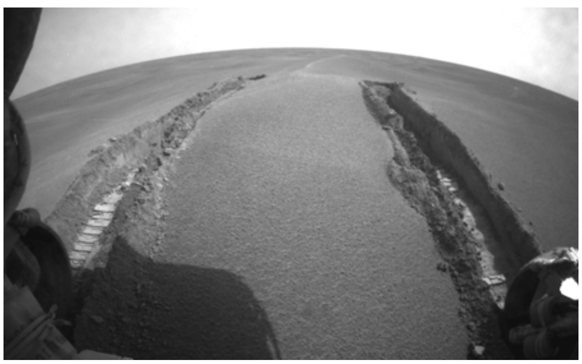

Figure 3.13. Opportunity rover image of Purgatory Dune.

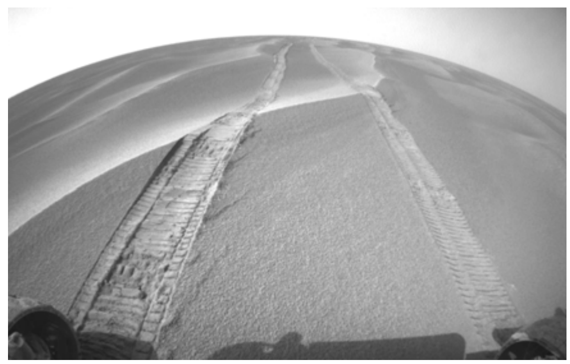

Figure 3.14. Opportunity image of rover tracks leading into Purgatory Dune.

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.

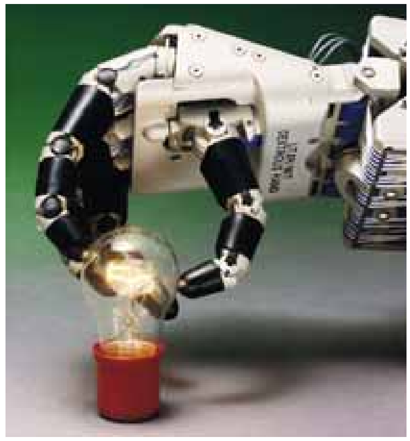

Figure 3.15. SARCOS dexterous hand capable of force control.

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.

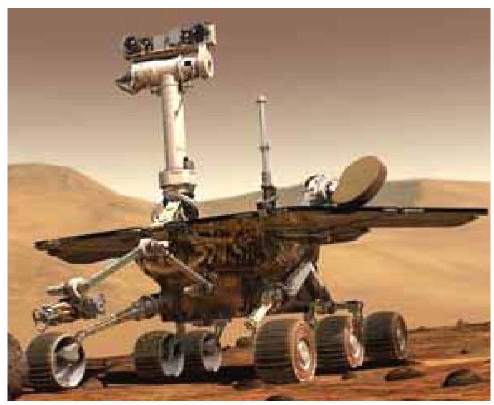

Figure 3.17. Artist's conception of Mars Exploration Rover.

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

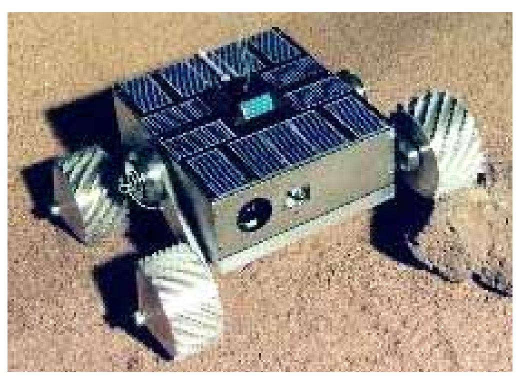

Figure 3.19. 1.5 kg Nanorover developed by JPL for asteroid or Mars exploration.

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.

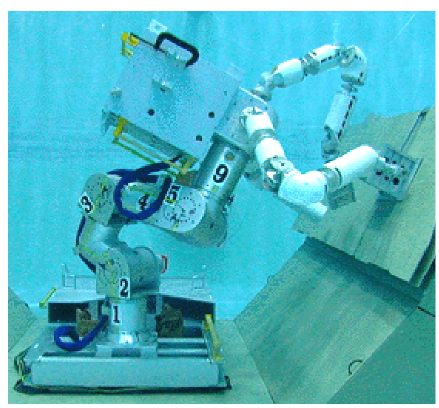

Figure 3.27. Ranger Manipulator, developed by the University of Maryland, to demonstrate a wide variety of competent manipulation tasks in Earth orbit. Flight hardware was developed in the 1990s for both an expendable launch vehicle and the Space Shuttle, but at present there is no manifest for a flight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

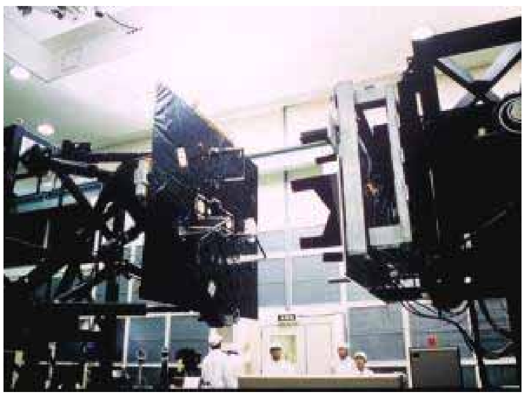

Figure 3.33. Docking adapter testing for the ETS-VII robotics technology experiment.

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

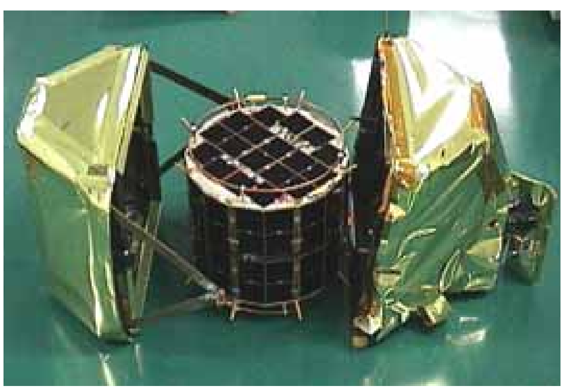

Figure 3.35. Minerva hopping robot developed in Japan for asteroid mission MUSES-C.

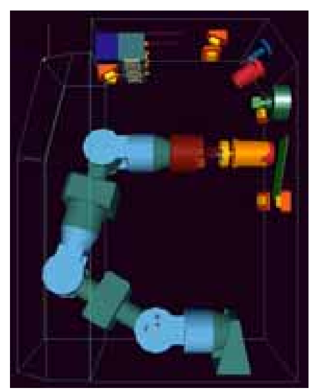

Figure 3.36. Schematic of German Rotex experiment flown in 1993 with a manipulator and task elements inside a protective cabinet.

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 (<u>RO</u>bot

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.

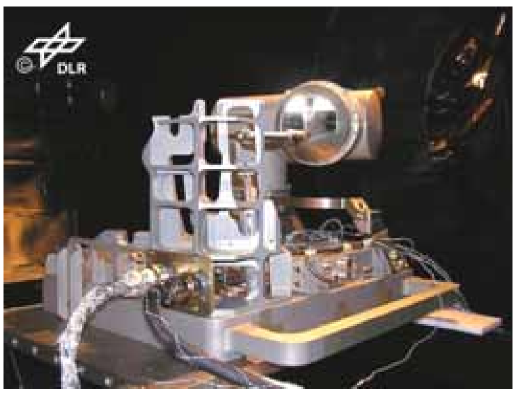

Figure 3.37. ROKVISS experiment currently flying on International Space Station.

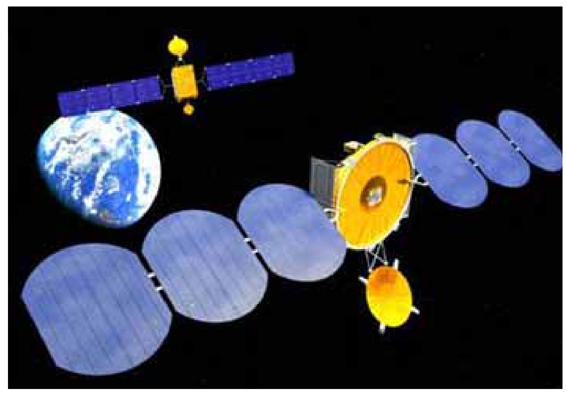

Figure 3.38. Spacecraft Life Extension System (SLES), which will use a DLR capture mechanism to grapple, stabilize, and refuel commercial communications satellites.

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

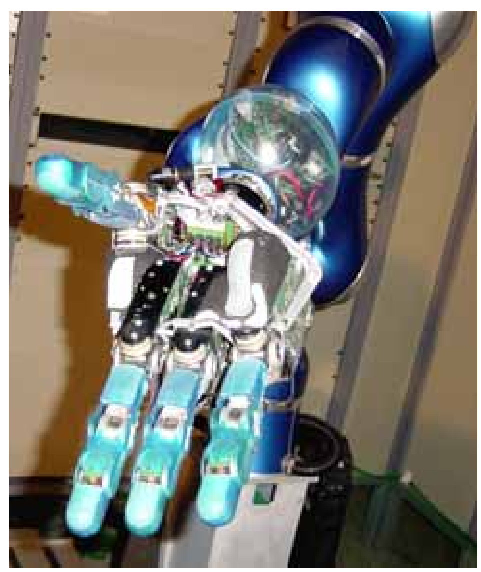

Figure 3.40. Dexterous four-fingered hand developed for space applications at DLR.

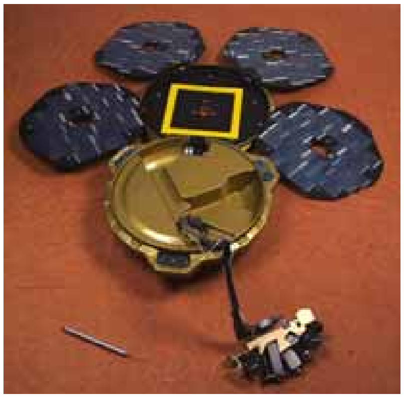

Figure 3.41. Beagle-2 Mars lander with robot arm developed in the U.K.

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.

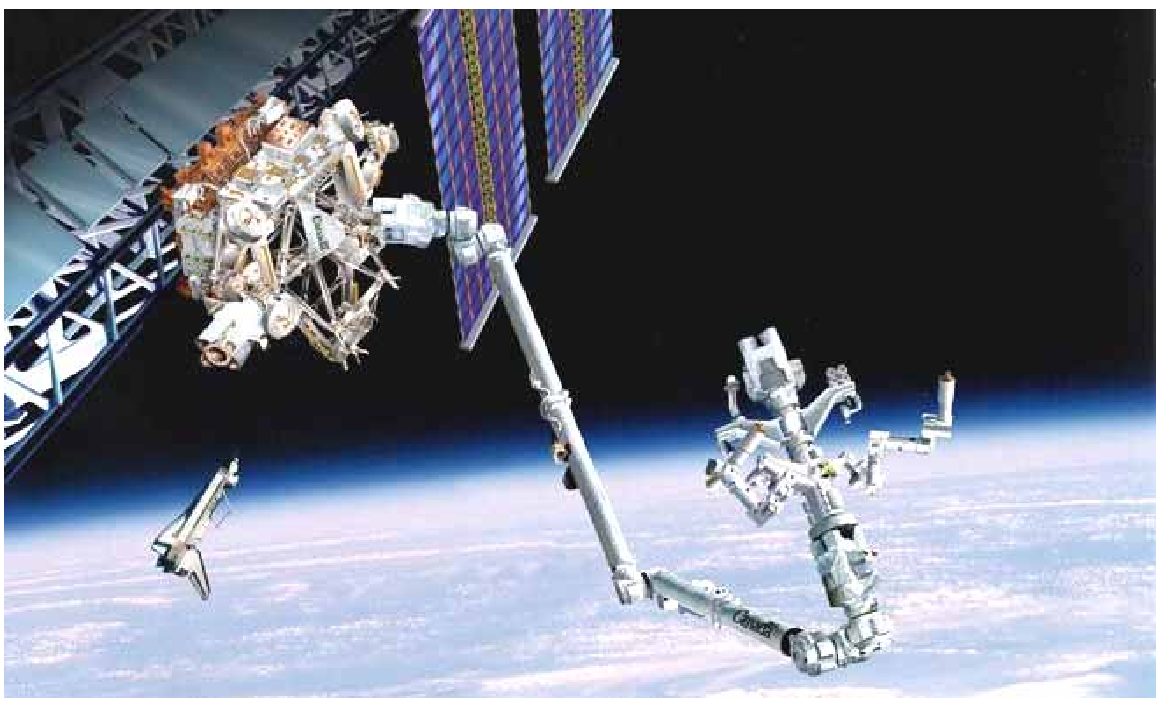

Figure 3.43. Special Purpose Dexterous Manipulator on the end of the Space Station Remote Manipulator System, both developed for the Canadian Space Agency. The SSRMS is now in-flight, and the SPDM is awaiting launch.

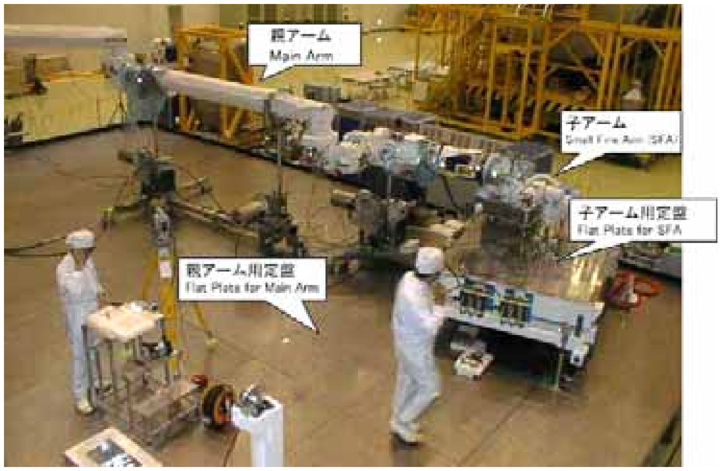

Figure 3.44. Main arm and Small Fine Arm undergoing air-bearing tests. Both were developed for the Japan Aerospace Exploration Agency (JAXA), and are awaiting launch to the International Space Station.

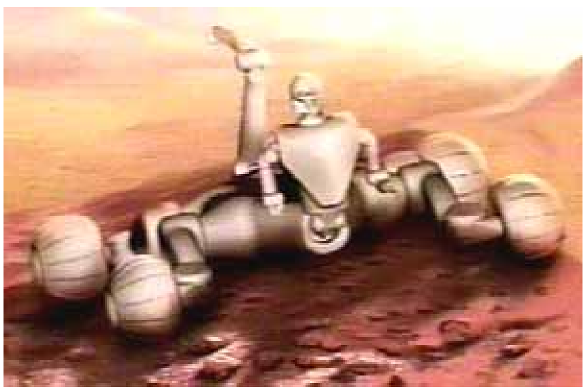

Figure 3.45. Artist conception of a centaur-like vehicle with a robonaut upper body on a rover lower body for use in Mars operations.

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.

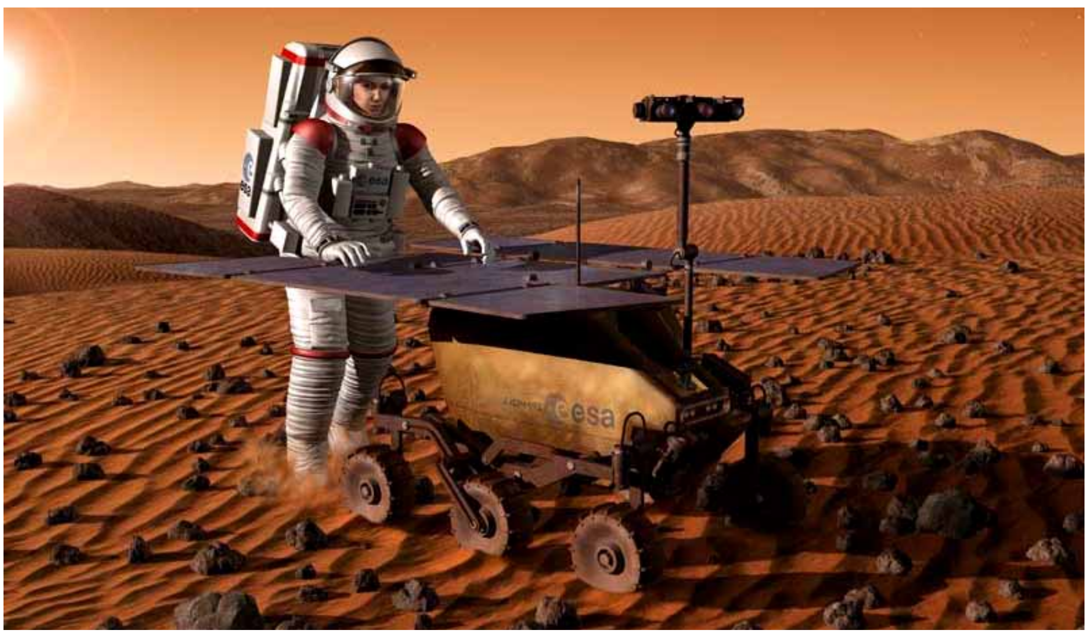

Figure 3.49. Artist's conception of a future European Space Agency astronaut examining the ExoMars rover.

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.

REFERENCES

Cowen, R. 2005. Roving on the Red Planet. *Science News* 167: 344–346.