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NASA Exploration Team (NEXT) Space Robotics Technology Assessment Report

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Executive Summary

This report summarizes an extensive survey done in 2002 to determine the then state-of-the-art in space robotics and to predict future robotic capabilities. It looks at both in-space operations (e.g., assembly, maintenance, inspection) and planetary exploration operations (e.g., mobility, manipulation, science perception). The conclusion of the report presents several possible areas in which investment by the space robotics community can lead to breakthrough technologies.

Robotic systems have been used since the beginning of space exploration (Surveyor, Lunakhod, Voyager, Sojourner) and are essential to its future, either alone or assisting humans. Knowing the current technological state-of-the-art and predicting near term technology advances is vital to planning missions and guiding the requisite technology development.

The NASA Space Architecture Team (formerly the NASA Exploration Team; NEXT) at NASA HQ is charged with determining NASA's exploration priorities and the technologies needed to attain them. For this purpose, through their Human-Robotic Working Group (HRWG), they commissioned a study on the current and future state-of-the-art of space robotics. This paper summarizes that study.

We explicitly address what robots and robotic systems can currently do, what the major space-related challenges are, and what we can plausibly expect in 10 years, under both nominal conditions and with intense effort. We also determine those capabilities requiring technological breakthroughs; these by their very nature are unpredictable.

We consider a broad range of space robotics functionalities (*Figure 1*) spanning planetary surface exploration with rovers and in-space operations. We focus explicitly on capabilities, not on the technologies through which they are accomplished. We omit planetary surface operations, such as construction and maintenance, from this study. Inputs were received from researchers and experts at NASA centers and universities, through site visits, interviews, and a web-based questionnaire through which the community consensus on space robotics technologies was assessed.

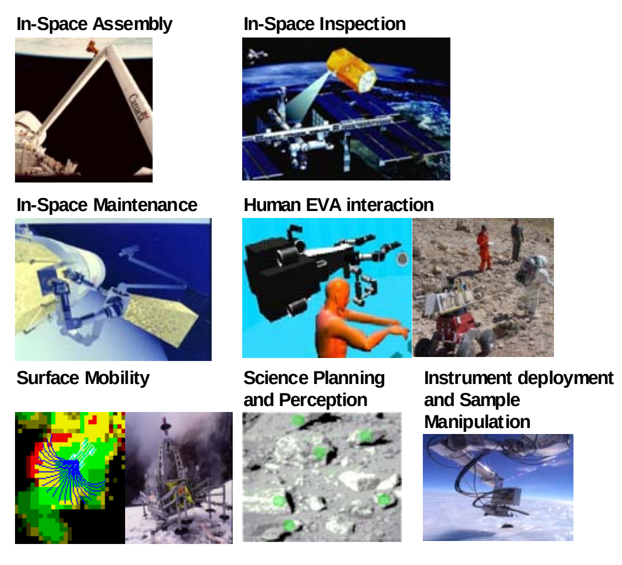


Figure 1 Space robotics functionalities considered.

Planetary Surface Exploration Robots

The current state of the art for deployed planetary surface exploration robots is the Sojourner robot (*Figure 2*), which visited Mars in July 1997, and the Mars Exploration

Rovers to be launched in 2003. They are both primarily teleoperated robots with images sent back from Mars each day and a rigid sequence of robot motions uploaded for the following day. Scientists dealt with Sojourner only through robot specialists and even simple operations such as placing an instrument against a rock took command cycles, each one being a full Martian day. MER will be more capable due to a larger size, greater science instruments, and a better communications infrastructure, but otherwise will be operated in a similar manner.

Figure 2 The sojourner robot on Mars

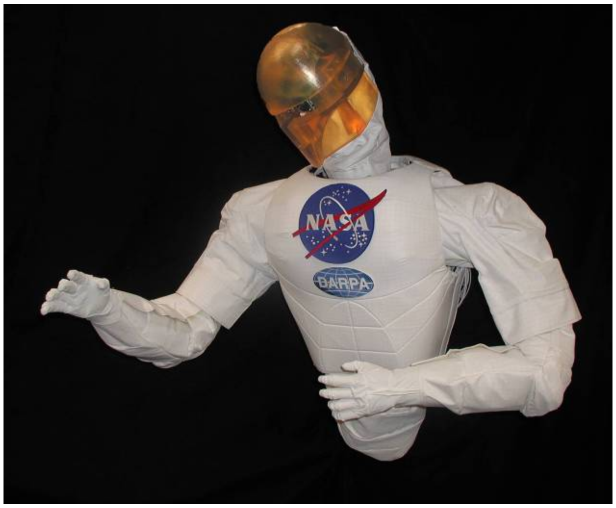


Figure 3 Robonaut at NASA Johnson Space Center

In contrast, terrestrially demonstrated planetary exploration robots have significantly greater capabilities. Autonomous robotic vehicles have performed multi-kilometer traverses in the Arctic (Hyperion, see page 101) and searched Antarctica to identify meteorites (Nomad, see page 106). Other robots can autonomously approach targets and place instruments in contact with them. Taken together these demonstrate the ability to traverse long distances between sites, intensively investigate them and perform some autonomous science in less time and with less human supervision than is currently the norm for flight rovers.

In the next ten to twenty years navigation and mobility will no longer be the constraining factors in planetary exploration – long traverses and access, with specialized robots, to most locations on a planetary surface will be possible. Ground based planning and visualization tools will enable mission scientists to interact directly with the robots. However, robotic performance at the level of a space suited human scientist in the field is and will continue to be a major challenge. Without significant breakthroughs, robot systems will perform only within narrowly defined areas of expertise and will lack the general cognitive and perceptual abilities of a field scientist.

In-Space Operations Robots

In-space operations focus on component assembly, inspection and replacement. Currently deployed in-space robots are confined to the Shuttle and Space Station Remote Manipulator Systems, which are teleoperated and perform only gross component assembly tasks (see page 110). Ground testbeds such as Ranger (see page 108) and Robonaut (see page 108) as well as in-space experiments like ROTEX (see page 109) have demonstrated more dexterous operations, including connecting cables and opening panels, but still under teleoperation. Other ground testbeds such as Skyworker (see page 110) and ASAL (see page 104) have demonstrated autonomous assembly of carefully designed components. In-space flight experiments such as AERCam Sprint (see page 98) have demonstrated the potential of teleoperated robots for remote inspection tasks. In the next ten to twenty years the mechanical dexterity of assembly and maintenance robots should approach or exceed that of a *space-suited* human (achieving the dexterity of a human hand unhampered by pressurized gloves is considerably more difficult). This capability is likely to be fully realized only under teleoperation, which requires high-bandwidth, low-latency communication between the human and the robot. Autonomous assembly and maintenance in space will likely require careful systems engineering and constant monitoring from the ground. Automated inspection, on the other hand, seems well within near-term robotic capability.

Detailed Functionalities

In-Space Assembly

Current in-space capabilities for robotic assembly consist of the space shuttle and space station remote manipulator systems (RMS). These teleoperated robots can move large components and mate those components under careful human teleoperation and supervision. Ground testbeds have demonstrated autonomous transport and mating of large components (e.g., CMU's Skyworker and NASA Langley's Automated Telescope Assembly). Other ground testbeds have demonstrated teleoperated robots performing fine assembly such as mating connectors (e.g., NASA JSC's Robonaut (Figure 3) and University of Maryland's Ranger). In ten years, we expect robots to perform delicate assembly tasks autonomously and even approach the dexterity of a space-suited human. With intense effort, robotic assembly of complicated structures in space is possible, but only under constant supervision and guidance (including occasional teleoperation) from space and ground-based humans. Robotic assembly of complex structures with little or no human supervision will require breakthrough technologies.

In-Space Inspection

Currently there are no inspection robots in operation in space. A test of a free-flying camera, AERCam Sprint (Figure 4), was conducted during STS-87 in 1997. This robot was purely teleoperated. A robot called Inspector was designed by the Germans to inspect Mir, but failed in flight (see page 100). In ten years, autonomous robotic inspection of some exterior surfaces is feasible. Limited autonomous screening of the sensor data is likely. With intense effort, a robot can autonomously inspect most exterior surfaces and detect anomalies.

Figure 4 AERCam Sprint during a flight test

In-Space Maintenance

The shuttle and station remote manipulator systems can move large objects, but cannot perform sophisticated maintenance. Several in-space experiments have been performed to demonstrate teleoperated robots doing maintenance, such as ROTEX and ETS-VII (see page 100). In ten years, expect to see more dexterous robots, such as the Space Dexterous Robotic Manipulator (SPDM), that can perform routine tasks such as changing out components under teleoperation (see page 110). With intense effort, robots may be able to autonomously access and change-out obstructed components. Breakthroughs are needed to achieve advanced, autonomous troubleshooting and repair of arbitrary faults.

Surface and In-Space Human Assistance

Surface human EVA assistance robotic concepts are being explored by the EVA Robotic Assistant (see page 101). In field tests with suited astronauts, it has demonstrated the ability to follow humans while carrying tools, and to help them deploy a solar panel and cables. The space shuttle and space station remote manipulators have been used to move crew members from one location to another and to assist in moving assembly components. The teleoperated robots Robonaut and Ranger have demonstrated tasks such as handing over tools, holding objects for astronauts and shining lights on the ground. In ten years, expect autonomous robots to work in physical proximity to EVA crew members with very limited physical interaction. With intense effort, robots may be able to approach being limited teammates, with natural language and gesture interfaces and strong physical interaction. Arbitrary human level interaction requires breakthroughs.

Surface Mobility

Mobility is achieved through the interaction of many robotic capabilities to achieve safe and effective navigation in an environment. Complexity increases dramatically with the degree of autonomy employed. With limited autonomy: localizing in the environment, navigating while avoiding obstacles and collecting scientific information have been accomplished. Current flight demonstrated surface mobility is the 1997 Sojourner rover which moved several meters per command cycle. Its capabilities are surpassed by the larger and therefore more capable Mars Exploration Rovers destined for Mars in 2004.

To achieve the longer durations and distances, greater science return, and reduced operations effort envisioned for future missions, enhanced robotic capabilities and increased robot autonomy are necessary. Significant capabilities include monitoring system state and health, acting in a resource-efficient manner, building maps, opportunistically seeking targets, and exploring to discover the unknown. Mechanical capabilities as well as energy and thermal issues are also relevant. These individual capabilities aggregate into the overall performance that can be achieved in terms of duration, distance, speed, complexity, and reliability. Terrestrial robots Hyperion, Dante and FIDO have demonstrated long-distance autonomous navigation, extreme terrain mobility, and relevant science operations, respectively.

Simultaneous localization and mapping is largely solved in theory with remaining problems and methods for data association being advanced in coming years. Planning systems from terrain navigation to mission resource scheduling are functional with a level of sophistication and effectiveness that will improve throughout the coming decade.

Surface Instrument Deployment

Recently, terrestrial robots, have demonstrated fully autonomous single cycle instrument placement against nearby large rock targets. The K9 robot (see page 103) approaches targets using deduced reckoning and evaluates the area in its workspace to locate the target and determine where and in what orientation to place an arm-mounted microscopic camera. FIDO (see page 101) and Rocky 7 (see page 108) have demonstrated autonomous approaches to targets using visual navigation and visual servoing respectively. Work is in progress that will enable K9 to navigate to multiple targets in a single command cycle. Within a couple years, NASA efforts currently underway will demonstrate sufficient robustness for deployment on missions, being able to place instruments with sub centimeter precision on multiple targets tens of meters away. Intense effort is needed to deal with more complex situations, such as extreme terrain, occlusions and operations in highly confined areas. There are no fundamental obstacles to developing robust, highly autonomous target approach and surface instrument placement capabilities sufficient for a rover to autonomously track multiple rock targets 10m away from it, and navigate to them to place instruments in contact with them within a centimeters of the requested point, and return to previously visited points for follow-up measurements. The emerging consensus is that the Mars ’09 rover could have this capability, provided that the appropriate research and development effort continues.

Coordinated sensor and manipulator systems that can intelligently and robustly interact with objects in an outdoor environment, beyond simple manipulation and sensor placement, are at least 10 years in the future.

Mission Planning and Sequence Generation

Current ground planning tools allow planning with contingencies, concurrencies, flexible temporal conditions, and resource constraints with task-level, prioritized science input to generate sequences (MAPGEN, PICo) , although their capabilities are curtailed on flight missions. For example, MER will only allow simple contingent branches that put the rover into a safe mode if its actions are not executed within a specified performance envelope. Furthermore, only a subset of the above capabilities are embodied by any one planner.

Figure 5 An example of automated instrument placement

Scientists can work directly with the planning tools to generate a sequence of actions more likely to be accepted by the flight engineering team. In ten years scientists may have full and direct control of the terrestrial rovers.

Onboard Science Planning and Perception

For terrestrial systems, the current state-of-art consists of onboard rover planners that maintain prioritized lists of science goals with multiple constraints between them, enabling fully autonomous operations for short durations (hours) in relatively simple outdoor environments (such as Antarctica). Within ten years we expect steady improvements in robustness allowing fully autonomous operations for days in desert-like environments, the ability to seek patterns and anomalies and generate discovery plans to thereupon collect interesting scientific data at dramatically reduced operational effort.

Performance at the level of a human scientist in the field is and will continue to be a major challenge. Without significant breakthroughs, the best systems will perform well only within narrowly defined areas of expertise (as expert systems do), but will lack the general cognitive and perceptual abilities of a field scientist.

Challenges

The information gathered in this report paints a very optimistic picture of the potential of space robotics from those working most closely on the problems. Very little of the necessary future robotic capabilities require fundamental breakthroughs; most require only a sustained engineering effort focused on developing methodologies and gaining experience in the role of robots in space exploration. Such a sustained effort will bear fruit in increasing the capability for a human virtual presence in space and pushing the boundaries of exploration. For this picture to be realized NASA needs to invest in infrastructure and experiments that will advance the state of the art.

Nevertheless, significant challenges remain. Robustness and interacting with robots at the mission level are two of several crosscutting significant challenges that emerge in space robotics.

Robustness

Robustness is a challenge because robots must interact with complex environments, which may not be amenable to standard approaches to verification and validation. Furthermore, human level adaptability remains beyond the technological grasp of robotics. Robots that are autonomous and self-reliant-- able to address any fault through self-diagnosis and repair/recovery, and long-lived (years of operation) against the physical challenges of power, temperature, wear, and stability-- will remain a technological challenge.

Careful system design is key to the success and robustness of any robotic mission. Robots cannot work in isolation, nor are they effective if added to a system that was not designed for robots. One cannot place a robot in a situation crafted for humans and expect even adequate performance. The entire system, including the robot, supporting infrastructure (such as power, communications, navigation and maintenance), including the human component, must be considered when designing a mission. This is far more important to the success of robotics than any robot-specific technology such as mobility, dexterity or intelligence. All of these are routinely considered (at great expense) for manned space missions; the same considerations apply for robotic ones. Appropriate system engineering can greatly increase the robustness of robot operations. For in-space operations this might mean the design of components and attachment mechanisms. For surface operations, this might mean centralized power generation or a GPS-like infrastructure.

Robustness is also achieved by bringing to bear human intelligence and flexibility where appropriate. This can be done via direct teleoperation or advice giving when the robot encounters a problem it cannot deal with itself.

Space robotic systems entails significant difficulties over and above the usual obstacles to space qualification. Autonomous systems with complex behaviors are hard to characterize to guarantee that minimal performance criteria are met under all reasonable circumstances.

Robotics is essentially an experimental science. Few capable robots have been flown in space. There is no statistical basis for validation and characterization of the interaction between the robot and its environment. Without this characterization, robustness will not be fully satisfied.

Mission Level Human-Robot Interactions

Humans will always be in loop of any space robotic system, whether as consumers of the data gathered by the robot or as directors of robot activities. As such, there is no such thing as a fully autonomous robot (if there was it would be on the beach in Miami drinking motor oil instead of working for us!).

The challenge is to shift the human from directing the minute-to-minute activities of the robot and allow the human to concentrate on the mission-level objectives and scientific strategies, while at the same time allowing for direct control when necessary. Currently robots work on goals that are very low-level, e.g., “go to this exact location” or “put your manipulator in this configuration.” Humans string together these low-level goals to accomplish mission objectives. This is tedious and inefficient.

Interacting with robots at the mission level implies interpreting ambiguous instructions that the robot can only resolve through intimate knowledge of both the task and humans with which it has to interact.

A long-range goal of space robotics is to allow for human cognitive presence in space or on a planetary surface without human physical presence. Imagine a planetary geologist roaming Mars, picking up rocks, feeling them, even tasting them, without leaving her laboratory. Or imagine a worker putting together a component for a complex space telescope and then troubleshooting it while sitting in a comfortable chair. Some of the technologies required to make this happen fall outside of robots (e.g., high-bandwidth, low-latency communications). However, replicating the dexterity and sensing modalities of a human are challenges for robotics and it is unlikely that even if the communication issues are solved that a complete virtual presence will be possible in the next ten to twenty years. However, robots such as Robonaut at NASA JSC demonstrate the future potential for virtual presence.

In addition to remote interaction, we also envision human-robot teams working together on the same tasks. This will require technology leaps in the areas of natural language processing and human intention recognition.

Future acceptance of robotics will be dependent on the ability to give robots mission-level objectives such as “explore that area over there and report anything interesting” or “put together these components to create a truss.” This will require significant advances in robot cognitive abilities including planning, diagnosis and adaptation.

Conclusions

Most useful space robotic capabilities are well within reach in the next ten to twenty years, although sustained investment is needed to attain many of these. Long traverses and access to, with specialized robots, most locations on a planetary surface will be possible. Sample measurements can be obtained autonomously. Ground based planning and visualization tools will enable users to interact more directly with the robots. Automated inspection of orbiting structures by free flying robots is feasible.

Other tasks, such as autonomous assembly and maintenance in space will likely require careful systems engineering and constant monitoring from the ground to be feasible.

Robotic performance at the level of a space suited human onsite is and will continue to be a major challenge. Breakthroughs are required if robot systems are to perform beyond narrowly defined areas of expertise and attain the general cognitive and perceptual abilities of a human.

Robustness and Mission Level Interaction are cross-cutting challenges that emerge across space robotics. Developing robust robots will require careful systems engineering of both the robot and the infrastructure within which it operates.

Sustained investment and significant experimentation is needed to build and verify robust robotic systems. This includes building the needed infrastructure, as well as re-usable robot hardware and software components.

Introduction

Robots have had a role in space exploration from the beginning. The Soviet Lunakhod Rover was teleoperated on the surface of the moon in 1970. More recently the surface of Mars was explored by Sojourner, and Remote Manipulator Systems have helped construct the international space station. However, robots have not lived up to the promises of science fiction stories such as I Robot, movies such as Star Wars and TV shows such as Star Trek. In particular, current robots lack the reasoning abilities necessary to deal with novel situations and the dexterity to perform human-like manipulation tasks. Why have robots failed to live up to their promise? What are their current capabilities and what does the future hold? Those are the motivating questions of this report, which examines the current (2002) and future state of the art in space robotics. Dozens of robotic experts with hands-on experience were polled to create a comprehensive overview of space robotic functionalities.

Several caveats are necessary before beginning. First, although this report, due to the report s limited scope and funding, looks at robotic technology in isolation from the overall system infrastructure, this is not the right approach. Just as astronauts have a massive support structure (life support, training, ground control, etc.), which allows them to be successful, so too will robots need a similar support structure (special tools, robot-friendly components, robot pre-training, ground controllers, energy and repair facilities etc.) to be successful. Second, robot functionality and requirements should be derived from a set of science and mission objectives. By carefully designing a mission with robots and robot infrastructure in mind from the beginning NASA can make successful use of advanced robotic technology. Terrestrial examples like car factories, computer chip factories and automated farms demonstrate this.

The motivation for this report, which was commissioned by the NASA Exploration Team (NEXT), is to provide mission designers with appropriate expectations for the roles that robots might play in the next ten to twenty years. Mission designers can then determine the optimal mix of human and robotic talent to achieve their mission and science objectives. The authors of this report believe that human-robot missions will be more effective than robot-only or human-only missions. However, there will be missions that will be robot-only because of cost or safety constraints and missions that will require significant human presence for scientific or political reasons.

This report looks at robot functionalities required to support two broad mission classes: planetary surface exploration and in-space operations. The former focuses on robotic mobility, science perception, instrument placement and sample manipulation. The latter focuses on robotic assembly, inspection and repair. In both classes the report also looks at those functionalities unique to human-robot teaming. Table 1 shows our functionality breakdown. While limited in scope, we believe that the results can generalize to other mission classes such as planetary surface assembly and in-space science exploration.

Table 1. Space Robotic Functionalities

In space operations	Planetary surface explorations
Assembly	Surface mobility
Maintenance	Instrument deployment and sample manipulation
Inspection	Science planning, perception and execution
Human EVA assistance	Human exploration assistance

To compile this report we decomposed the functionalities in Table 1 into a set of metrics that measure the current and future state of the art for each functionality. These metrics were then distributed to robotic experts who were asked to rate each metric on a scale that ranged from that metric being within the current robotic state of the art to that metric requiring a fundamental breakthrough in robotic technology. In the middle of the scale were metrics that could be achieved in the next ten years with either nominal or intensive work. The authors then distilled the responses to these metrics into a comprehensive set of current and predicted robotic capabilities. We include the responses of each robotic expert in the appendix of this report so that others can draw their own conclusions.

Overview of Robotic Functionalities

In-Space Assembly

Robotic in-space assembly consists of a complicated series of tasks that must be performed with precision and, in the case of gossamer components, delicacy. The series of tasks include grasping components, mating them to each other or to another structure and then connecting the various conduits for fluids and electricity. The tasks can be made easier by carefully designing the components for easy manipulation and mating.

Current in-space assembly is done using a combination of the Shuttle and Station Remote Manipulator System (RMS) and human EVAs. In additional to assembling large space structures, there may also be a need to assembly small structures such as experiments or satellites. While the series of tasks is the same, the scale of the robots and the dexterity they require will be different. In this section we look at both types of robotic assembly.

Robotic in-space assembly can be broken into several distinct functionalities:

- Transporting and mating of components: This involves using a robotic manipulator to capture, move and mate components that are more massive than it.
- Making connection between assembled components: This involves using a robot manipulator and end effector to connect intricate components such as electrical and fluid connectors.
- Assembly sequence planning and execution: This involves creating an assembly plan whose elements are movement, manipulation and sensing tasks and constraints on those tasks and then executing that plan.
- Assembly of small structures: This involves the subset of issues concerning assembling structures that are smaller in mass to the robot.

Transporting and mating of components: In-space operational robots are limited to the Shuttle Remote Manipulator System (SRMS) (see Robots Rogue Gallery, page 156) and the Space Station Remote Manipulator System (SSRMS) (see Robots Rogue Gallery, page 156). These two robots are completely teleoperated and can transport and mate only large components. Current state-of-the-art robots, including Langley s Automated Structural Assembly Robot (see Robots Rogue Gallery, page 147) and Carnegie Mellon University s Skyworker (see Robots Rogue Gallery, page 155) robot show the capability to assembly fixed structures autonomously. In ten years expect robots to be able to assembly autonomously more complex structures, including those with soft (i.e., gossamer) components.

Making connections between assembled components: Currently, all in-space connections are done using human EVA. There are no operational robots with the dexterity to perform fine electrical or fluid connections. The ROTEX robot, which flew on Columbia in 1993, did experimentally open and close connector plugs (*see Robots Rogue Gallery, page 154*). Robonaut (*see Robots Rogue Gallery, page 153*) has successfully made connections using EVA plugs under teleoperation. This is the current state-of-the-art. In ten years the state-of-the-art should be autonomous connections using robot-friendly plugs.

Assembly sequence planning and execution: There has been little work in this area. Even the most advanced experimental robots performing autonomous assembly use pre-scripted plans that leave little room for changes. However, for the purposes of planning and execution, assembly in-space does not differ significantly from other planning and execution domains. Thus, expected advances in robotic planning and execution will easily apply to this functionality.

Assembly of small structures: There are no operational in-space robots to assemble small structures. Several demonstrations of fine assembly have been performed in space; these include: ETS7, a Japanese experiment that performed small parts manipulation using a robot controlled from the ground in 1997 (*see Robots Rogue Gallery, page 141*); and ROTEX, a German robot that performed simple capture and assembly via on-board teleoperation, ground teleoperation and some autonomy in 1993 (*see Robots Rogue Gallery, page 154*). Current state-of-the-art robots in ground demonstration testbeds include Robonaut (*see Robots Rogue Gallery, page 153*) and Ranger (*see Robots Rogue Gallery, page 152*). Both are teleoperated robots that have dexterous manipulators that can assembly small parts. In ten years expect autonomous assembly of small parts in a relevant environment.

Performance Metrics

Metric 1: Component capture with a manipulator

Description (reflecting increasing levels of sophistication):

1. Grasp component attached to same structure as robot with human operator in high-bandwidth, low-latency communication.
2. Grasp component attached to same structure as robot with human operator in low-bandwidth, high-latency communication.
3. Grasp component that is free-flying with human operator in high-bandwidth, low-latency communication.
4. Grasp component that is free-flying with human operator in low-bandwidth, high-latency communication.
5. Grasp soft component such as a gossamer structure with no damage to the component. Component has built-in hard attach point.
6. Grasp soft component such as a gossamer structure with no damage to the component. Component has no built-in hard attach point.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 1 through 3 above]. The shuttle RMS can grasp components under teleoperation and autonomous robots such as Skyworker can grasp components autonomously.
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 3-5 above] Autonomous grasping of free-flying structures has been demonstrated in the laboratory. Extending these to relevant environments and reliable operations will be nominal.
Projected State of the Art in 10 Years, Given Intense Effort	[Level 6 above] Soft component manipulation is still a challenge and will require intensive effort.
Breakthrough Capabilities	None

Metric 2: Moving component from capture position to goal position, human operator in low-bandwidth, high-latency communication

Description (reflecting increasing levels of sophistication):

1. Move a simple and rigid component to the goal through a known, fixed structure.
2. Move a simple and rigid component to the goal through a partially known, fixed structure.
3. Move a component that has multiple degrees of freedom and complex geometry through a partially known, fixed structure.
4. Move a component through a partially known, dynamic structure.
5. Move a poorly characterized component through a partially known, dynamic structure.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 1-2 above]. The shuttle RMS can move parts under teleoperation and robots such as Skyworker have done this autonomously.
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 3-4 above] Laboratory solutions to complicated motion control problems (see Latombe ref) exist and can be extended to real robot systems.
Projected State of the Art in 10 Years, Given Intense Effort	[Level 5 above] Advancements in sensing and control for robots in dynamic environments will be necessary to move components through complex, unknown environments.
Breakthrough Capabilities	None

Metric 3: Soft component manipulation; minimizing both robotic impact to soft components and to structure if movement requires contact with soft structures

Description (reflecting increasing levels of sophistication):

1. Robot motion minimizing accelerations/impact.
2. Component motion minimizing component forces.
3. Sensing component/structure forces and minimizing sensed forces.
4. Dynamic damping by robot.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 1-4 above] Current motion control techniques can take into account payload forces during robot motion.
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 1-4 above] Some work will need to be done to move these techniques from the laboratory to a relevant environment
Projected State of the Art in 10 Years, Given Intense Effort	None
Breakthrough Capabilities	None

Metric 4. Small structure capture with manipulator

Description (reflecting increasing levels of sophistication):

1. Grasp component attached to same structure as robot, with human operator in high-bandwidth, low-latency communication.
2. Grasp component attached to same structure as robot, with human operator in low-bandwidth, high-latency communication.
3. Grasp component that is free-flying, with human operator in high-bandwidth, low-latency communication.
4. Grasp component that is free-flying, with human operator in low-bandwidth, high-latency communication.
5. Grasp soft component such as a gossamer structure with no damage to the component

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 1-3 above] Robots such as Robonaut and Ranger perform small structure assembly under teleoperation
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 3-5 above] Current efforts in automating Robonaut and Ranger will provide for manipulation and assembly of small structures in space.
Projected State of the Art in 10 Years, Given Intense Effort	None
Breakthrough Capabilities	None

Metric 5. Mating/docking of two components

Description (reflecting increasing levels of sophistication):

1. Components have mechanical alignment capability that engages when components are close to one another. Robot operator in high-bandwidth, low-latency communication.
2. Components have mechanical alignment capability that engages when components are close to one another. Robot operator in low-bandwidth, high-latency communication.
3. Components have fiducials but no mechanical alignment capability. Robot operator in high-bandwidth, low-latency communication.
4. Components have fiducials but no mechanical alignment capability. Robot operator in low-bandwidth, high-latency communication
5. Components have no fiducials or mechanical alignment capability. Robot operator in high-bandwidth, low-latency communication.
6. Components have no fiducials or mechanical alignment capability. Robot operator in low-bandwidth, high-latency communication.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 1-4 above] The shuttle RMS has successfully mated with external parts and has mated space station parts to each other under teleoperation.
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 4-5 above] Both the Skyworker robot and the Langley assembly robot have autonomously mated components.
Projected State of the Art in 10 Years, Given Intense Effort	[Level 6 above] Robot vision is still an obstacle to fully autonomous mating of two components that have no special vision tags.
Breakthrough Capabilities	None

Metric 6: Grasping connectors

Description (reflecting increasing levels of sophistication):

1. Robot gets connector from custom dispenser in fixed, known location. Connectors specially built for easy grasping.
2. Connectors from custom dispenser in fixed, known location, but connectors not built for easy robot use. Human operator in high-bandwidth, low-latency communication with robot.
3. Connectors from custom dispenser in fixed, known location, but connectors not built for easy robot use. Human operator in low-bandwidth, high-latency communication with robot.
4. Robot gets connector from a bag of connectors. Human operator in high-bandwidth, low-latency communication with robot.
5. Robot gets connector from a bag of connectors. Human operator in low-bandwidth, high-latency communication with robot.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 1-2 above] Both Robonaut and Ranger have grasped connectors under teleoperation. Other robots have autonomously grasped connectors from a fixed location.
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 3-5 above]. Both Robonaut and Ranger have grasped EVA connectors under teleoperation. Work is underway to automate that process.
Projected State of the Art in 10 Years, Given Intense Effort	None
Breakthrough Capabilities	None

Metric 7. Mating connectors

Description (reflecting increasing levels of sophistication):

1. Mating of robot-friendly connectors. Human operator in high-bandwidth, low-latency communication with robot.
2. Mating of robot-friendly connectors. Human operator in low-bandwidth, high-latency communication with robot.
3. Mating of standard (i.e., non-robot-friendly) connectors. Human operator in high-bandwidth, low-latency communication with robot.
4. Mating of standard (i.e., non-robot-friendly) connectors. Human operator in low-bandwidth, high-latency communication with robot.
5. Mating of arbitrary connectors — either those with complex orientation requirements or those that require large forces to engage.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	Both Robonaut and Ranger have mated robot-friendly connectors under teleoperation. Robonaut has mated standard EVA connectors under teleoperation.
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 4-5 above]. Current work will allow for autonomous mating of standard EVA connectors.
Projected State of the Art in 10 Years, Given Intense Effort	[Level 5 above] Arbitrary connectors, such as video cables, serial cables, etc. will require sophisticated sensing capabilities that will require intense research.
Breakthrough Capabilities	None

Metric 8. Running conduit

Description (reflecting increasing levels of sophistication):

1. Running rigid, yet pliable conduit (e.g., tubing). Human operator in high-bandwidth, low-latency communication with robot.
2. Running rigid, yet pliable conduit (e.g., tubing). Human operator in low-bandwidth, high-latency communication with robot.
3. Running very flexible conduit (e.g., electrical cables). Human operator in high-bandwidth, low-latency communication with robot.
4. Running very flexible conduit (e.g., electrical cables). Human operator in high-bandwidth, low-latency communication with robot.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 1-3 above] Robonaut has run pliable conduit in laboratory tests under teleoperation.
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 2-4 above]. Robonaut has demonstrated the ability to work with flexible conduit and with ropes in a laboratory environment. Moving to a space-relevant environment and becoming autonomous are challenges.
Projected State of the Art in 10 Years, Given Intense Effort	None
Breakthrough Capabilities	None

Metric 9: Pre-assembly planning and sequencing

Description (reflecting increasing levels of sophistication):

1. Robot operations personnel generate detailed task sequence to accomplish assembly. Robot personnel work closely with the engineers who designed the structure. Plan contains no contingencies except to stop if a fault is detected.
2. Initial task plan automatically generated from software models of structure to be assembled. Robot operations personnel thoroughly check the plan (by hand or through a simulation) and add robot-specific details and additional tasks. Plan allows for some contingencies and flexible execution times.
3. Task plan automatically generated from software models is nearly complete. Robot operations personnel fine tune the plan. Plan allows for significant contingencies and robot flexibility.
4. All task planning and sequencing is done from software models. Minimal involvement by robot operations personnel. Plan copes with major failures

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 1-2 above] Very little work has been done on planning and scheduling for assembly. Current state-of-the-art is based on existing planners and schedulers.
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 2-3 above] Predicted progress in planning and scheduling software will make these attainable for robot assembly.
Projected State of the Art in 10 Years, Given Intense Effort	[Level 3 above]
Breakthrough Capabilities	[Level 4 above]

Metric 10: Assembly-time planning and execution:

Description (reflecting increasing levels of sophistication):

1. Plan is a detailed sequence of low-level commands. Behavior of the robot(s) is defined by input; system s default response to problems is to halt.
2. Plan allows flexible time specification and contingencies enabling a family of behaviors.
3. Plan is a prioritized list of tasks with constraints amongst them. System responds to opportunities and recovers from most faults.
4. Plan is a prioritized list of tasks with constraints amongst them. System responds to opportunities and recovers from most faults. System adapts to robot degradation and failures.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 1-2 above] A great deal of work has been done on robotic architectures for executing a plan, including NASREM [ref?].
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 2-3 above] Continued research into plan execution will continue and produce more flexible robots.
Projected State of the Art in 10 Years, Given Intense Effort	[Level 3 above]
Breakthrough Capabilities	[Level 4 above]

Metric 11: Overall assembly performance

Description (reflecting increasing levels of sophistication):

1. Robots that move large components and mate parts with a human operator in high-bandwidth, low-latency communication.
2. Robots that move large components and mate parts with a human operator in low-bandwidth, high-latency communication.
3. Robots that can mate components and do fine assembly, including making connections with a human operator in high-bandwidth, low-latency communication.
4. Robots that can mate components and do fine assembly, including making connections with a human operator in low-bandwidth, high-latency communication.
5. Robots that perform complete assembly of complicated structure (e.g., large telescope) from start to finish with human operator in high-bandwidth, low-latency communication.
6. Robots that perform complete assembly of complicated structure (e.g., large telescope) from start to finish with human intervention.
7. Robots that perform complete assembly of complicated structure that includes gossamer components from start to finish with minimal human intervention.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 1-2 above] Space station RMS and shuttle RMS perform these operations under teleoperation. ROTEX and ETS-VII demonstrated some of these autonomously in in-space tests.
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 2-4 above] Robonaut and Ranger currently perform these operations under teleoperation in laboratory and neutral buoyancy settings. Autonomous control is expected.
Projected State of the Art in 10 Years, Given Intense Effort	[Level 5-7 above] With intense effort and much system engineering a large structure could be robotically assembled with significant help from ground-based humans.
Breakthrough Capabilities	[Level 7 above]. Completely autonomous assembly of complex structures will require breakthroughs in robotics and artificial intelligence.

In-Space Inspection

In-space inspection consists of using a robot to examine the exterior of space structures to verify correct assembly or to detect anomalies. This can be routine inspection or anomaly-driven inspection. The robots may be free-flyers or may be manipulators, possibly with high degrees of freedom (e.g., a snake robot). An in-space inspection operation may consist of the following sub-tasks: moving the robot to visit all of the structure; interpreting sensory data to find anomalies; taking some action at the anomaly site. This functionality considers both the teleoperation of robots for inspection and the ability of a robot to plan and execute assembly tasks autonomously.

Performance Metrics

Metric 1: Inspecting Structures

Description (reflecting increasing levels of sophistication):

1. Visual inspection of a specific anomaly site; teleoperated.
2. Complete visual inspection of a simple exterior surface; teleoperated.
3. Complete visual inspection of simple exterior surface; supervised autonomous operation.
4. Complete visual inspection of complex exterior surface; supervised autonomous operation.
5. Complete visual inspection of complex, open 3D surfaces (e.g., a truss); supervised autonomous operation.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 1-2 above] AERCam Sprint and SCAMP demonstrated teleoperated robots for inspection of anomalies.
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 3-5 above] Ongoing research on the AERCam project and applicable research from NASA Ames in the Personal Satellite Assistant (PSA) project show the way to more complete autonomy.
Projected State of the Art in 10 Years, Given Intense Effort	None
Breakthrough Capabilities	None

Metric 2: Inspection planning and execution.

Description (reflecting increasing levels of sophistication):

1. Robot given detailed sequence of inspection path. Default response to problems is to halt.
2. User selects inspection area with robot-planned coverage path. Automatic workarounds for many problems.
3. User selects multiple inspection tasks and robot optimizes its execution of those tasks. Robot notices unexpected situations while traveling to inspection areas.
4. High-level inspection tasks with little human input. Robot adapts to degradations in performance.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 1 above] Current AERCam research at NASA JSC involves giving a detailed path to the robot.
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 2-3 above] More sophisticated planning and execution tools are under development by many projects.
Projected State of the Art in 10 Years, Given Intense Effort	[Level 4 above] Completely autonomous inspection will require a significant development effort.
Breakthrough Capabilities	None

Metric 3: Sensor Data Interpretation

Description (reflecting increasing levels of sophistication):

1. No data interpretation; all data stored or sent off-board in raw form.
2. Mosaicing to provide single, continuous view; no analysis.
3. Filtering of data — only potentially anomalous data is stored or sent.
4. Autonomous detection of clearly defined and modeled anomalies.
5. Autonomous detection of unmodeled off-nominal anomalies.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 1-2 above] The AERCam IGD project used mosaicing to create a single view of multiple images
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 3-4 above] Research in computer vision is addressing these problems. Industry is committed to solving these problems for their manufacturing processes.
Projected State of the Art in 10 Years, Given Intense Effort	[Level 5 above]
Breakthrough Capabilities	[Level 5 above] Unrestricted computer vision is still a very hard problem that is looking for breakthroughs.

Metric 4: Autonomous actions at anomaly site

Description (reflecting increasing levels of sophistication):

1. No action taken.
2. Station-keeping such that anomaly is continuously monitored.
3. Approach anomaly for closer look.
4. Deploy additional sensor modalities or views to further characterize anomaly.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 1-2 above] Current systems do little more than station-keep at an anomaly site.
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 3-4 above] Reasoning about additional sensing actions will be possible in the next several years.
Projected State of the Art in 10 Years, Given Intense Effort	[None]
Breakthrough Capabilities	[None]

Metric 5: Recharging/refueling of inspection robot

Description (reflecting increasing levels of sophistication):

1. Robot can be recharged/refueled only by human.
2. Robot can be recharged/refueled only with human operator in high-bandwidth, low-latency communication.
3. Robot can autonomously recharge/refuel.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 1-2 above] The AERCam Sprint and AERCam IGD activities required human refueling. Teleoperating a robot to a properly constructed refueling station should be within current technology.
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 3 above] With an appropriately designed refueling station and sensory beacons autonomous refueling/recharging is within our grasp.
Projected State of the Art in 10 Years, Given Intense Effort	[None]
Breakthrough Capabilities	[None]

Metric 6: Summary of overall capabilities

Description (reflecting increasing levels of sophistication):

1. Robotic visual inspection of some exterior surfaces with no interpretation of sensory data; teleoperated
2. Robotic visual inspection of some exterior surfaces with no interpretation of sensory data; human operator closely supervising robot via high-bandwidth communication.
3. Robotic visual inspection of some exterior surfaces; sensory data filtered before being stored or sent; supervised autonomous operation
4. Robotic visual inspection of most exterior surfaces; autonomous interpretation of most data; supervised autonomous operation.
5. Robotic visual inspection of most exterior surfaces; autonomous interpretation of most data; autonomous refueling and recharging.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 1-2 above] AERCam Spring, AERCam IGD and SCAMP all demonstrated Level 1 and some of Level 2
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 2-3 above] Current research into AERCam should provide more autonomy in the coming years.
Projected State of the Art in 10 Years, Given Intense Effort	[Level 4 above] Truly autonomous operation, including interpretation of data will take intense development.
Breakthrough Capabilities	[Level 5 above] Autonomous interpretation of data is a challenging computer vision problem and will require a breakthrough in this area.

In-Space Maintenance

Robotic in-space maintenance involves using a robot to repair a structure that is already assembled. This includes routine, pre-planned maintenance as well as fault-driven maintenance. Maintenance includes change-out of existing components with new ones, accessing and repairing hidden components and troubleshooting of anomalies. An in-space maintenance operation may consist of the following sub-tasks:

- **Change-out of components.** This involves using a robotic manipulator to exchange one component for another component. Typically, the components are designed to be easily replaced (e.g., Orbital Replacement Units or ORUs), but not always.
- **Accessing obstructed components**. This involves using a robot to get at components that are behind panels, covers or debris.
- **Robotic refueling of satellites/spacecraft.** Sometimes the only maintenance that is necessary is additional fuel. This capability looks at the ability of robots to refuel spacecraft.

Change-out of components: There have been several space demonstrations of robotic change-out of ORUs, including the ROTEX and ETS-VII robots (see pages 109 and 100). Some of these experiments were teleoperated and some were autonomous with visual markers on the ORU. The Ranger robot (see page 108) has also demonstrated change-out of ORUs and other components. The BAT robot (see page 98) performed some of the change-out procedures of the first Hubble Space Telescope (HST) servicing missions. Both of these robots are teleoperated. Future progress in robotics should allow for autonomous change-out of components like ORUs and even components that are not as robot-friendly.

Accessing obstructed components: Many components, like ORUs, are designed for easy replacement. However, maintenance may also involve accessing components that are behind panels, covers or other obstructions. Little in-space work has been done in this area. Several ground-based robots like Ranger, Robonaut and BAT have worked this area. In the future, opening of panels and covers by both teleoperated and autonomous robots should be possible.

Robotic refueling of satellites/spacecraft: The ETS-VII robot (see page 100) captured a satellite under teleoperation, which is the first step in refueling. We expect that robots will be able to refuel satellites and spacecraft that are designed for robotic refueling under close human supervision.

Performance Metrics

Metric 1. Autonomously locating the component

Description (reflecting increasing levels of sophistication):

1. Open loop control using known position on structure and no sensing.
2. Closed loop control using fiducial markers.
3. No special markers, but *a priori* model of undamaged component.
4. *A priori* model but component has been damaged or changed.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Levels 1-2] Work on the ground in autonomous ORU change out has demonstrated this capability.
Projected State of the Art in 10 Years, Given Nominal Effort	[Levels 3-4] Current research into computer vision should allow for object recognition given an *a priori* model
Projected State of the Art in 10 Years, Given Intense Effort	[Level 4]
Breakthrough Capabilities	None

Metric 2. Grasping the component

Description (reflecting increasing levels of sophistication):

1. Grasp of special purpose component handle with corresponding end effector; human operator in high-bandwidth, low-latency communication with robot.
2. Grasp of special purpose component handle with corresponding end effector; human operator in low-bandwidth, high-latency communication with robot.
3. Grasp of pre-designed component handle with general purpose end effector; human operator in high-bandwidth, low-latency communication with robot.
4. Grasp of pre-designed component handle with general purpose end effector; human operator in low-bandwidth, high-latency communication with robot.
5. Grasp of component with no pre-designed handle; human operator in high-bandwidth, low-latency communication with robot.
6. Grasp of component with no pre-designed handle; human operator in low-bandwidth, high-latency communication with robot.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Levels 1-5] In-space demonstrations of ROTEX and ETS-VII have demonstrated the first four metrics. Ground based systems such as Robonaut and Ranger have demonstrated the fifth.
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 6] Current research should provide for autonomous grasping in a few years.
Projected State of the Art in 10 Years, Given Intense Effort	None
Breakthrough Capabilities	None

Metric 3. Inserting new component

Description (reflecting increasing levels of sophistication):

1. Component designed to lock into place when inserted; human operator in high-bandwidth, low-latency communication with robot.
2. Component designed to lock into place when inserted; human operator in low-bandwidth, high-latency communication with robot.
3. Component requires bolts or screws after being inserted; human operator in high-bandwidth, low-latency communication with robot.
4. Component requires bolts or screws after being inserted; human operator in low-bandwidth, high-latency communication with robot.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Levels 1-3] In-space experiments with ROTEX and ETS-VII have demonstrated these capabilities.
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 4] Autonomous control of robot manipulators that can turn bolts or screws is a few years away.
Projected State of the Art in 10 Years, Given Intense Effort	None
Breakthrough Capabilities	None

Metric 4. Opening panels and covers

Description (reflecting increasing levels of sophistication):

1. Opening rigid panel with robot-friendly handle; human operator in high-bandwidth, low-latency communication with robot.
2. Opening rigid panel with robot-friendly handle; human operator in low-bandwidth, high-latency communication with robot.
3. Opening rigid panel without a handle; human operator in high-bandwidth, low-latency communication with robot.
4. Opening rigid panel without a handle; human operator in low-bandwidth, high-latency communication with robot.
5. Opening soft, attached blanket; human operator in high-bandwidth, low-latency communication with robot.
6. Opening soft, attached blanket; human operator in low-bandwidth, high-latency communication with robot.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Levels 1-3] In-space experiments with ROTEX and ETS-VII have demonstrated these capabilities.
Projected State of the Art in 10 Years, Given Nominal Effort	[Levels 3-6] Current research should accomplish all of the goals in this metric
Projected State of the Art in 10 Years, Given Intense Effort	None
Breakthrough Capabilities	None

Metric 5. Removing bolts and fasteners

Description (reflecting increasing levels of sophistication):

1. Removing bolt with built-in bolt tool; human operator in high-bandwidth, low-latency communication with robot.
2. Removing bolt with built-in bolt tool; human operator in low-bandwidth, high-latency communication with robot.
3. Removing bolt by grasping bolt tool; human operator in high-bandwidth, low-latency communication with robot.
4. Removing bolt by grasping bolt tool; human operator in low-bandwidth, high-latency communication with robot.
5. Automatically adjusting torque to overcome stuck bolts.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Levels 1-3]
Projected State of the Art in 10 Years, Given Nominal Effort	[Levels 4-5]
Projected State of the Art in 10 Years, Given Intense Effort	None
Breakthrough Capabilities	None

Metric 6. Removing debris

Description (reflecting increasing levels of sophistication):

1. Robot can remove loose debris that is blocking a component; human operator in high-bandwidth, low-latency communication with robot.
2. Robot can remove loose debris that is blocking a component; human operator in low-bandwidth, high-latency communication with robot.
3. Robot can untangle wires that are hindering extraction of a component; human operator in high-bandwidth, low-latency communication with robot.
4. Robot can untangle wires that are hindering extraction of a component; human operator in low-bandwidth, high-latency communication with robot.
5. Robot can bend metal that has obstructed extraction of a component; human operator in high-bandwidth, low-latency communication with robot.
6. Robot can bend metal that has obstructed extraction of a component; human operator in low-bandwidth, high-latency communication with robot.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Levels 1-2] Robonaut has been teleoperated to do some of these tasks.
Projected State of the Art in 10 Years, Given Nominal Effort	[Levels 1-5]
Projected State of the Art in 10 Years, Given Intense Effort	[Levels 4-6]
Breakthrough Capabilities	None

Metric 7. Robotic refueling of satellites/spacecraft

Description (reflecting increasing levels of sophistication):

1. Refueling of stationary (relative to the robot) satellite/spacecraft that are designed for robotic refueling (e.g., have sensory tags, easily accessible tanks, etc.); human operator in high-bandwidth, low-latency communication with robot.
2. Refueling of stationary (relative to the robot) satellite/spacecraft that are designed for robotic refueling (e.g., have sensory tags, easily accessible tanks, etc.); human operator in low-bandwidth, high-latency communication with robot.
3. Refueling of moving spacecraft that are designed for robotic refueling (e.g., have sensory tags, easily accessible tanks, etc.); human operator in high-bandwidth, low-latency communication with robot.
4. Refueling of moving spacecraft that are designed for robotic refueling (e.g., have sensory tags, easily accessible tanks, etc.); human operator in low-bandwidth, high-latency communication with robot.
5. Refueling of spacecraft that are not designed for robotic refueling; human operator in high-bandwidth, low-latency communication with robot.
6. Refueling of spacecraft that are not designed for robotic refueling; human operator in low-bandwidth, high-latency communication with robot.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 1] Some simple, teleoperated refueling experiments were conducted by ETS-VII in a space setting.
Projected State of the Art in 10 Years, Given Nominal Effort	[Levels 1-4]
Projected State of the Art in 10 Years, Given Intense Effort	[Levels 3-6]
Breakthrough Capabilities	None

Metric 8. Summary of Overall Performance

Description (reflecting increasing levels of sophistication):

1. Robotic change-out of pre-designed components (e.g., ORUs); human operator in high-bandwidth, low-latency communication with robot.
2. Robotic change-out of pre-designed components (e.g., ORUs); human operator in low-bandwidth, high-latency communication with robot.
3. Robotic refueling of satellites/spacecraft; human operator in high-bandwidth, low-latency communication with robot.
4. Robotic refueling of satellites/spacecraft; human operator in low-bandwidth, high-latency communication.
5. Robotic change-out of arbitrary, exposed components; human operator in high-bandwidth, low-latency communication with robot.
6. Robotic change-out of arbitrary, exposed components; human operator in low-bandwidth, high-latency communication with robot.
7. Robotic access to and change-out of arbitrary, obstructed components; human operator in high-bandwidth, low-latency communication with robot.
8. Robotic access to and change-out of arbitrary, obstructed components; human operator in low-bandwidth, high-latency communication with robot.
9. Robotic troubleshooting of anomalies and arbitrary repairs; human operator in low-bandwidth, high-latency communication with robot.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 1] SPDM, Ranger and BAT demonstrate the current state of the art
Projected State of the Art in 10 Years, Given Nominal Effort	[Levels 2-7] Robots like Robonaut can be improved to accomplish these levels of performance.
Projected State of the Art in 10 Years, Given Intense Effort	[Level 8]
Breakthrough Capabilities	[Level 9] Troubleshooting requires advanced cognitive abilities that will require a breakthrough.

In-Space Human EVA Assistance

Robots can be used to assist human crew members during their extravehicular activities. Use of robots can increase the efficiency and safety of EVAs. There are several ways in which robots can assist. The robots might simply monitor or document EVA tasks. Or the robots might prepare a worksite before an EVA or clean up after an EVA. The robots might also interact directly with an astronaut, by handing them tools or shining a light. In these cases the astronaut will want to interact with the robot naturally using language and gestures. True human-robot teams will arise when robots can be given high-level goals while helping a human crew member—in these cases the robot will simply be another team member.

Performance Metrics

Metric 1. Autonomously tracking EVA crew member

Description (reflecting increasing levels of sophistication):

1. Robot keeps crew member in view.
2. Robot keeps crew member in view while avoiding obstacle.
3. Robot reacquires crew member following occlusion.
4. Track multiple crew members.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 1] AERCam IGD, Robonaut and the EVA Robotic Assistant robots all can track crew members.
Projected State of the Art in 10 Years, Given Nominal Effort	[Levels 2-4] Ongoing research in the EVA Robotic Assistance project and Robonaut should lead to these capabilities shortly.
Projected State of the Art in 10 Years, Given Intense Effort	None
Breakthrough Capabilities	None

Metric 2. Autonomous video archiving of EVA tasks

Description (reflecting increasing levels of sophistication):

1. Robot points camera at given location.
2. Robot responds to simple voice or gesture commands for camera position fine-tuning.
3. Robot moves camera to avoid occlusion.
4. Robot moves camera to get best view angle based on the task being performed.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Levels 1-2] Similar to Metric 1 above.
Projected State of the Art in 10 Years, Given Nominal Effort	[Levels 3-4] Reasoning about task activities and determining the best vantage point are elements of on-going research.
Projected State of the Art in 10 Years, Given Intense Effort	[Level 4]
Breakthrough Capabilities	None

Metric 3. Setting up and taking down portable foot restraints and other aids

Description (reflecting increasing levels of sophistication):

1. Robot puts up and takes down restraints and other aids; human operator in high-bandwidth, low-latency communication with robot.
2. Robot puts up and takes down restraints and other aids; human operator designates exact location and configuration of restraints and aids, but does not directly control the robot.
3. Robot puts up and takes down restraints and other aids; robot decides location and configuration of restraints and aids from task description.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Levels 1] Robonaut and Ranger have demonstrated this capability in the laboratory and a neutral buoyancy facility respectively. Both were teleoperated.
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 3] Reasoning about tasks to determine placement will take more research and development.
Projected State of the Art in 10 Years, Given Intense Effort	None
Breakthrough Capabilities	None

Metric 4. Human-robot communication

Description (reflecting increasing levels of sophistication):

1. Voice commands routed to robot operator.
2. Text commands given to robot using keyboard or mouse.
3. Low-level voice commands interpreted by robot (e.g., stop, faster, move right, etc.).
4. High-level voice commands with referents interpreted by robot (e.g., pick up that).
5. Multi-modal communication (e.g., integration of speech and gesture or speech and graphics tablet).
6. Dialog between robot and human about goals and actions.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Levels 1-3] Low-level voice commands using COTS software has been demonstrated by many robots in many applications.
Projected State of the Art in 10 Years, Given Nominal Effort	[Levels 4-6] Only a few current robots in laboratory settings have robust natural language interfaces
Projected State of the Art in 10 Years, Given Intense Effort	[Level 6] Dialog managements is an area of active research, but there are still many hurdles remaining.
Breakthrough Capabilities	[Level 6]

Metric 5. Sensing of humans Description (reflecting increasing levels of sophistication):

Description (reflecting increasing levels of sophistication):

1. Generic obstacle avoidance and safe movement around humans (e.g., humans are just another obstacle to avoid).
2. Tracking of humans in work site.
3. Tracking of human body parts (e.g., gestures).
4. Recognition of humans and their activities/plans/intentions.
5. Recognition of human physical, mental and emotional state.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Levels 1-2] Obstacle avoidance and human tracking are both regularly demonstrated on many robots.
Projected State of the Art in 10 Years, Given Nominal Effort	[Levels 2-4] Gesture recognition and plan recognition are both areas of research that are progressing at a fast pace.
Projected State of the Art in 10 Years, Given Intense Effort	None
Breakthrough Capabilities	[Level 5] Recognition of human emotional and mental state by robots will require a breakthrough. However, given proper instrumentation, recognition of physical state might be possible without a breakthrough.

Metric 6. Gesture recognition Description (reflecting increasing levels of sophistication):

Description (reflecting increasing levels of sophistication):

1. Simple, static gestures.
2. Dynamic gestures (e.g., waving).
3. Hand signals.
4. Gestures linked to natural language for grounding of referents (e.g., pick up that).

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Levels 1-2] Simple gesture recognition is being demonstrated on a number of robots.
Projected State of the Art in 10 Years, Given Nominal Effort	[Levels 2-4] Current research should lead to all of these capabilities being state of the art in ten years.
Projected State of the Art in 10 Years, Given Intense Effort	None
Breakthrough Capabilities	None

Metric 7. Physical interaction

Description (reflecting increasing levels of sophistication):

1. Holding objects (light, tool, cable) for human.
2. Handing objects to human.
3. Taking objects from human.
4. Carrying/rescuing disabled human.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Levels 1-3] Several robots have demonstrated this capability.
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 4] The EVAHR robot demonstrated rescuing a disabled human on an air bearing floor, but in a very constrained manner.
Projected State of the Art in 10 Years, Given Intense Effort	[Level 4]
Breakthrough Capabilities	None

Metric 8. Summary of overall capabilities:

Description (reflecting increasing levels of sophistication):

1. Robots move humans from one work site to another; human operator in high-bandwidth, low-latency communication with robot.
2. Robots move humans from one work site to another; human operator in low-bandwidth, high-latency communication with robot.
3. Robots do site preparation and cleanup for EVA; human operator in high-bandwidth, low-latency communication with robot.
4. Robots do site preparation and cleanup for EVA; human operator in low-bandwidth, high-latency communication.
5. Robots in same proximity as humans and working same tasks, but no physical interaction; human operator in high-bandwidth, low-latency communication with robot.

6. Robots in same proximity as humans and working same tasks, but no physical interaction; human operator in low-bandwidth, high-latency communication with robot.
7. Robots that physically interact with humans; human operator in high-bandwidth, low-latency communication with robot.
8. Robots that physically interact with humans; human operator in low-bandwidth, high-latency communication with robot.
9. Robots that are true teammates with humans, working on same tasks, responding to natural language, gestures and high-level goals and recognizing human intentions.
10. Synergistic relationship between human and machine with direct, physical connections and prostheses, i.e., super humans augmented with machines.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Levels 1-3,5,7] Simple automated assistance and complicated teleoperated assistance has been demonstrated.
Projected State of the Art in 10 Years, Given Nominal Effort	[Levels 4-8] Complex automated assistance will be available in ten years.
Projected State of the Art in 10 Years, Given Intense Effort	[Levels 8-10] Robots that are true teammates with humans will require intense development efforts and possibly breakthroughs.
Breakthrough Capabilities	[Level 10] Augmenting humans with mechanical devices will require a breakthrough according to many respondents.

Surface Mobility Functionality

Robotic surface mobility demands a fusion of competencies to move safely and effectively throughout the environment. The competency required for surface mobility, and the attendant complexity, increases with the level of autonomy employed. Necessary capabilities include localizing in the environment, identifying goal locations, planning a path to a goal, and executing the path while detecting and avoiding obstacles. Surface mobility may also require monitoring system state and health, acting in a resource-efficient manner, collecting routine data, seeking targets of opportunity, constructing maps, and communicating information. Mechanical capabilities as well as energy and thermal issues are also relevant. These individual capabilities aggregate into the overall performance that can be achieved in terms of distance, duration, speed, complexity, reliability and degree of autonomy. In this survey, metrics for specific capabilities for surface mobility will be followed by metrics of overall rover performance.

Performance Metrics

Metric 1: Localization: the capability for determining position and orientation in a relative or absolute sense.

Description (reflecting increasing levels of sophistication):

1. Estimate motion using proprioception (internal sensing) like dead reckoning or inertial measurement
2. Estimate motion by tracking nearby landmarks or natural features
3. Localize with respect to fixed beacons or artificial features
4. Localize using perception including a sun sensor or star tracker
5. Localize with respect to orbital data, using features visible from orbit, such as skyline features)

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 1 above]. Current state of the art is primitive in this regard, demonstrated by Sojourner, enabling at best partial localization within the relative reference frame of the robot and its local surroundings. Although demonstrations of high-precision and long-term localization exist, they are limited mainly to the laboratory.
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 1-3 above]. Significant advances in localization are not predicted according to consensus at nominal research effort. EVE is a successor to Adam and demonstrates this.
Projected State of the Art in 10 Years, Given Intense Effort	[Level 4-5 above]. Consensus opinion holds that intense 10 year effort can lead to advanced localization that brings together local sensor data with orbital data to provide robust estimates of position.
Breakthrough Capabilities	None

Metric 2: Goal definition: the form and degree of specificity by which goals are conveyed to the rover.

Description (reflecting increasing levels of sophistication):

1. Goals are localized in the global reference frame
2. Goals are localized in the local reference frame (relative to the rover)
3. Goals are imprecisely localized and are refined by rover
4. Goals are broadly defined and selected by rover
5. Mission is objective-based and goals are generated by rover

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 1 above]. Current state-of-the-art is limited to the specification of goals relative to the rover's current position. Once again Sojourner is an example.
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 3 above]. Nominally, consensus holds that in 10 years time approximate goals can be specified to a rover, which will then further refine the goals during operation. Hyperion and K9 show this level of competence.
Projected State of the Art in 10 Years, Given Intense Effort	[Level 5 above]. With intense effort and possibly breakthrough technological discoveries, it is possible to achieve mission-level goal specification within 10 years.
Breakthrough Capabilities	[Level 5]. Breakthrough technologies can enable objective-based mission specification as well as, and possibly in conjunction with, intense effort.

Metric 3 Goal scheduling, which refers to the extent to which goals are defined in time.

Description (reflecting increasing levels of sophistication):

1. Goals are sequentially scheduled by rover.
2. Goals dynamically reschedule during execution based on rover performance.
3. Goals reschedule during execution based on mission objectives.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 1 above]. Current state-of-the-art is limited to sequential scheduling of goals ahead-of-time. Sojourner exemplifies this.
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 2-3 above]. Nominally, consensus holds that in 10 years time goals will be dynamically rescheduled, possibly even in view of overall mission objectives. K9 and FIDO exemplify this.
Projected State of the Art in 10 Years, Given Intense Effort	[Level 3 above]. With intense effort goals can be dynamically rescheduled in view of mission objectives.
Breakthrough Capabilities	None

Metric 4. Path Planning: the tactical determination of rover motion in the local area.

Description (reflecting increasing levels of sophistication):

1. Plan paths with a complete world model in-hand
2. Plan paths in well characterized environment.
3. Path planning in uncertain environment with efficient incremental re-planning as more information becomes available.
4. Plan (and replan) paths in uncertain environment subject to additional spatial constraints (keep targets in view) and/or monotonic constraints (limit total energy or fuel use).
5. Plan (and replan) paths in uncertain environments optimizing several parameters and subject to monotonic and non-monotonic constraints.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 2-3 above]. Current state-of-the-art enables path planning incrementally with uncertainty. Examples include K9, FIDO, and Bullwinkle.
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 4 above]. Consensus holds that in 10 years time path planning will be robustly state-of-the-art while keeping additional spatial constraints in view. [Hyperion]
Projected State of the Art in 10 Years, Given Intense Effort	[Level 5 above]. With intense effort in 10 years path planning will be generally solved, including both monotonic and non-monotonic constraints.
Breakthrough Capabilities	None

Metric 5. Coverage planning: the solution to the problem of exhaustively exploring an area and examining the entire terrain to a resolution related to the sensing or study to be performed.

Description (reflecting increasing levels of sophistication):

1. Apply fixed coverage patterns
2. Adapt coverage patterns to known terrain
3. Adapt coverage patterns in unknown terrain
4. Ensure coverage in complex terrain

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 1-2 above]. Current methods enable simple coverage patterns with only limited adaptation to known terrain. Nomad is an example of such.
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 3 above]. Consensus holds that in 10 years nominally coverage patterns will adapt on-line to unknown terrain being explored.
Projected State of the Art in 10 Years, Given Intense Effort	[Level 4 above]. With intense effort, in 10 years coverage can be guaranteed even for complex terrain.
Breakthrough Capabilities	None

Metric 6. Power planning is reasoning about power levels and adapting behavior, possibly including path or coverage plans or mission goals, to adapt to power constraints.

Description (reflecting increasing levels of sophistication):

1. Rover monitors power levels
2. Rover modifies behavior in response to decreasing power level
3. Rover changes behavior to actively increase power level
4. Rover plans in advance to provide sufficient power for activities
5. Rover plans to optimize power performance over mission
6. Rover adapts plans during operation to optimize power levels

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 1-2 above]. Current state of the art enables automatic modification of behavior due to low power as well as some active power-increasing decision-making of a limited nature, exemplified by Hyperion.
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 4 above]. 10 years nominal effort will lead to both planning for power management combined with active adaptation of those plans to optimize power budget.
Projected State of the Art in 10 Years, Given Intense Effort	[Level 6 above]. With intense effort power planning can fulfill all desired functionality, enabling planning to optimize power levels at the mission level.
Breakthrough Capabilities	None

Metric 7. Plan execution: the process of translating plans into actions. This may be controlled by a dedicated process such as a mission executive or, for example in a behavior-based system, may result from actions designed (preplanned) to occur given a particular stimulus.

Description (reflecting increasing levels of sophistication):

1. Plan is executed directly if within nominal conditions
2. Fixed strategies are employed to maintain plan
3. Plan incorporates reactive capabilities to maintain progress
4. Rover detects inability to succeed at the goal
5. Plan is modified/replanned as necessary
6. Evolving plan guides various strategies and behaviors to achieve high-level goal
7. Robot replans or employs additional strategies to reach goal
8. Robot attends to mission objectives and generates new goals to achieve mission as needed

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 2-3 above]. Consensus is not well focused but certainly includes competencies for direct execution and fixing strategies, possibly including reactive capabilities to ensure fast response to unforeseen circumstances, exemplified by K9.
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 6 above]. Nominal effort will result in more continuous planning and execution techniques such that the robot employs a variety of lower level behaviors and strategies as needed to achieve the specified goals.
Projected State of the Art in 10 Years, Given Intense Effort	[Level 8 above]. With intense effort and possibly with the need for breakthrough technologies, it is conceivable that robots in 10 years will be able to accept high-level mission objectives, selecting and generating near-term goals as needed to maximize performance at the mission level.
Breakthrough Capabilities	See above

Metric 8: Mechanism Stability: State-of-the-art robotic mechanisms push their envelope of performance but are also designed to maintain stability.

Description (reflecting increasing levels of sophistication):

1. Self-righting recovery from all upset conditions.
2. Static stability within kinematic configuration space
3. Dynamic stability within control envelope
4. Self-righting recovery from all upset conditions.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 1 above]. Current state-of-the-art is limited to static stability of a simple nature; for example, Dante, IARES.
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 2-3 above]. Nominally, consensus holds that in 10 years time rovers will achieve dynamic stability as well as limited self-righting and recovery. Current examples include Inflatable Rovers as well as Ariel.
Projected State of the Art in 10 Years, Given Intense Effort	[Level 3-4 above]. With intense effort and possibly requiring breakthrough technologies also, it is possible that rovers will be able to self-right from all conditions.
Breakthrough Capabilities	[Level 4 above.] Self-righting robustly is challenging and will require breakthrough level technologies for achievement in 10 years.

Metric 9. Chassis adaptability: the capability for adjusting the physical properties or configuration of the mechanism to alter performance.

Description (reflecting increasing levels of sophistication):

1. Passive reconfiguration via underactuation
2. Active joint reconfiguration or center-of-gravity control.
3. Locomotion modality switching (for example from rolling to walking).
4. Modular mechanism that reassembles for the task.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 1 above]. Current state-of-the-art enables only passive reconfiguration such as for example a rocker bogie suspension. Examples include K9, FIDO, and MER.
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 2-3 above]. Nominally, consensus holds that in 10 years time the chassis will certainly be able to reconfigure some joints actively and may additionally enable multiple modes of locomotion. Examples include Marsokhod, IARES.
Projected State of the Art in 10 Years, Given Intense Effort	[Level 3-4 above]. With intense effort and possibly breakthrough technological discoveries, it is possible to achieve both multi-modal locomotion as well as modular reassembly, the latter in the opinion of approximately half of the survey respondents.
Breakthrough Capabilities	[Level 4]. A number of respondents (about half) claim the need for breakthrough technologies to enable modular reconfiguration.

Metric 10. Energy Efficiency: Energy is often the crucial resource in a robot surface mission, so efficiency is a concern.

Description (reflecting increasing levels of sophistication):

1. Negative work is avoided by mechanism.
2. Passive mechanism power regeneration.
3. Mechanism power regeneration opportunities sought by rover.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 2 above]. Current state-of-the-art includes passive regeneration according to consensus.
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 1-2 above]. In the 10 year nominal case there is no clear consensus about capabilities. Level 1 may be more difficult in view of this than level 2.
Projected State of the Art in 10 Years, Given Intense Effort	[Level 3 above]. With intense effort active decision-making to support power regeneration is viable.
Breakthrough Capabilities	None.

Metric 11. Health monitoring: the rover's ability for self-awareness of its own health and safety.

Description (reflecting increasing levels of sophistication):

1. Rover monitors state for out-of-nominal performance (fault detection)
2. Rover self-identifies causes of out-of-nominal performance
3. Rover changes behavior/operating state to correct performance
4. Rover anticipates dangerous conditions and modifies behavior
5. Rover develops long-term strategies for recovering from faults (self-recovery/repair)

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 1 above]. State of the art is only currently capable of detecting an out-of-nominal reading: FIO, K9 and Hyperion.
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 2 above]. Nominally in 10 years self-diagnostics will be feasible.
Projected State of the Art in 10 Years, Given Intense Effort	[Level 3-4 above]. With intense effort 10 years will see both performance correction by the rover as well as anticipation of dangerous conditions and avoidance thereafter, but without actual active fault recovery in the general case.
Breakthrough Capabilities	[Level 5]. Self-repair and self-recovery in the general case requires significant technological breakthrough discoveries according to consensus.

Metric 12. Obstacle detection: the ability of the robot to perceive features that constitute an obstacle to its motion (for example rocks or holes).

Description (reflecting increasing levels of sophistication):

1. Detect obstacles in close proximity before collision
2. Detect obstacles in the local area, beyond the minimum stopping distance
3. Detect finer traversability distinctions than obstacle/no-obstacle (e.g., estimate energy required to move through different areas)
4. Refine obstacle model based on performance
5. Resolve likelihood of obstacles in region around rover
6. Resolve large traversability features such as boulder fields in regions with size up to kilometers (e.g., from a hill-top view)

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 1-2 above]. Consensus holds that the state of the art certainly includes close-proximity obstacle detection immediately prior to collision as well as some limited degree of local area obstacle detection. For examples see FIDO, Hyperion and Bullwinkle.
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 3-4 above]. In 10 years, nominally, a rover should be capable of fine traversability distinctions as well as creation and adaptation of a performance-based obstacle model.
Projected State of the Art in 10 Years, Given Intense Effort	[Level 5 above]. With intense effort 10 years can see the development of more complex obstacle detection, including likelihoods associated with various obstacles in the model.
Breakthrough Capabilities	[Level 6]. Breakthrough technology is required to gauge the traversability of large, extended regions such as a boulder field.

Metric 13. Obstacle avoidance: the ability of the robot to respond to obstacles that it has detected.

Description (reflecting increasing levels of sophistication):

1. Avoids obstacles immediately adjacent to the robot. Includes emergency stops and basic techniques for driving around obstacles.
2. Diverts motion around an obstacle some distance away, before it is reached which may complement motion that is fast relative to vehicle speed
3. Steering optimized in response to fine distinctions in local traversability (steering through terrain that is not just safe, but easy)
4. Dynamics accommodated during high-speed avoidance maneuvers

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 1-2 above]. The consensus view holds that state-of-the-art rovers can avoid obstacles immediately in the rover s path and can provide more limited functionality at diverting motion when some distance away from an obstacle. For instance: FIDO, Bullwinkle, Hyperion, ROCKY 7 and ROCKY 8.
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 3 above]. 10 years nominally will see a significant improvement in that the rover will be able to optimize its path during motion to maximize terrain traversability.
Projected State of the Art in 10 Years, Given Intense Effort	[Level 4] All respondents agree that with intense effort dynamics can be fully accounted for in obstacle avoidance functionality.
Breakthrough Capabilities	None.

Metric 14. Visual servoing: the capability to track and move towards (or relative to) a visual target.

Description (reflecting increasing levels of sophistication):

1. Move directly toward a target which is in view throughout the motion
2. Servo to a precise location relative to the target (for precision placement of a sensor on the target)
3. Servo while avoiding obstacles, including the ability to track target through gross viewpoint and moderate environment condition (such as lighting) changes
4. Reacquire targets lost during tracking
5. Integrate with path planning in order to reach more distant targets

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 1 above]. Visual servoing state of the art is limited to direct motion toward a visual target that is viewed continuously. For examples see K9 and Nomad.
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 3 above]. Respondents expect significant improvements to this competency over the next 10 years, even nominally, reaching the ability to servo toward a target while avoiding obstacles
Projected State of the Art in 10 Years, Given Intense Effort	[Level 4-5 above]. With intense effort in 10 years a rover will be able to track multiple targets and (to a lesser degree) integrate visual servoing with long-distance path planning.
Breakthrough Capabilities	None.

Metric 15. Map Building: Map building should be unambiguous. Form local terrain maps, registering data sets naively (using pose from localization system)

Description (reflecting increasing levels of sophistication):

1. Use local terrain maps, naively registering multiple maps
2. Improve registration by matching features in overlapping data sets
3. Store uncertainty of feature positions and make global readjustments to improve mapping over multiple visits to a site
4. Global mapping, including fusion with orbital data

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 1 above] Consensus holds that current state of the art includes only creation of local terrain maps and naive registration of multiple such maps. The state of the art is demonstrated by K9.
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 3 above] Consensus expects significant nominal improvements in map building performance in the next 10 years, leading to both high-resolution map fusion and use of uncertainty.
Projected State of the Art in 10 Years, Given Intense Effort	[Level 4 above]. Significantly, consensus holds that with intense effort in 10 years a rover will be able to perform global mapping, including fusion of mapping information from orbital data. This is the functional extreme for mapping technology, and respondents feel this is viable with intense effort without need for breakthrough technologies.
Breakthrough Capabilities	None

Metric 16. Exploration: the capability for reasoning about the achievement of mission objectives. It is broadly addressing the purposes of the mission rather than narrowly focusing on the next goal.

Description (reflecting increasing levels of sophistication):

1. Rover follows path plan with no awareness of encountered phenomena
2. Rover detects unusual patterns
3. Rover collects unusual data
4. Rover investigates opportunities for new data
5. Rover actively seeks out anomalies
6. Rover actively generates discovery plan and collects relevant data
7. Rover generates scientific hypotheses

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 1-2 above]. The state of the art is extremely limited in this regard, capable of virtually no intelligent exploration, although capable of identifying unusual data.
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 3 above]. In 10 years consensus holds that a rover will be able to identify and collect unusual or anomalous data.
Projected State of the Art in 10 Years, Given Intense Effort	[Level 6 above]. After 10 years of focused effort, consensus holds that a robot would be able to actively generate a discovery plan in order to explore an area.
Breakthrough Capabilities	[Level 7 above]. Only a major breakthrough would enable a rover in the future to autonomously generate and test scientific hypotheses.

Metric 17. Communication: Robotic explorers must communicate their results and discoveries. Providing information is their essential function. Communication can be about the robot itself.

Description (reflecting increasing levels of sophistication):

1. Communicates partial status information
2. Communicates partial status information
3. Communicates comprehensive status information
4. Derives, interprets, or distills status information for efficiency
5. Varies information stream based on constraints (bandwidth, power)

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 1-2 above] The consensus holds that the state of the art includes communication of both partial and comprehensive status information. Most rovers demonstrate state-of-art capability in this regard.
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 3-4 above] In 10 years time consensus holds that a rover will be able to distill information for communication and will be able to provide a varying information stream based on changes to constraints such as bandwidth, power, etc.
Projected State of the Art in 10 Years, Given Intense Effort	[Level 3-4] Consensus is that high-competence communication is possible with only nominal 10-year effort, and so intense effort is not required.
Breakthrough Capabilities	None

Metric 18. Aggregate Autonomy Metric: Some aspects of rover capability may be completely automated while others require significant human guidance. A rover may be adept at detecting faults but not in recovering from them; for example it may know when it cannot navigate to its goal but not how to reverse itself sufficiently to find another route.

Description (reflecting increasing levels of sophistication):

1. Direct operation by human with high-bandwidth, low-latency communication.
2. Supervised teleoperation by human with medium bandwidth and latency.
3. Autonomous operation with human control of predetermined actions (medium bandwidth).
4. Autonomous operation with robot-initiated assistance by humans (medium bandwidth).
5. Autonomous operation with mission guidance from humans (low bandwidth).

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 1-2 above]. Current state-of-the-art is limited to direct teleoperation and supervised teleoperation with at least medium bandwidth and latency between the human operator and the rover. Examples include Sojourner and Nomad.
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 3-4 above]. Nominally, consensus holds that in 10 years time autonomous rover operation with human control of actions as well as robot-initiated requests for operator assistance are feasible. FIDO/K9, Hyperion and Bullwinkle demonstrate such competency.
Projected State of the Art in 10 Years, Given Intense Effort	[Level 4-5 above]. With intense effort and possibly breakthrough technological discoveries, it is possible to achieve long-term autonomy, with mission guidance from humans.
Breakthrough Capabilities	[Level 5]. Breakthrough technology is probably required for mission-level autonomy, with overall guidance from humans and high degrees of autonomy at the rover.

Metric 19. Distance per command cycle: The distance traveled per command cycle is an aggregate metric that depends on systemic performance. What is the distance traveled per command cycle by robotic surface explorers?

Description (reflecting increasing levels of sophistication):

1. Less than 1 meter: rover is directly teleoperated.
2. Less than 10 meters: rover relies on stationary base and must remain within fixed distance.
3. More than 10 meters: rover independent of base but cannot go beyond its own visual horizon in single command cycle.
4. More than 100 meters: rover goes beyond visual horizon in single cycle. Distance is limited primarily by power and endurance, not basic autonomy (navigation, path planning and obstacle avoidance).
5. More than 1000 meters: rover autonomy sufficiently robust to allow high speed autonomous travel.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 1-2 above]. Current state of the art consensus is that a rover can move up to 10m from a stationary, fixed base. Most rovers can demonstrate 10m performance, while Hyperion has demonstrated 100m performance.
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 4-5 above]. Nominally, consensus holds that in 10 years time a rover will be able to travel greater than 100m per command cycle, well beyond the visual horizon.
Projected State of the Art in 10 Years, Given Intense Effort	[Level 4-5 above] Consensus holds that with intense effort the chance for exceeding 100m per command cycle does not improve significantly over nominal 10 years effort, probably due to the need for breakthrough technologies to enable this.
Breakthrough Capabilities	[Level 5]. Breakthrough technological discovery may be required to achieve 1 kilometer autonomy on a single command cycle.

Metric 20. Total Mission Duration: The duration of a mission is the total time expected in the accomplishment of a complete mission. This may be the rover s entire lifecycle, as in the case of Sojourner, or the duration of a typical experiment that is limited by available power. With no physical limitation and self-generation of new goals, the probability of mission-ending fault provides the expected duration.

Description (reflecting increasing levels of sophistication):

1. 1 hour
2. 1 day
3. 1 week
4. 1 month
5. 1 year
6. Multi-year

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 2-4 above]. Current state of the art is limited to day- to week-level mission life. Exemplified by Sojourner.
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 4-5 above]. Nominally, consensus holds that in 10 years time mission lifetime can range from 1 month to 1 year at most.
Projected State of the Art in 10 Years, Given Intense Effort	[Level 5-6 above]. With intense effort and probably requiring breakthrough technological discoveries, it is possible to achieve mission-level life of 1 year and possibly multiple years.
Breakthrough Capabilities	[Level 6]. It will almost certainly require breakthrough technologies to extend mission life to the multi-year level.

Metric 21. Terrainability: This metric aims to identify the terrainability of locomotion of state-of-the-art rovers with respect to a variety of surface types:

Description (reflecting increasing levels of sophistication):

1. Hard flat surface
2. Hard rough surface
3. Soft flat surface
4. Soft rough surface
5. Interior spaces
6. Boulder fields
7. Steep soft slopes
8. Steep hard slopes

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 1 above]. The consensus view holds that rovers are currently capable of robust locomotion over hard flat surfaces only. Most rovers can demonstrate this level of competency.
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 3-4 above]. Rovers can generally negotiate soft surfaces that are both flat and rough but will not have locomotory abilities extending to more challenging constrained or steep environments. Demonstrated by Marsokhod.
Projected State of the Art in 10 Years, Given Intense Effort	[Level 6 above]. Occasionally the state of the art can negotiate constrained environments such as interior spaces and boulder fields, although without sufficient robustness to be of immediate use. Demonstrated by Sojourner.
Breakthrough Capabilities	[Level 8 above]. No current mechanism currently enables practical climbing or descending steep, hard slopes. Dante demonstrates aspects of this.

Surface Instrument Deployment and Sample Manipulation

Instrument deployment consists of placing a specified scientific instrument so it is pointing at, near to, or in contact with a specified sample. It includes moving or actuating the instrument while it is in contact. The deployed instrument may be a small measuring device, a large subsurface drill or a set of instruments (e.g., seismometers) that need to be placed in a particular pattern.

Sample manipulation involves picking up an un-modeled sample, orienting it in a specified fashion and placing it in a different location. It also includes preparation of samples such as breaking, scraping, cleaning, brushing, etc.

These are both required for taking measurements from a sample using multiple instruments not all necessarily mounted on the arm at the same time, including the acquisition of a sample from the environment and transfer to rover interior instruments.

An instrument deployment or sample manipulation operation may consist of the following sub-tasks:

Target detection — target rock or other scientific sample is detected (see section on Science Planning and Perception, as this task is not considered here), relative position and appearance noted.

Approach — robot maneuvers to bring target within range of sensor or workspace of manipulator. This requires the robot to somehow keep track of where the target is in relation to itself.

Placement — sensor or tool placed at appropriate location and relative orientation on or inside target. This does not apply to remote sensors that need only be pointed at a target.

Measurement or manipulation operation - scientific data acquired from a target using correctly positioned instruments, or target manipulated or otherwise operated upon by correctly positioned effectors.

Most sample manipulation and handling tasks can be accomplished by direct teleoperation, given suitable engineering resources but no new technological developments. Furthermore, direct teleoperation is not an option except for a manned mission.

<u>Performance Metrics</u>

Metric 1: Target approach and instrument placement: The ability of the robot to approach a target (designated either autonomously or by mission control) from approximately 10m distance and subsequently place a tool or instrument against the target surface. Failures include losing track of a target and placing the instrument or tool against the wrong sample.

Metric 1A: Target approach and instrument placement without nearby human presence. Direct teleoperation is not possible in this situation.

Description (reflecting increasing levels of sophistication):

1. Remote sensing, vehicle possibly maneuvers to get optimal viewing geometry or to ensure target fills sensor field of view; accomplished in several command cycles by supervised teleoperation with nominal robustness.
2. Simple surface contact measurement. Robot approaches target and places single instrument against target surface with centimeter precision and arbitrary orientation with respect to sample surface; accomplished in several command cycles by supervised teleoperation with nominal robustness.
3. Highly autonomous simple surface contact measurement in one or fewer command cycles.
4. Highly autonomous, complex surface contact measurement. Robot approaches target and places one or more instruments against sample surface with millimeter precision, control of instrument orientation against surface, and/or force control; mission critical robustness achieved by supervised teleoperation as necessary.
5. Highly autonomous complex surface contact measurements of multiple targets in single command cycle.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 2+] [Flight is 2] Current flight state of art [Sojourner] requires 3-5 command cycles to position a simple spring loaded compliant sensor against a rock sample. Terrestrial demonstrations have shown autonomous placement of simple instruments against targets in restricted circumstances [Nomad, Rock 7, FIDO] but with insufficient robustness for mission applications.
Projected State of the Art in 10 Years, Given Nominal Effort	[Levels 3-4] Robust, single cycle instrument placement with millimeter precision from 10m is expected to be flown on the 2009 Mars Smart Lander mission. The required technologies already exist, there are several active research programs to integrate them.
Projected State of the Art in 10 Years, Given Intense Effort	[Level 5] With robust simultaneous localization and mapping technologies coming online it will be possible to keep track of multiple targets as a robot moves, enabling it to visit many designated targets in a single communications cycle. Precise measurements of rock shapes along with 6 DOF manipulator arms with force sensing and visual feedback allow precise placement of instruments against most rock targets.
Breakthrough Capabilities	None

Metric 1B: Target approach and instrument placement with nearby human presence. Human operators nearby may directly teleoperated robot.

Description (reflecting increasing levels of sophistication):

1. Remote sensing under direct teleoperation; vehicle possibly maneuvers to get optimal viewing geometry or to ensure target fills sensor field of view.
2. Simple surface contact measurement under direct teleoperation. Robot approaches target and places single instrument against target surface with centimeter precision and arbitrary orientation with respect to sample surface.
3. Complex surface contact measurement under direct teleoperation. Robot approaches target and places one or more instruments against sample surface with millimeter precision, control of instrument orientation against surface, and/or force control.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 2+] Current teleoperation technologies are quite mature (consider the undersea robotics community). Bomb disposal robots easily get close to a target and place sensors or tools against them. Current deficiencies are the force feedback interfaces for a user to effectively sense the forces on a complex manipulator, such as one similar to a human hand.
Projected State of the Art in 10 Years, Given Nominal Effort	[Levels 3] Sensory feedback devices for dexterous manipulation allow highly precise and predictable tool placement and object manipulation.
Projected State of the Art in 10 Years, Given Intense Effort	None
Breakthrough Capabilities	None

There is considerable integration effort needed to produce an effective teleoperative instrument placement system for planetary exploration applications. This has not happened because of lack of interest in this area.

Metric 2: Target tracking

Description (reflecting increasing levels of sophistication):

1. Track target while maintaining view of the target throughout the traverse.
2. Track target with obstacle avoidance enabled. Require the tracker to reacquire target after maneuvering to avoid an obstacle.
3. Robustly track target using knowledge of surrounding features as well as target. Can re-acquire after occlusions and significant duration deviations.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 1] Current systems (Marsokhod, Rocky 8) can visually track distinct targets on simple backgrounds (sand). Occlusions, lighting variations and significant changes in the appearance of the target, such as caused by approaching too close) cause a loss of target lock.
Projected State of the Art in 10 Years, Given Nominal Effort	[Levels 2-3] Nominal future systems will have greater knowledge of the 3 dimensional nature of the world, and therefore be robust to target appearance changes due to robot motion. Improved navigation and mapping allows enables robot to keep track of target location even after temporary occlusions.
Projected State of the Art in 10 Years, Given Intense Effort	[Level 3+] Achieving 6 sigma reliability levels in the difficult and uncertain environment of a planetary surface requires intense effort.
Breakthrough Capabilities	

Metric 3: Whole sample manipulation: ability of system to nudge, pick-up, or otherwise manipulate an unbroken scientific sample within the vehicle weight and power range. Excludes breaking, coring, abrading or otherwise altering sample. Assumes robot has already approached target to bring it within manipulator range and knows location of sample.

Metric 3A: Whole sample manipulation with nearby human presence; on-site astronaut presence enabling direct teleoperation as needed.

Description (reflecting increasing levels of sophistication):

1. Imprecise and unpredictable manipulation in simple environment. Includes picking up sample with clamshell or shovel, nudging, flipping or otherwise perturbing a sample with imprecise results. Sample is simply shaped, not attached to ground or other objects, and environment is uncluttered; Direct teleoperation with nominal robustness.
2. Precise and predictable manipulation in simple environment. Includes grasping a sample to pick it up or otherwise predictably and precisely change its position or orientation; Direct teleoperation with nominal robustness, previous level tasks with mission critical robustness.
3. Precise and predictable manipulation of arbitrarily shaped, partially buried or otherwise constrained samples in cluttered environments; direct teleoperation and mission critical robustness.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Levels 2-3] Current manipulators [Robonaut hand] are mechanically highly capable, approaching the mechanical dexterity of a suited human hand. Even without force feedback a trained operator can pick up rocks and work with tools. Devices permitting teleoperated surgery have been developed. Highly precise motions with force feedback and the ability to sense and correct for involuntary motions have been demonstrated. Force feedback interfaces for complex manipulators, such as one comparable to a human hand, are not well developed. They are essential for truly precise remote manipulation.
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 3+] Sensory feedback devices for dexterous manipulation allow highly precise and predictable tool placement and object manipulation.
Projected State of the Art in 10 Years, Given Intense Effort	
Breakthrough Capabilities	

Teleoperation has been well studied in the undersea and nuclear industries. NASA has not recently emphasized this capability (in a planetary environment).

There is considerable integration effort needed to produce an effective teleoperative instrument placement system for planetary exploration applications. This has not happened because of lack of interest in this area.

Metric 3B: Whole sample manipulation without nearby human presence; direct teleoperation not possible.

Description (reflecting increasing levels of sophistication):

1. Imprecise and unpredictable manipulation in simple environment. Includes picking up sample with clamshell or shovel, nudging, flipping or otherwise perturbing a sample with imprecise results. Sample is simply shaped, not attached to ground or other objects, and environment is uncluttered. Operations by supervised teleoperation, achieved with nominal robustness.
2. Precise and predictable manipulation in simple environment. Includes grasping a sample to pick it up or otherwise predictably and precisely change its position or orientation. Operations by supervised teleoperation with nominal robustness. Previous level tasks can be done with highly autonomous systems and mission critical robustness.
3. Precise and predictable manipulation of complex shaped, but still loose samples in uncluttered environments; highly autonomous operations with nominal robustness, mission critical robustness achieved with more communications cycles (supervised teleoperation).
4. Precise and predictable manipulation of arbitrarily shaped, partially buried or otherwise constrained samples in cluttered environments; highly autonomous operations with nominal robustness, mission critical robustness achieved with more communications cycles (supervised teleoperation).

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 2] The Viking landers had shovels and executed pre-defined sequences to gather soil samples. Recent systems [Rocky 7] can autonomously grasp rocks in a simple environment
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 3] Greater onboard computing power and sensors to determine rock 3D shape allow deployment of more advanced algorithms.
Projected State of the Art in 10 Years, Given Intense Effort	[Level 4]
Breakthrough Capabilities	

Metric 4: In-Situ Sample Preparation Metrics; in situ preparation or processing of samples in order to acquire measurements. Assumes robot has already approached target to bring it within range and placed manipulator against sample (c.f. Approach and Placement metrics). Robot does not pick up or retrieve sample. (This metric is irrelevant to manned missions where the expectation is that samples would be retrieved and analyzed in the lab. Therefore, direct teleoperation is not a viable operating mode.)

Description (reflecting increasing levels of sophistication):

1. Mechanical, single step, surface preparation, such as exposing fresh surface with abrasion tool. Cross contamination not a major concern; supervised teleoperation with nominal robustness.
2. Multi-step surface preparation, by mechanical, chemical or other means. Cross contamination not primary concern. For example, application of reagent followed by mechanical cleaning; supervised teleoperation with nominal robustness. Simpler tasks above achievable with mission critical robustness.
3. Multi-step surface preparation, by mechanical, chemical or other means. Cross contamination not primary concern. For example, application of reagent followed by mechanical cleaning; supervised teleoperation with nominal robustness. Simpler tasks above achievable with mission critical robustness; Highly autonomous operations (including limited autonomous interpretation of scientific data to verify correctness of operations) with nominal robustness.
4. Highly autonomous advanced surface preparation with stringent controls to prevent cross contamination so that large numbers of samples may be so prepared. Supervised teleoperation for particularly difficult tasks.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 1] Manipulator mounted rock abrasion tools are the current state-of-art [FIDO]
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 2+]
Projected State of the Art in 10 Years, Given Intense Effort	[Level 4]
Breakthrough Capabilities	

This capability is driven by the scientific instrument research and development efforts and is not explicitly addressed by any robotics effort.

Metric 5: Advanced Sample Preparation and Measurement Metric; ability to process and prepare sample that has been picked up by robot to be analyzed by inside sensors.

Description (reflecting increasing levels of sophistication):

1. Single shot transfer of sample to measuring device. Sample is not removed from device after measurement, so further measurements not possible. Sample preparation limited to pulverizing.
2. Same as above but with capacity to eject measured sample so that multiple samples may be measured.
3. Same as above but with advanced cleaning to prevent cross contamination.
4. Advanced sample preparation, possibly with multiple stages (chemical and mechanical), such as producing and then imaging thin sections.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 2]
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 3+]
Projected State of the Art in 10 Years, Given Intense Effort	[Level 4]
Breakthrough Capabilities	

This capability is driven by the scientific instrument research and development efforts and is not explicitly addressed by any robotics effort.

Metric 6: Invasive Sample Manipulation

Description (reflecting increasing levels of sophistication):

1. Robot can break sample into smaller pieces, blast force placed through teleoperation
2. Robot can be teleoperated to break off a piece of large sample
3. Robot can be tasked and can autonomously break sample into sub-samples using blast force.
4. Robot can be tasked to autonomously break a controlled, small piece of sample off a large sample for analysis

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 2]
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 3+]
Projected State of the Art in 10 Years, Given Intense Effort	[Level 4]
Breakthrough Capabilities	

Metric 7: Mars Drilling; Drilling depths attainable in the Mars surface exploration scenario. This implies low power, limited total mass, and no nearby humans. We consider only drilling systems subject to the following constraints:

- **Supervised or high autonomy**
- **Power < 1000 W**
- **Total vehicle mass < 1000 kg**
- **Need to drill through sand, rock, permafrost and cryogenic ice**
- **Sparing use of imported lubricants, if at all.**

Metric 7A: Max depth attainable over mission duration (approx 100 days)

Description (reflecting increasing levels of sophistication):

1. < 1 m
2. 10 m
3. 100 m
4. 1000 m

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 1]
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 3]
Projected State of the Art in 10 Years, Given Intense Effort	[Level 4]
Breakthrough Capabilities	

Metric 7B: Max depth attainable / sol.

Description (reflecting increasing levels of sophistication):

1. < 1 cm
2. 10 cm
3. 1m
4. 10 m

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 2]
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 3]
Projected State of the Art in 10 Years, Given Intense Effort	[Level 4]
Breakthrough Capabilities	

Surface Science Perception, Planning and Execution

Science perception consists of locating scientifically interesting targets and making scientifically relevant observations of the environment.

Science planning creates a plan whose elements are science tasks to be performed, and constraints on those tasks, taking into account the robot s resources (power, instruments, time, etc.), and the value of different kinds of future science observations, given the current state of knowledge. Science planning may be completely autonomous or done in collaboration with scientists.

Science execution consists of using the robot and its instruments to perform the science tasks and collect relevant science data. Science execution monitors the state of the robot and its environment, reacting to changes either with actions in the existing plan, or by requesting a new or modified plan.

Planning and execution includes the architecture for interactions between planners, the executive, and other system components. It includes the method for extending the planning horizon, and for generating or modifying plans in response to new information.

Performance Metrics

Metric 1: Ground science operations planning tools: The ability of scientists to directly run a robotic exploration mission.

Description (reflecting increasing levels of sophistication):

1. Large rover staff. Scientists specify instrument and target tasks. Rover operations personnel generate detailed sequence to accomplish tasks, possibly rejecting some tasks that don t fit resource & operational constraints.
2. No major changes to science plan by rover ops. Rover ops personnel add engineering details and housekeeping tasks to plan.
3. Scientist-generated plan is nearly complete. Rover ops personnel add navigation and arm placement trajectories.
4. Tools allow all robot planning and sequencing to be accomplished by scientists with no follow-on refinements and verifications by rover operations personnel.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 2] Science team can generate partially verified sequences (Europa + MAPGEN for MER 2003).
Projected State of the Art in 10 Years, Given Nominal Effort	[Levels 3-4] Science team can generate plans with concurrency, flexible temporal executions, resource constraints with task-level, prioritized input.
Projected State of the Art in 10 Years, Given Intense Effort	[Level 4+] Modifications to plan rarely, if ever, need to be made by rover operations personnel. Science team effectively runs mission.
Breakthrough Capabilities	None

The capability of ground tools is also contingent upon rover robustness and onboard autonomous capabilities. A more capable robot can execute more sophisticated plans that don t need to be as rigorously checked by ground operations personnel.

Metric 2: Ground science visualization tools: Ability of robots and ground tools to give scientists a virtual presence at the planetary exploration site.

Description (reflecting increasing levels of sophistication):

1. Raw data returned. Individual images available.
2. Derived 2-D data products (e.g., panoramas).
3. High-fidelity terrain model with ability to interrogate and annotate terrain features.
4. High-fidelity virtual presence in remote environment.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 3] 3D virtual terrain models, generated from returned stereo image data, are available (VIZ tool used for Mars Pathfinder and K9) and allow uses to annotate features and make basic measurements such as size, position, etc. Current systems are restricted to using images obtained from a stationary rover or lander to create the virtual environment. They cannot handle images from multiple camera positions. This leads to degraded quality and missing data for occluded regions. Separate terrain models for each site are needed.
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 4+]Very high quality virtual terrain models, using data obtained from multiple, not necessarily well known a priori, locations possible. Therefore, new data from a moving rover can be seamlessly integrated with the existing terrain model.
Projected State of the Art in 10 Years, Given Intense Effort	None
Breakthrough Capabilities	None

Metric 3: On-board planning and execution: Complexity and sophistication of science related operations a rover can accomplish autonomously in between communication cycles. This excludes autonomous interpretation of science data.

Description (reflecting increasing levels of sophistication):

1. Plan is a detailed, time-stamped sequence of low-level commands. Behavior entirely defined by input; system's default response to problems is to halt.
2. Plan allows flexible time specification and contingencies, enabling a family of behaviors.
3. Planner allows a prioritized list of tasks (instrument and target tasks), with constraints among them.
4. Very high-level science goal commanding (e.g., characterize site, find life). System responds to science opportunities and recovers from most faults. System adapts to rover degradation.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Levels 2-3] Onboard rover planners that permit task sequences with flexible execution times and contingent branches have been terrestrially demonstrated (K9 Conditional Executive, CLEaR and CASPER on Rocky 7 and 8 Rovers). In addition, onboard systems can monitor and reason about resource consumption, making small modifications to initial plans as necessary. Systems allowing a prioritized list of tasks (with constraints amongst them) to be executed concurrently have been demonstrated in the more predictable orbital environment (DS1/ Remote Agent) but are not yet ready for rovers. Robustness is sufficient for short durations (hours) before human intervention is necessary, and can handle environments similar in complexity to Antarctic ice sheets or uncluttered deserts.
Projected State of the Art in 10 Years, Given Nominal Effort	[Level 3] Steady improvements in robustness of planners and executives will allow autonomous rover operations for days, if not weeks, without human interventions, and will cope with environments as complex as uncluttered terrestrial deserts
Projected State of the Art in 10 Years, Given Intense Effort	[Level 4-] Steady improvements in robustness of planner, allowing autonomous rover operations for weeks, if not months, without human interventions in environments as complex as Antarctic moraines. Limited high-level science goal commanding, response to science opportunities, fault recovery and adaptation to rover degradation.
Breakthrough Capabilities	[Level 4+] Performance at capabilities of a human in the field is limited by difficulties of achieving human level (HAL 9000) cognition and understanding of environment, including common sense which has not been achieved at all.

The autonomous capabilities of flown systems (Mars Pathfinder and Sojourner) is significantly below the current state-of-art due to conservatism amongst mission people and their concerns about robustness and verifiability. The limits of this capability, including human level cognition, adaptation and common sense require fundamental breakthroughs.

Metric 4A: Site exploration and characterization:

Description (reflecting increasing levels of sophistication):

1. Scientist selects targets. Data acquisition performed without interpretation
2. Scientist selects targets. System selectively returns data based on pre-defined filters.
3. System selects targets based on scientist-specified tests.
4. System characterizes site. E.g. recognizing groups of similar objects and finding representative samples, determining gross site properties such as rock size and shape distributions.
5. System recognizes unforeseen opportunities to collect data confirming or denying existing scientific hypotheses about the site.

Qualifier (a): Onboard data reduction to eliminate redundant or irrelevant measurements. E.g. generating image panoramas, 3D models in lieu of multiple images.

Metric 4B: Site complexity handled by onboard science perception capabilities:

Description (reflecting increasing levels of sophistication):

1. Antarctic ice sheet complexity: Candidate science targets sparsely distributed (one per image), easily distinguished from a uniform background (e.g. meteorites on Antarctic ice sheet).
2. Desert complexity: Moderate target density, background maybe similar to targets (e.g. rocks on sandy desert), slight variations in background.
3. Moraine complexity: Extreme clutter, potential science targets everywhere, occluding each other.
4. Stream bed complexity: Diversity of target types and sizes.

Qualifier (a): Unstable environment, noticeable changes occur during course of investigation, possibly because of rover actions.

Qualifier (b): Unknown environment, no prior knowledge to guide investigation (e.g. no prior visits or orbital images).

	Description of Technical Capabilities
Current State of the Art	[Metric 4A Level 1+; Metric 4B Level 2-] A few simple science perception capabilities such as identifying some rock types or finding layered rocks have been demonstrated onboard rovers (Nomad 2000, GSOM on K9), albeit in simple environments (Antarctic or Desert complexity]. Because of rovers having limited autonomy, and therefore unable to obtain more data than can be sent back, the onboard interpretation of scientific data has been restrained. No flight system (Sojourner, MER 2003) has such capabilities.
Projected State of the Art in 10 Years, Given Nominal Effort	[Metric 4A Level 3-; Metric 4B Levels 2-4] Improvements in rover autonomy, including instrument placement, will improve the potential of on-board science perception to increase science return. The capability to automate various high level measurements for characterizing a site will be built from the ground up: • Detection and measurement of rocks near the rover, using images and 3D sensors. • Rock and soil particle size, shape and color distributions. • Autonomous categorization of rocks present, selection of representative samples from each group. • Mineral and rock type identification. • Onboard data reduction. There is concern that onboard science perception will have little impact because it is not integrated with capable operationally autonomous rovers.
Projected State of the Art in 10 Years, Given Intense Effort	[Metric 4A Level 3-4-; Metric 4B Levels 3-4] Most standard observations for characterizing (from the geological or astrobiological perspective) can be automated. Areas can be statistically profiled
Breakthrough Capabilities	[Metric 4A Level 4; Metric 4B Level 4+] As with onboard planning and execution, exploring the limits of this capability, including human level perception and cognition require fundamental breakthroughs. In particular, the human ability to locate a previously unspecified object of scientific interest in a cluttered environment, such as an Antarctic moraine, will remain difficult.

Surface Human EVA Assistance

Robots can be used to assist human crew members during their surface extravehicular activities. Use of robots can increase the efficiency and safety of EVAs. There are several ways in which robots can assist. The robots might simply monitor or document EVA tasks. Or the robots might prepare a worksite before an EVA or document after an EVA. The robots might also interact directly with an astronaut, by handing them tools or shining a light. In these cases the astronaut will want to interact with the robot naturally using language and gestures. Robots could also scout out and survey areas before human EVAs. True human-robot teams will arise when robots can be given high-level goals while helping a human crew member — in these cases the robot will simply be another team member

Performance Metrics

Metric 1. Autonomously tracking EVA crew member

Description (reflecting increasing levels of sophistication):

1. Robot keeps crew member in view and at a specified distance.
2. Robot keeps crew member in view while avoiding obstacles.
3. Robot reacquires crew member following occlusion.
4. Track multiple crew members.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROM THE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Levels 1-3] The EVA Robotic Assistant has demonstrated these capabilities in a field test.
Projected State of the Art in 10 Years, Given Nominal Effort	[Levels 2-4] Laboratory research has demonstrated all of these capabilities.
Projected State of the Art in 10 Years, Given Intense Effort	
Breakthrough Capabilities	

Metric 2. Autonomous video archiving of EVA tasks

Description (reflecting increasing levels of sophistication):

1. Robot points camera at given location.
2. Robot responds to simple voice or gesture commands for camera position fine-tuning.
3. Robot moves camera to avoid occlusion.
4. Robot moves camera to get best view angle based on the task being performed.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROMTHE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Levels 1-2] The EVA Robotic Assistant has demonstrated these capabilities in a field test.
Projected State of the Art in 10 Years, Given Nominal Effort	[Levels 3-5] Laboratory research has demonstrated all of these capabilities.
Projected State of the Art in 10 Years, Given Intense Effort	[Level 4]
Breakthrough Capabilities	

Metric 3. Pre-EVA site reconnaissance

Description (reflecting increasing levels of sophistication):

1. Robot covers a designated area and returns video to crew members.
2. Robot covers a designated area and creates a topographical map for crew members.
3. Robot covers a designated area and plans paths that are appropriate for a suited astronaut.
4. Robot covers a designated area and determines scientifically valuable areas of interest.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROMTHE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	No robot has yet demonstrated any of these capabilities
Projected State of the Art in 10 Years, Given Nominal Effort	[Levels 1-3] Integration of some existing algorithms should lead to a solution to many of these problems
Projected State of the Art in 10 Years, Given Intense Effort	[Level 4] This is similar to the Science Perception task.
Breakthrough Capabilities	

Metric 4. Post-EVA documentation

Description (reflecting increasing levels of sophistication):

1. Robot covers a designated area and compiles overlapping pictures.
2. Robot covers a designated area and collects samples that have been designated by a human EVA.
3. Robot covers area and picks up tools, litter and other EVA equipment.
4. Robot sets up experiments and sensors based on human EVA instructions.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROMTHE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	No robot has yet demonstrated any of these capabilities
Projected State of the Art in 10 Years, Given Nominal Effort	[Levels 1-2] Integration of some existing algorithms should lead to a solution to many of these problems
Projected State of the Art in 10 Years, Given Intense Effort	[Level 3-4]
Breakthrough Capabilities	

Metric 5. Human-robot communication

Description (reflecting increasing levels of sophistication):

1. Voice commands routed to robot operator.
2. Text commands given to robot using keyboard or mouse.
3. Low-level voice commands interpreted by robot (e.g., stop, faster, move right, etc.).
4. High-level voice commands with referents interpreted by robot (e.g., pick up that).
5. Multi-modal communication (e.g., integration of speech and gesture or speech and graphics tablet).
6. Dialog between robot and human about goals and actions.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROMTHE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Levels 1-3] Low-level voice commands using COTS software has been demonstrated by many robots in many applications.
Projected State of the Art in 10 Years, Given Nominal Effort	[Levels 5-6] Only a few current robots in laboratory settings have robust natural language interfaces
Projected State of the Art in 10 Years, Given Intense Effort	[Level 4] Dialog management is an area of active research, but there are still many hurdles remaining.
Breakthrough Capabilities	

Metric 6. Sensing of humans

Description (reflecting increasing levels of sophistication):

1. Generic obstacle avoidance and safe movement around humans (e.g., humans are just another obstacle to avoid).
2. Tracking of humans in work site.
3. Tracking of human body parts (e.g., gestures).
4. Recognition of humans and their activities/plans/intentions.
5. Recognition of human physical, mental and emotional state.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROMTHE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Levels 1-2] Obstacle avoidance and human tracking are both regularly demonstrated on many robots.
Projected State of the Art in 10 Years, Given Nominal Effort	[Levels 2-4] Gesture recognition and plan recognition are both areas of research that are progressing at a fast pace.
Projected State of the Art in 10 Years, Given Intense Effort	
Breakthrough Capabilities	[Level 5] Recognition of human emotional and mental state by robots will require a breakthrough. However, given proper instrumentation, recognition of physical state might be possible without a breakthrough.

Metric 7. Gesture recognition

Description (reflecting increasing levels of sophistication):

Simple, static gestures.

1. Dynamic gestures (e.g., waving).
2. Hand signals.
3. Gestures linked to natural language for grounding of referents (e.g., pick up that).

SUMMARY OF QUESTIONNAIRE FEEDBACK FROMTHE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 1] Simple gesture recognition is being demonstrated on a number of robots.
Projected State of the Art in 10 Years, Given Nominal Effort	[Levels 2-4] Current research should lead to all of these capabilities being state of the art in ten years.
Projected State of the Art in 10 Years, Given Intense Effort	[Level 4]
Breakthrough Capabilities	

Metric 8. Physical Interaction

Description (reflecting increasing levels of sophistication):

1. Holding objects (light, tool, cable) for human.
2. Handing objects to human.
3. Taking objects from human.
4. Carrying/rescuing disabled human.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROMTHE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Levels 1-2] Several robots have demonstrated this capability.
Projected State of the Art in 10 Years, Given Nominal Effort	[Levels 2-4] EVA Robotic Assistant is expected to demonstrate some of these capabilities in the next year.
Projected State of the Art in 10 Years, Given Intense Effort	[Level 4]
Breakthrough Capabilities	[Level 4]

Metric 9. Summary of overall capabilities:

Description (reflecting increasing levels of sophistication):

1. Robot tracks an EVA crew member while carrying tools and a camera.
2. Robots do site survey and preparation as well as post-EVA documentation.
3. Robots carry tools, which they hand to the EVA crew member. Robots can also collect designated samples.
4. Robots physically interact with humans via high-level voice commands and gestures.
5. Robots that are true teammates with humans, working on same tasks, responding to natural language, gestures and high-level goals and recognizing human intentions.
6. Synergistic relationship between human and machine with direct, physical connections and prostheses, i.e., super humans augmented with machines.

SUMMARY OF QUESTIONNAIRE FEEDBACK FROMTHE ROBOTICS COMMUNITY

	Description of Technical Capabilities
Current State of the Art	[Level 1] EVA Robotic Assistant demonstrated this capability with a suited astronaut in a field test.
Projected State of the Art in 10 Years, Given Nominal Effort	[Levels 2-4] Complex automated assistance will be available in ten years.
Projected State of the Art in 10 Years, Given Intense Effort	[Level 5] Robots that are true teammates with humans will require intense development efforts and possibly breakthroughs.
Breakthrough Capabilities	[Level 6] Augmenting humans with mechanical devices will require a breakthrough according to many respondents.

Robot Rogues Gallery

AERCAM IGD

In 1998 an experimental roving camera was tested on an airbearing table at NASA JSC. The camera could autonomously scan a mock-up of a spacecraft.

David Kortenkamp, M. MacMahon, D. Ryan, R. P. Bonasso and L. Moreland, Applying a Layered Control Architecture to a Freeflying Space Camera IEEE Symposium on Intelligence in Automation and Robotics, 1998

AERCAM ECS

The NASA Engineering for Complex Systems (ECS) program is working to develop more autonomy for an AERCam-like flying camera. This project has just started and some of the entries in the table below reflect expected, near-term capabilities.

AERCAM SPRINT

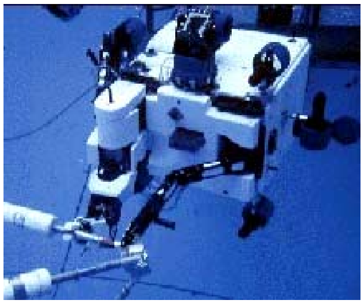
The AERCam Sprint free-flyer is a 14-inch diameter, 35-pound sphere that contains two television cameras. It is teleoperated and flew as an experiment on STS-87 in 1997.

ASRO

The Astronaut and Rover (ASRO) Interaction Project took place in 1999 as part of the Marsokhod rover field test in Silver Lake, California. Five days were devoted to study the interaction between EVA astronauts and teleoperated rovers in future surface planetary operations. The goal of the ASRO project was to define and document the ability of the rover and a spacesuited astronaut to operate as an interactive team in an outdoor planetary environment.

BAT

The Beam Assembly Teleoperator (BAT) was developed at the University of Maryland. BAT was designed to build large structures in space. During its lifetime, BAT demonstrated the ability of robots to perform space construction tasks and also to repair satellites, service space hardware, and work in cooperation with astronauts.



BEAGLE 2

The Beagle 2 is a robotic lander destined for Mars via the Mars Express orbiter in 2004 and sponsored by ESA. Once it has landed, the Beagle 2 opens to deploy solar panels and launch a mole robot, which uses percussive means to travel across the surface to a large boulder, then burrow underground to position itself for compositional analysis of that hidden soil. A robotic arm on the Beagle lander provides further measurement capabilities and degrees of freedom to reach nearby soil and rock.

Sims, M.R., Pillinger, C.T. and 27 co-auteurs: 1999, Beagle 2: a proposed exobiology lander for ESA'S 2003 Mars Express Mission, Adv. Space Res. 23, No. 11, 1925-1928.

Bullwinkle/MARS AUTONOMY — CARNEGIE MELLON

The rover, Bullwinkle, is an RWI Inc. ATRV-II, selected because its similar size gives it mobility and vision problems like those of the next-generation Mars rover, although its rigid suspension and four skid-steered wheels are quite different. Like the Mars rover, it uses two forward-pointing cameras for obstacle detection. The project is focused on autonomous navigation and achieved a 100 meter autonomous traverse at 15 cm/s, integrating previously developed local obstacle avoidance and global path planning algorithms and adapting them to a Mars-relevant rover in order to demonstrate reliable long-distance navigation in Mars-like terrain.

Dante I & II — CARNEGIE MELLON

Carnegie Mellon developed an eight-legged walking robot, Dante I, as part of the Erebus Project to attempt the exploration of an active volcano, Mount Erebus, Antarctica. Technological development of walking locomotion in extreme terrain and tethered rappelling on steep slopes was achieved but remote volcanology was not. Development of Dante II, with experimental focus Erebus led to the Dante II mission (see following).

[Bares99] J. Bares, D. Wettergreen Dante II: Technical Description, Results, and Lessons Learned, International Journal of Robotics Research, Sage Publications, Palo Alto, USA, vol. 18, no. 7, July 1999.

EPFL SHRIMP

This fielded system consists of a six-wheeled, independent drive system with twin bogies augmented by single-centered and driven forward and rear wheels

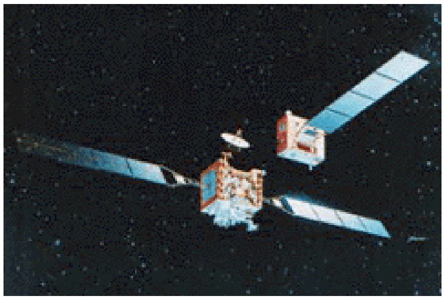
before and behind the chassis. Passive parallel arm joints are designed so that the remote center of rotation is well below actual joint position. The robot has relatively high ground clearance and CG but is capable of extremely good slope negotiation due to the large number of independently driven wheels combined with the highly compliant, passive jointed chassis that ensures that every wheel has maximum traction with the ground. The existence of six separate motors for translation is indicative of drive inefficiency. Steering is performed by servoing only the front-most and rear-most two wheels, forcing the four inner wheels to under skid-translation during steering. This limits turning radius and induces lateral wear on the wheels, limiting longevity. Nevertheless, the highly jointed suspension mechanism is completely passive, advantageous for longevity of that component of the chassis. Due to its remote center of rotation design and 6-wheel configuration, this robot has demonstrated ledge climbs of more than triple its wheel diameter, which may be a standing record at this time. Due to the large number of wheels and overall high traction, the Shrimp mechanism has the potential for very accurate odometry.

INSPECTOR

Inspector was designed as an inspection robot for the Mir space station. Unfortunately, it failed shortly after launch.

ETS-VII

In March 1998 the Japanese Satellite ETS-VII carried a robot manipulator. The manipulator was teleoperated from the ground and also had some autonomous modes.



ETS-VII: Achievements, Troubles and Future, Oda Mitsushige, in Proceedings of the 6th International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS), 2001.

EVAHR

The Extravehicular Activity Helper/Retriever robotic system developed by the Automation and Robotics Division at NASA Johnson Space Center used a vision-guided intelligent system to grasp a free-flying ball in the simulated zero-G environment of the NASA KC-135 aircraft in February 1994.

EVA ROBOTIC ASSISTANT

The Extra-Vehicular Activity Robotic Assistant (ERA) is a wheeled robotic testbed developed at NASA Johnson Space Center for research into technologies for astronaut and autonomous rover interactions.

FIDO — JPL; AND K9 — NASA AMES

The FIDO rover is JPL's advanced technology rover that supports both current and future robotic missions on the surface of Mars. In particular, the FIDO rover conducts mission-rele-vant field trials that simulate mission operations scenarios and validate rover technology in the areas of rover navigation and control, instrument placement, remote sensing, scientific data collection, intelligent behaviors, telemetry processing, data visualization, and mission operations tools. Work on the K9 rover at NASA Ames focuses on mission autonomy and execution and autonomous science in sensor placement and interpretation. The Athena-class chassis design enables low CG relative to wheelbase, but are most well known for the uncontrolled DOF in vertical wheel motion that enables a high degree of traction in uneven terrains. The bogie mechanism enhances individual wheel pair accommodation to terrain while the differential side-side connection stabilizes the chassis and thereby sensors and effectors that are attached. Fielded systems have used 4-wheel independent steering and 4-wheel independent hub motors, yielding high levels of traction and zero turning radius.

FIDO

The FIDO rover has demonstrated [Huntsberger] autonomous target approach towards targets 5.9m away on average on relatively flat terrain (Arroyo Seco near JPL). It does this by visually tracking various landmarks in order to get very accurate position estimation. Upon reaching the spot where the target was initially believed to be, the rover lowers a manipulator mounted camera towards the ground until the images are in focus. It does not explicitly keep track of the target, nor does it make contact measurements.

Terry Huntsberger, Hrand Aghazarian, Yan Chen, Eric Baumgartner, Edward Tunstel, Chris Leger, Ashitey Trebi-Ollennu, and Paul Schenker, Rover Autonomy for Long Range Navigation and Science Data Acquisition on Planetary Surfaces , in IEEE International Conference on Robotics and Automation, Washington DC, 2002

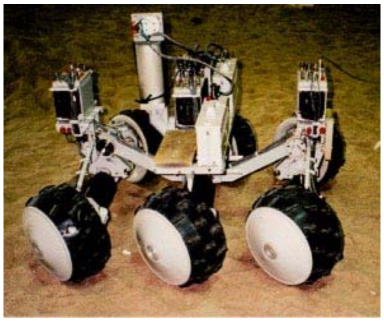
Hyperion — CARNEGIE MELLON

Carnegie Mellon has developed Hyperion, a prototype sun-synchronous circumnavigation robot. Hyperion will explore terrain while being cognizant of the broader environment: the time, its global position and orientation, the position of the sun, and the available and required energy levels for exploration. It optimizes a path through the terrain based on all these factors.

In July 2001 Hyperion completed two sun-synchronous exploration experiments in the Canadian high arctic (75¡N). Hyperion planned a sun-synchronous route to visit designated sites while obtaining the necessary solar power for continuous 24-hour operation. Hyperion executed its plan (90% autonomous and 10% supervised teleoperation) and returned to its starting location with batteries fully charged after traveling more than 6 kilometers in barren, Mars analog terrain.

[Wettergreen02] D. Wettergreen, M. Dias, B. Shamah, J. Teza, P. Tompkins, C. Urmson, M. Wagner, W. Whittaker, First Experiment in Sun-Synchronous Navigation, IEEE International Conference on Robotics and Automation (ICRA), Washington D.C., May 2002. *http://www.frc.ri.cmu.edu/sunsync/*

IARES - CNES

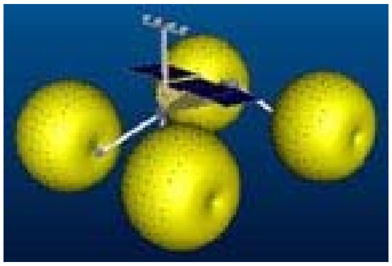


The IARES project is sponsored by the Eureka Programme of the European Communities and managed by the French national space agency, CNES. Its main objectives are to demonstrate the feasibility of a planetary rover vehicle and to collect data needed to evaluate the vehicle's characteristics and performance. With definition of future operational rovers in mind, a flexible prototype has been designed to allow quantitative evaluation of different vehicle configurations.

The vehicle chassis, designed in Russia by VNII Transmash, has advanced capabilities. Its six wheels are independently powered and steerable through angles of –40 degrees. An articulated frame allows it to adapt passively along its transverse axis to obstacles in its path. A combination of passive and active longitudinal deformation together with active equalization of wheel loading is used to traverse an arbitrary slope. A two-speed gearbox provides a maximum velocity of 0.10 m/s in first gear and 0.35 m/s in second gear. Varying the separation between the wheels allows the vehicle to walk on its wheels.

http://esapub.esrin.esa.it/pff/pffv7n2/boisv7n2.htm

INFLATABLE ROVER —JPL



Inflatable wheel solutions deliver high performance obstacle negotiation and stability using extremely large wheel diameter, and therefore extremely large ground clearance. High torque is required to drive large-diameter wheels, raising potential longevity issues. In addition, large wheelbase is gained at the expense of high center of gravity, creating potential limitations for static stability in slope conditions. Dynamic stability can suffer from elasticity of air-filled wheels. On the positive side, the inflated wheels can act as energy-absorbing bumpers in the case of a fall (e.g. over a short cliff wall) and can also provide buoyancy in liquids, as demonstrated already by the JPL prototype. Early tests with scale models of inflatable rovers showed that this type of vehicle could easily scale rocks that were 1/3 the diameter of the wheels. Thus a wheel size of 1.5 m diameter was chosen to allow the rover to traverse well over 99% of the Martian surface. In order to minimize mass and complexity, a three-wheeled vehicle was chosen with a wide wheel base to enhance stability in rugged and steep terrain.

http://www.jpl.nasa.gov/adv_tech/rovers/bigwheel.htm

[Jones01] Jones, Jack, 2001, Inflatable Robotics for Planetary Applications, 6th International Symposium on Artificial Intelligence, Robotics, and Automation in Space, I-SAIRAS, Montreal, Canada, June 19-21.

IROBOT ARIEL CRAB

This six-legged servo-driven robot is a reproduction of the standard crab gait. Its most radical non-biomimetic feature is the total range of motion of each leg vertically, enabling the crab to crawl in both top-side up and inverted attitudes, enhancing the system's envelope of static and dynamic stability. The fielded system is amphibious, demonstrating walking over dry land and in over a river bed. This demonstrates environmental isolation of power electronics and motor components that is of use for environmental isolation from dust as well. As with many legged vehicles, significant power is consumed to keep the chassis off the ground, limiting power efficiency and placing high torque demands on the legs that raise longevity issues. Also as with legged vehicles in general, isolated point contacts with the ground limit odometric resolution and often lead to high levels of cumulative odometric error.

http://www.irobot.com/rd/p10_Ariel.asp
Robo Sapiens. Peter Menzel and Faith D Aluisio. MIT Press, 2000.

K9

The K9 robot is equipped with a 5 DOF manipulator arm on which can be mounted various instruments. Currently K9 can only position the instruments using deduced reckoning from a compass and odometry, and therefore has no more autonomy than Sojourner. A research effort is underway to give K9 single

communications cycle instrument deployment capability in 2003/4.

The K9 robot onboard Conditional Executive (CX) [Rich Washington reference] can accommodate flexible time sequences with conditional branches. Furthermore, it monitors current resource use and can forecast future levels, terminating current actions if they will lead to a resource being depleted in the future.

K9 demonstrated limited onboard science autonomy in 1999 and 2001 field trials [I-SAIRAS reference], recognizing layers, rocks and carbonates using the GSOM [LPSC Reference] suite of programs The executive allowed it to crudely prioritize targets and move towards them.

Liam Pedersen, 3D Rock Ground Segmentation for Mars Rover Instrument Placement , submitted to IROS 2002.

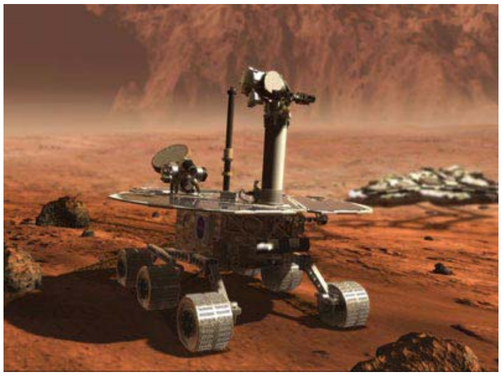
John Bresina, Keith Golden, David Smith, Rich Washington, Increased Flexibility and Robustness of Mars Rovers , in i-SAIRAS 1999.

T.L. Roush, V. Gulick, R. Morris, P. Gazis, G. Benedix, C. Glymour, J. Ramsey, L. Pedersen, M. Ruzon, W. Buntine, and J. Oliver, Autonomous Science Decisions for Mars Sample Return , in Lunar and Planetary Science Conference XXX, 1999.

LANGLEY AUTOMATED STRUCTURAL ASSEMBLY ROBOT

In 1996 a robot was designed and built at NASA Langley Research Center that autonomously assembled a telescope mock-up. The robot assembled and disassembled 204 struts and 24 panels to create a large structure.

MARS EXPLORATION ROVERS (MER 03) JPL



The Mars Exploration Rovers are in development and due to be launched to Mars in 2003. Two independent rovers will be landed. Each rover will carry instruments that will allow it to search for evidence of liquid water. The rovers will be identical to each other, but will land at different regions of Mars. Using images and spectra taken daily from the rovers, scientists will command the vehicle to go to rock and soil targets of interest and evaluate their composition and their texture at microscopic scales. Rocks and soils will be analyzed with a set of five instruments on each rover, and a special tool called the RAT, or rock abrasion tool, will be used to expose fresh rock surfaces for study. Each rover has a mass of nearly 180 kilograms (about 400 pounds) and has a range of up to 100 meters (about 110 yards) per sol, or Martian day. Surface operations will last for at least 90 sols, extending to late May 2004, but could continue longer, depending on the health of the vehicles. MER 03 will provide for contingent plans to be uploaded, but the number of branches in a plan is conservatively limited to one. The contingent sequence is a fixed time tagged operation using one of the many onboard cameras to take images that could help in diagnosing the fault in the next sol. No autonomous science capability is planned. After Viking, this is the first scientific mission expecting to produce significant science. Given the inherent risks involved (cost, schedule and environment), it is unclear what will actually happen.

http://mars.jpl.nasa.gov/missions/future/2003.html

Marsokhod

A joint US-Russia effort in 1993, the Marsokhod rover has been deployed in numerous venues terrestrially to demonstrate human-rover interaction interfaces. The rover is of a large, six-wheeled design, with hip twist degrees of freedom to enable obstacle surmounting competency.

Cabrol, N.A., J.J. Kosmo, R.C. Trevino, C.R. Stoker, the Marsokhod Rover Team, and the Advanced EVA Technology Team Astronaut-Rover Interaction for Planetary Surface Exploration: 99 Silver Lake first ASRO experiment, LPSC XXX, Abstr. #1069 (1999).

[Christian98] D. Christian, D. Wettergreen, M. Bualat, et. Al, Field Experiments with the Ames Marsokhod Rover, Field and Service Robots, Springer-Verlag, Berlin, Germany, 1998.

MARS PATHFINDER AND Sojourner ROVER (1997)

The Sojourner micro-rover, built by JPL, was deployed on Mars by the Pathfinder lander which landed there in 1997. It is the only rover to have operated on Mars to date. It traveled about 100m over the course of 83 Martian days (sols), never going out of view of the lander, and returning spectra from 16 science targets. Sojourner was small (63 x 48 cm footprint, 11.5 kg) and power limited (16 W max solar input), and therefore faced tight computational and memory constraints. Advanced autonomy was neither a priority nor an option for Sojourner, and the technology fielded there should be taken as a lower bound for what can be accomplished with a more capable rover platform and more ambitious goals.

The tight computational and memory constraints of Sojourner precluded the onboard use of maps and sophisticated range sensors. Obstacles in front of the rover were detected using a camera and laser light striper. Other hazards, such as slopes or holes, could not be autonomously detected.

Path planning was done offline, and in advance, by mission control, using maps generated from the lander images. Each sol they would upload a new command sequence to the rover. Each command was to move the robot in a roughly straight line to a point in the fixed reference frame of the lander. The longest total motion in a single command sequence (over the course of one sol) was 8 meters.

While in motion, Sojourner tracked its position using deduced-reckoning, with position updates once per sol obtained by mission control who could locate the rover in images from the lander.

Sojourner had an APX spectrometer that could be extended out from the rover by a compliant, spring loaded mechanism. The rover would be commanded to drive to an area in front of a rock, and the instrument extended outwards until pushing against the rock, typically taking between three and five command cycles to do so. Navigation and placement verification were considerably simplified by the rover being in view of the lander at all times.

The Sojourner Mars rover could execute simple rigid command sequences. All scientific sensor data was returned, unprocessed, to mission control for analysis. Science analysis and planning was done offline, on the ground using 3D visualization tools.

MINI-AERCAM

The success of AERCam Sprint led to an on-going effort to reduce the size of AERCam and create an operational unit. Mini-AERCam is this effort and currently consists only a design effort and a simulation. [Ref to RRG]

Nomad 2000 ROBOTIC ANTARCTIC METEORITE SEARCH

The Nomad rover built by Carnegie Mellon University n 1997, was developed to demonstrate technology for future lunar missions. It is a large (700kg) class, 4 wheeled vehicle, built to demonstrate long distance long duration travel over harsh terrain. Teleoperated from the United States via a geostationary satellite link, Nomad traveled 200 kilometers through planetary analog terrain in the Atacama desert of Chile, conducting remote science experiments and demonstrating safeguarded teleoperation.

Nomad was subsequently retrofitted for cold weather, had a manipulator arm with a spectrometer attached, and deployed to Antarctica, where it autonomously identified a meteorite in January 2000.

Nomad s four-wheel design demonstrates a classical four-wheel-drive, four-wheel-steering mechanism for negotiating steep terrain and enabling zero turning radius. In addition, a second travel axis for the wheels provides adjustable wheelbase and footprint for the robot, aiding in the case of confined space travel while not compromising static and dynamic stability in sloped conditions. Sealed hub motors provide limited environmental isolation for some of the mechanism as well. Independent passive suspension in the vertical direction is used to maximize wheel traction of all wheels in varied terrain. Once again, overactuation of the controlled DOF indicate inefficiency in power consumption during motion.

Nomad avoids hazards with the Morphin algorithm using either stereo cameras or a laser rangefinder to construct a local map of the immediate environment ahead. Detectable hazards are large objects, holes and excessive slopes.

In 1997, Nomad deployed magnetometers and a metal detector on a sled dragged behind the vehicle in the Atacama Desert.

Nomad has a manipulator arm for deploying a spectrometer fiber optic probe to a rock sample. The spectrometer and probe were designed to minimize the required placement precision to about 1 cm in the vertical direction. The arm has 3 degrees of freedom, and would lower the spectrometer onto the rock samples from above. A downward looking camera on the end effector enabled autonomous placement above rock samples. Vertical placement required human intervention. Success rates of 75% were typical for the uncluttered Antarctic environment. The system would not work in a desert environment.

In January 2000, Nomad autonomously identified meteorites amongst terrestrial rocks in Antarctica. Traveling at 10 cm/s it could locate dark objects on the ice sheet and then attempt to classify them using close up images and visible light reflection spectroscopy [Pedersen et al, 2001]. Candidates were assessed using a Bayes network, with the ability to handle multiple sensors and exploit any dependencies between rock samples by creating a basic geological map (demonstrated offline) [Pedersen, 2001].

Nomad could not detect anomalies or schedule sensors readings.

Pedersen, L., Wagner, M., Apostolopoulos, D., Whittaker, W., Autonomous Meteorite Identification in Antarctica , ICRA 2001, Seoul, Korea.

[Pedersen, 2001] Pedersen, L., Autonomous Characterization of Unknown Environments, ICRA 2001, Seoul, Korea.

[Wettergreen99] D. Wettergreen, D. Bapna, G. Thomas, M. Maimone., Developing Nomad for Robotic Exploration of the Atacama Desert, Robotics and Autonomous Systems, Elsevier, Amsterdam, Netherlands, vol. 26, no. 2-3, February 1999.

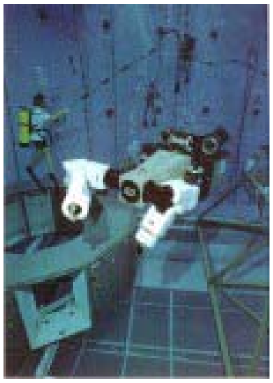
PIONEER - CARNEGIE MELLON

Pioneer is a remote reconnaissance system for structural analysis of the Chornobyl Unit 4 reactor building. Its major components are a teleoperated mobile robot for deploying sensor and sampling payloads, a mapper for creating photorealistic 3D models of the building interior, coreborer for cutting and retrieving samples of structural materials, and a suite of radiation and other environmental sensors.

http://www.frc.ri.cmu.edu/projects/pioneer/

RANGER

Ranger is a teleoperated robot at the University of Maryland that performs operations in a neutral buoyancy tank. It's operations include assembly, maintenance and human EVA assistance.



Science Planning for the Ranger Telerobotic Shuttle Experiment, David L. Akin, in Proceedings of the 6th International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS), 2001.

ROBONAUT

Robonaut is a humanoid robot designed and built at the NASA Johnson Space Center. Robonaut has two fully dexterous arms and two five-fingered hands. Robonaut is nominally teleoperated, but some autonomy work has been done. Robonaut has demonstrated complicated assembly tasks such as connecting EVA electrical connectors.

Robonaut: A Robotic Astronaut Assistant, M. A. Diftler and Robert O. Ambrose, in Proceedings of the 6th International Symposium on Artificial Intelligence, Robotics and Automation in Space (i- SAIRAS), 2001.

ROCKY 7

The NASA Mars 2003 mission consists of a 150 kg long range science rover that lands using the Pathfinder technique, then operates as a self-contained and fully mobile rover. Range is expected to be 100 meters per sol, with a lifetime target of 90 sols. Rocky 7 represents the rover technology to be used on the Long Range Science Rover, including stereo vision and vision-based detection of digging success; 4 DOF arm-based manipulation on a 3 DOF mast, and stereo vision-based obstacle detection. This rover autonomously approached rock outcrops from 5m away using stereo based visual servoing. It is however restricted to benign terrains (uniform sand with occasional rocks or outcrops). Rocky 7 has also demonstrated the ability to autonomously grasp small rocks (5cm) sitting on the sand. It has a simple gripper, and needs human intervention should it fail.

R. Volpe, Navigation Results from Desert Field Tests of the Rocky 7 Mars Rover Prototype International Journal of Robotics Research, Special Issue on Field and Service Robots, 18(7), July 1999.

R. Volpe, J. Balaram, T. Ohm, R. Ivlev. Rocky 7: A Next Generation Mars Rover Prototype. Journal of Advanced Robotics., 11(4), December 1997.

Mark Maimone, Issa Nesnas, Hari Das, Autonomous Rock Tracking and Acquisition from a Mars Rover , in i-SAIRAS 1999.

ROCKY 8

The Mars 2007 mission will use navigation and other technologies being developed on the Rocky 8 platform. Rocky 8 serves as a testbed for CLARAty, the robot software architecture system to be utilized by NASA on future projects, and will also demonstrate high-competency position estimation technologies.

R. Volpe, I. Nesnas, T. Estlin, D. Mutz, R. Petras, H. Das, The CLARAty Architecture for Robotic Autonomy. Proceedings of the 2001 IEEE Aerospace Conference, Big Sky, Montana, March 10-17, 2001

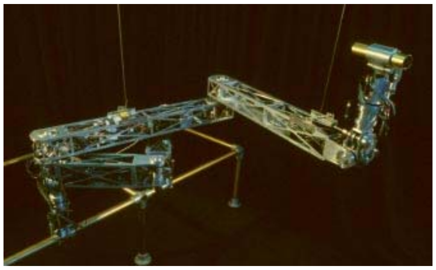
ROTEX

In April ’93 the space robot technology experiment ROTEX was flown on space-shuttle COLUMBIA (STS 55). The robot was teleoperated from on-board, teleoperated from the ground and ran autonomous scripts. It moved various knobs and replaced a simulated Orbital Replacement Unit (ORU).

SCAMP

SCAMP is an underwater roving camera developed at the University of Maryland’s Space Systems Laboratory.

SKYWORKER



Skyworker is an autonomous assembly robot designed and built at Carnegie Mellon University. It walks across structures to mate new components to existing components. A gravity compensation system allows for simulated 0G operation. [Ref to RRG]

SPDM

The Special Purpose Dexterous Manipulator (SPDM) is an extremely advanced, highly dexterous dual-armed robot) that is designed to attach to the end of the SSRMS. It will be teleoperated and can carry out delicate maintenance and servicing tasks. [Ref to RRG]

Special Purpose Dexterous Manipulator (SPDM) Advanced Control Features and Development Test Results, Raja Mukherji, Daniel A. Ray, M. Stieber, J. Lymer, in Proceedings of the 6th International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS), 2001.

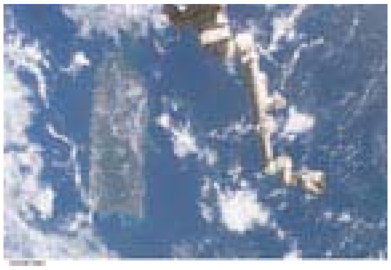
SRMS

The Shuttle Remote Manipulator System (SRMS) is a teleoperated robot that has been used for a number of assembly tasks. It is capable of moving large objects.

Canadarm: 20 Years of Mission Success Through Adaptation, Michael Hiltz, Craig Rice, Keith Boyle and Ronald Allison, in Proceedings of the 6th International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS), 2001.

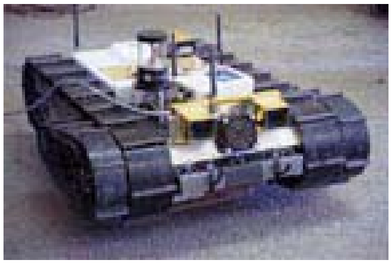
SSRMS

The Space Station Remote Manipulator System (SSRMS) is a teleoperated robot that has been used for a number of assembly tasks. It is capable of moving large objects.



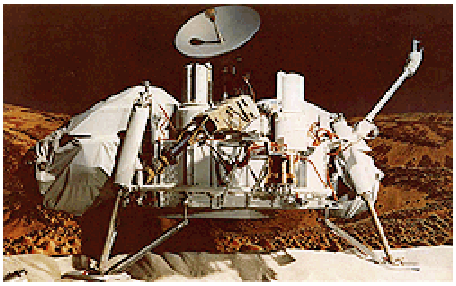
Flight 6A: Deployment and Checkout of the Space Station Remote Manipulator System (SSRMS), Rod McGregor and Layi Oshinowo, in Proceedings of the 6th International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS), 2001.

URBAN RECONNAISSANCE ROBOT, URBIE—IROBOT AND JPL



This hardened fielded system employs four separate tracks, one pair in a standard parallel tracked configuration with a second pair that changes pitch on a swing axis. The robot has a very low CG and a low overall height, useful in various confined spaces and on slopes. The lack of a suspension means that chassis stability is compromised; no mechanical isolation of the chassis is possible during motion. However, by controlling the swinging tread pair, the chassis attitude can be adjusted actively along the pitch axis. The robot is able to locomote both top-side up and inverted, and can use the swinging joint to switch between configurations, maximizing static and dynamic stability. Active control of the swinging tread is particular interesting in the case of terrain slope variation because effective locomotory modalities can be changed, as the footprint shape of the robot is adjustable. Wear considerations are significant in this robot due to the use of tracks, which will limit overall life. The fielded system employs the drive motors for track driving and for the swinging axle, thereby limiting the number of motors to the minimum possible. This reduces weight and is a positive consideration for power usage. However, the robot steers by means of slip-skid steering, which is high-friction and power-inefficient as well as imprecise and therefore undesirable for odometry accuracy.

VIKING I & II



The Viking 1 and Viking 2 missions to Mars consisted of two orbiters and landers launched in 1975. The Viking 1 Lander touched down at Chryse Planitia on July 20, 1976 and the Viking 2 Lander touched down at Utopia Planitia on September 3, 1976. The Viking landers were equipped with simple scoops that could be extended from the craft. They would execute a preset sequence of motions to (hopefully) gather samples of soil.

Appendices

Robotics Community Response Tables

The following pages contain tables showing the responses for each of the metrics for each functionality. The numbers in the table indicate the number of respondents who felt that a particular level of capability fell in that particular category. The actual respondents to the questionnaire are shown below each table.

IN-SPACE MAINTENANCE METRIC 1: REMOVING DEBRIS

	Currently	**10 Years with Nominal Effort**	**10 Years with Intense Effort**	**Breakthrough Required**
1. Robot can remove loose debris that is blocking a component; teleoperated	3	2		
2. Robot can remove loose debris that is blocking a component; supervised autonomous operation		4	1	
3. Robot can untangle wires that are hindering extraction of a component; teleoperation	2	2	1	
4. Robot can untangle wires that are hindering extraction of a component; supervised autonomous operation		3	2	
5. Robot can bend metal that has obstructed extraction of a component; teleoperated	1	3	1	
6. Robot can bend metal that has obstructed extraction of a component; supervised autonomous control		3	2	

IN-SPACE MAINTENANCE METRIC 2: OPENING PANELS AND COVERS

	Currently	**10 Years with Nominal Effort**	**10 Years with Intense Effort**	**Breakthrough Required**
1. Opening a rigid panel with robot-friendly handle; teleoperated	5			
2. Opening a rigid, undamaged panel with robot-friendly handle; supervised autonomous operation	4	1		
3. Opening a rigid panel with no handles; teleoperation	3	2		
4. Opening a rigid panel with no handles; supervised autonomous operation		5		
5. Opening soft, attached blanket; teleoperated	3	2		
6. Opening a soft, attached blanket; supervised autonomous control	1	3	1	

Respondents: Bill Doggett (NASA LaRC), Peter Staritz (CMU), Ron Diftler (JSC), Dave Akin (UMd), Chris Culbert (NASA JSC)

IN-SPACE MAINTENANCE METRIC 3: AUTONOMOUSLY LOCATING A COMPONENT

	Currently	**10 Years with Nominal Effort**	**10 Years with Intense Effort**	**Breakthrough Required**
1. Open loop control using known position on structure and no sensing.	5			
2. Closed loop control using fiducial markers.	5			
3. No special markers, but a priori model of an undamaged component.	1	4		
4. A priori model, but component has been damaged or changed.		3	2	

Respondents: Bill Doggett (NASA LaRC), Peter Staritz (CMU), Ron Diftler (JSC), Dave Akin (UMd), Chris Culbert (NASA JSC)

IN-SPACE MAINTENANCE METRIC 4: INSERTING NEW COMPONENTS

	Currently	**10 Years with Nominal Effort**	**10 Years with Intense Effort**	**Breakthrough Required**
1. Component designed to lock into place when inserted; teleoperated	5			
2. Component designed to lock into place when inserted; supervised autonomous operation	5			
3. Component requires bolts or screws after being inserted; bolts or screws are already attached; human operator in high teleoperation	4	1		
4. Component requires bolts or screws after being inserted; bolts or screws are already attached; supervised autonomous operation		5		

Respondents: Bill Doggett (NASA LaRC), Peter Staritz (CMU), Ron Diftler (JSC), Dave Akin (UMd), Chris Culbert (NASA JSC)

IN-SPACE MAINTENANCE METRIC 5: GRASPING A COMPONENT

	Currently	**10 Years with Nominal Effort**	**10 Years with Intense Effort**	**Breakthrough Required**
1. Grasp of special-purpose component handle with corresponding end-effector; teleoperated	5			
2. Grasp of special-purpose component handle with corresponding end-effector; supervised autonomous operation	4	1		
3. Grasp of pre-designed component handle with general purpose end-effector; teleoperation	5			
4. Grasp of pre-designed component handle with general purpose end-effector; supervised autonomous operation	4	1		
5. Grasp of component with no pre-designed handle; teleoperated	4	1		
6. Opening a soft, attached blanket Grasp of component with no pre-designed handle; supervised autonomous control		5		

Respondents: Bill Doggett (NASA LaRC), Peter Staritz (CMU), Ron Diftler (JSC), Dave Akin (UMd), Chris Culbert (NASA JSC)

IN-SPACE MAINTENANCE METRIC 6: REMOVING BOLTS AND FASTENERS

	Currently	**10 Years with Nominal Effort**	**10 Years with Intense Effort**	**Breakthrough Required**
1. Removing bolt with built-in bolt tool; teleoperated	5			
2. Removing bolt with built-in bolt tool; supervised autonomous operation	4	1		
3. Removing bolt by grasping bolt tool; teleoperation	4	1		
4. Removing bolt by grasping bolt tool; supervised autonomous operation	1	4		
5. Automatically adjusting torque to overcome stuck bolts	1	3	1	

Respondents: Bill Doggett (NASA LaRC), Peter Staritz (CMU), Ron Diftler (JSC), Dave Akin (UMd), Chris Culbert (NASA JSC)

IN-SPACE MAINTENANCE METRIC 7: SUMMARY OF OVERALL CAPABILITIES

	Currently	10 Years with Nominal Effort	10 Years with Intense Effort	Breakthrough Required
1. Robotic change-out of predefined components (e.g., ORUs); teleoperated	5			
2. Robotic change-out of predefined components (e.g., ORUs); supervised autonomous operation	2	3		
3. Robotic refueling of satellite/ spacecraft; teleoperation	1	4		
4. Robotic refueling of satellite/ spacecraft; supervised autonomous operation		3	1	
5. Robotic change-out of any graspable, exposed components; teleoperated	3	2		
6. Robotic change-out of any graspable, exposed components; supervised autonomous control		4	1	
7. Robotic access to and change-out of any graspable, obstructed components; teleoperation	2	2	1	
8. Robotic access to and change-out of any graspable, obstructed components; supervised autonomous control		1	4	
9. Robotic troubleshooting of anomalies and arbitrary repairs; teleoperation		1	1	4

Respondents: Bill Doggett (NASA LaRC), Peter Staritz (CMU), Ron Diftler (JSC), Dave Akin (UMd), Chris Culbert (NASA JSC)

IN-SPACE INSPECTION METRIC 1: INSPECTING STRUCTURES

	Currently	**10 Years with Nominal Effort**	**10 Years with Intense Effort**	**Breakthrough Required**
1. Visual inspection of a specific anomaly site; teleoperated.	3	1		
2. Complete visual inspection of a simple exterior surface; teleoperated.	3	1		
3. Complete visual inspection of simple exterior surface; supervised autonomous operation.	1	2	1	
4. Complete visual inspection of complex exterior surface; supervised autonomous operation.		3	1	
5. Complete visual inspection of complex, open 3D surfaces (e.g., a truss); supervised autonomous operation.		3	1	

Respondents: Ella Atkins (UMd), Peter Staritz (CMU), Stephen Fredrickson (JSC), Dave Akin (UMd)

IN-SPACE INSPECTION METRIC 2: INSPECTION PLANNING AND EXECUTION

	Currently	**10 Years with Nominal Effort**	**10 Years with Intense Effort**	**Breakthrough Required**
1. Robot given detailed sequence of inspection path. Default response to problems is to halt.	2	2		
2. User selects inspection area with robot-planned coverage path. Automatic work-arounds for many problems.		4		
3. User selects multiple inspection tasks and robot optimizes its execution of those tasks. Robot notices unexpected situations while traveling to inspection areas.		3	1	
4. High-level inspection tasks with little human input. Robot adapts to degradations in performance.			4	

Respondents: Ella Atkins (UMd), Peter Staritz (CMU), Stephen Fredrickson (JSC), Dave Akin (UMd)

IN-SPACE INSPECTION METRIC 3: INSPECTION DATA INTERPRETATION

	Currently	10 Years with Nominal Effort	10 Years with Intense Effort	Breakthrough Required
1. No data interpretation; all data stored or sent off-board in raw form.	4			
2."Mosaicing to provide single, continuous view; no analysis.	3	1		
3. Filtering of data — only potentially anomalous data is stored or sent.		3	1	
4. Autonomous detection of clearly defined and modeled anomalies.		3	1	
5. Autonomous detection of unmodeled off-nominal anomalies.		1	1	2

Respondents: Ella Atkins (UMd), Peter Staritz (CMU), Stephen Fredrickson (JSC), Dave Akin (UMd)

IN-SPACE INSPECTION METRIC 4: INSPECTION AUTONOMOUS ACTIONS AT ANOMALY SITE

	Currently	10 Years with Nominal Effort	10 Years with Intense Effort	Breakthrough Required
1. No action taken.	4			
2. Station-keeping such that anomaly is continuously monitored.	2	2		
3. Approach anomaly for closer look.	2	2		
4. Deploy additional sensor modalities or views to further characterize anomaly.		4		

Respondents: Ella Atkins (UMd), Peter Staritz (CMU), Stephen Fredrickson (JSC), Dave Akin (UMd)

IN-SPACE INSPECTION METRIC 5: SUMMARY OF OVERALL CAPABILITIES

	Currently	10 Years with Nominal Effort	10 Years with Intense Effort	Breakthrough Required
1. Robotic visual inspection of some exterior surfaces with no interpretation of sensory data; teleoperated	4			
2. Robotic visual inspection of some exterior surfaces with no interpretation of sensory data; human operator closely supervising robot via high-bandwidth communication.	2	2		
3. Robotic visual inspection of some exterior surfaces; sensory data filtered before being stored or sent; supervised autonomy		3	1	
4. Robotic visual inspection of most exterior surfaces; autonomous interpretation of most data; supervised autonomous operation		1	3	
5. Robotic visual inspection of most exterior surfaces; autonomous interpretation of most data; autonomous refueling and recharging.			4	

Respondents: Ella Atkins (UMd), Peter Staritz (CMU), Stephen Fredrickson (JSC), Dave Akin (UMd)

IN-SPACE ASSEMBLY METRIC 1: COMPONENT CAPTURE WITH A MANIPULATOR

	Currently	10 Years with Nominal Effort	10 Years with Intense Effort	Breakthrough Required
1. Grasp component attached to same structure as robot; teleoperation	5			
2. Grasp component attached to same structure as robot; supervised autonomous operation	4	1		
3. Grasp payload that is free-flying; teleoperation	4	1		
4. Grasp component that is free-flying; supervised autonomous operation	3	1	1	
5. Grasp soft components such as gossamer structures with no damage to the component. Component has built-in hard attach point.	1	4		
6. Grasp soft component such as gossamer structures with no damage to the component. Component has no built-in hard attach point.		2	3	

Respondents: Peter Staritz (CMU), Ron Diftler (JSC), Bill Doggett (LaRC), Dave Akin (UMd), Chris Culbert (JSC)

IN-SPACE ASSEMBLY METRIC 2: SOFT COMPONENT MANIPULATION (MINIMIZING ROBOTIC IMPACT TO SOFT COMPONENTS)

	Currently	10 Years with Nominal Effort	10 Years with Intense Effort	Breakthrough Required
1. Robot motion minimizing acceleration/impact.	4	1		
2. Component motion minimizing component forces.	2	3		
3. Sensing component/ structure forces and minimizing sensed forces.	2	2		
4. Dynamic damping by robot.	2	3		

Respondents: Peter Staritz (CMU), Ron Diftler (JSC), Bill Doggett (LaRC), Dave Akin (UMd), Chris Culbert (JSC)

IN-SPACE ASSEMBLY METRIC 3: MOVING COMPONENT FROM CAPTURE POSITION TO GOAL POSITION (AUTONOMOUSLY)

	Currently	10 Years with Nominal Effort	10 Years with Intense Effort	Breakthrough Required
1. Move a simple and rigid component to the goal through a known, fixed structure.	5			
2. Move a simple and rigid component to the goal through a partially known, fixed structure.	4	1		
3. Move a component that has multiple degrees of freedom and complex geometry through a partially known, fixed structure.		5		
4. Move a simple and rigid component through a partially known, dynamic structure.		3	1	
5. Move a poorly characterized component through a partially known, dynamic structure.		1	3	1

Respondents: Peter Staritz (CMU), Ron Diftler (JSC), Bill Doggett (LaRC), Dave Akin (UMd), Chris Culbert (JSC)

IN-SPACE ASSEMBLY METRIC 4: SMALL STRUCTURE CAPTURE WITH A MANIPULATOR

	Currently	**10 Years with Nominal Effort**	**10 Years with Intense Effort**	**Breakthrough Required**
1. Grasp component attached to same structure as robot; teleoperated	5			
2. Grasp component attached to same structure as robot; supervised autonomous operation	3	2		
3. Grasp component that is free-flying; teleoperated	4	1		
4. Grasp component that is free-flying; supervised autonomous operation	3	1	1	
5. Grasp soft component such as gossamer structures with no damage to the component.		4	1	1

Respondents: Peter Staritz (CMU), Ron Diftler (JSC), Bill Doggett (LaRC), Dave Akin (UMd), Chris Culbert (JSC)

IN-SPACE ASSEMBLY METRIC 5: DOCKING/MATING TWO COMPONENTS

	Currently	**10 Years with Nominal Effort**	**10 Years with Intense Effort**	**Breakthrough Required**
1. Components have mechanical alignment capability that engages when components are close to one another; teleoperated	5			
2. Components have mechanical alignment capability that engages when components are close to one another; supervised autonomous operation	5			
3. Components have fiducials but no mechanical alignment capability; teleoperated	5			
4. Components have fiducials but no mechanical alignment capability; supervised autonomous operation	3	2		
5. Components have no fiducials or mechanical alignment capability; teleoperated	2	3		

Respondents: Peter Staritz (CMU), Ron Diftler (JSC), Bill Doggett (LaRC), Dave Akin (UMd), Chris Culbert (JSC)

IN-SPACE ASSEMBLY METRIC 6: GRASPING CONNECTORS

	Currently	10 Years with Nominal Effort	10 Years with Intense Effort	Breakthrough Required
1. Robot gets connector from custom dispenser in fixed, known location. Connectors specially built for easy grasping.	5			
2. Connectors from custom dispenser in fixed, known location, but connectors not built for easy robot use; teleoperated	4	1		
3. Connectors from custom dispenser in fixed, known location, but connectors not built for easy robot use; supervised autonomous operation	2	2	1	
4. Robot gets connector from bag of connectors; teleoperated	2	1	1	
5. Robot gets connector from bag of connectors; supervised autonomous operation	1	3		1

Respondents: Peter Staritz (CMU), Ron Diftler (JSC), Bill Doggett (LaRC), Dave Akin (UMd), Chris Culbert (JSC)

IN-SPACE ASSEMBLY METRIC 7: MATING CONNECTORS

	Currently	**10 Years with Nominal Effort**	**10 Years with Intense Effort**	**Breakthrough Required**
1. Mating of robot-friendly connectors; teleoperated	5			
2. Mating of robot-friendly connectors; supervised autonomous operation	4	1		
3. Mating of standard (i.e., non-robot-friendly) connectors; teleoperated	5			
4. Mating of standard (i.e., non-robot-friendly) connectors. supervised autonomous operation		5		
5. Mating of connectors that require complex orientation requirements or those that require large forces to engage.		3	1	1

Respondents: Peter Staritz (CMU), Ron Diftler (JSC), Bill Doggett (LaRC), Dave Akin (UMd), Chris Culbert (JSC)

IN-SPACE ASSEMBLY METRIC 8: RUNNING CONDUIT

	Currently	**10 Years with Nominal Effort**	**10 Years with Intense Effort**	**Breakthrough Required**
1. Running rigid, yet pliable conduit (e.g., tubing); teleoperated	3	2		
2. Running rigid, yet pliable conduit (e.g., tubing); supervised autonomous operation	1	3	1	
3. Running very flexible conduit (e.g., electrical cables); teleoperated	4		1	
4.Running very flexible conduit (e.g., electrical cables); supervised autonomous operation.		4		1

Respondents: Peter Staritz (CMU), Ron Diftler (JSC), Bill Doggett (LaRC), Dave Akin (UMd), Chris Culbert (JSC)

IN-SPACE ASSEMBLY METRIC 9: PRE-ASSEMBLY PLANNING AND SEQUENCING

	Currently	10 Years with Nominal Effort	10 Years with Intense Effort	Breakthrough Required
1. Robot operations personnel generate detailed task sequence to accomplish assembly tasks. Robot personnel work closely with the engineers who designed the structure. Plan contains no contingencies except to stop if a fault is detected.	5			
2. Initial task plan automatically generated from software models of structure to be assembled. Robot operations personnel thoroughly check the plan (by hand or through a simulation), add robot-specific details and any additional tasks. Plan allows for some contingencies and robot flexibility.	3	2	1	
3. Task plan automatically generated from software models is nearly complete. Robot operations personnel fine tune the plan. Plan allows for significant contingencies and robot flexibility.	1	1	3	
4. All task planning and sequencing is done from software models. Minimal involvement by robot operations personnel. Plan copes with major failures.		1	1	3

Respondents: Peter Staritz (CMU), Ron Diftler (JSC), Bill Doggett (LaRC), Dave Akin (UMd), Chris Culbert (JSC)

IN-SPACE ASSEMBLY METRIC 10: ASSEMBLY-TIME PLANNING AND EXECUTION

	Currently	**10 Years with Nominal Effort**	**10 Years with Intense Effort**	**Breakthrough Required**
1. Plan is a detailed sequence of low-level commands. Behavior of robot(s) is defined by input; system s default response to problems is to halt.	5			
2. Plan allows flexible time specification and contingencies, enabling a family of behaviors.	2	3		
3. Plan is a prioritized list of tasks, with constraints amongst them. System responds to opportunities and recovers from most faults.		5		
4. Plan is a prioritized list of tasks, with constraints amongst them. System responds to opportunities and recovers from most faults. System adapts to robot degradation and failures.			5	

Respondents: Peter Staritz (CMU), Ron Diftler (JSC), Bill Doggett (LaRC), Dave Akin (UMd), Chris Culbert (JSC)

IN-SPACE ASSEMBLY METRIC 11: SUMMARY OF CAPABILITIES

	Currently	10 Years with Nominal Effort	10 Years with Intense Effort	Breakthrough Required
1. Robots that move large components and mate parts; teleoperated	5			
2. Robots that move large components and mate parts; autonomous	3	2		
3. Robots that can mate components and do fine assembly, including making connections; teleoperated	3	2		
4. Robots that can mate components and do fine assembly, including making connections; autonomous		4	1	
5. Robots that perform complete assembly of a complicated structure (e.g., large telescope) from start to finish; teleoperated		3	2	
6. Robots that perform complete assembly of a complicated structure (e.g., large telescope) from start to finish with significant human intervention.		1	2	2
7. Robots that perform complete assembly of a complicated structure that includes gossamer components from start to finish with minimal human intervention.			2	3

Respondents: Peter Staritz (CMU), Ron Diftler (JSC), Bill Doggett (LaRC), Dave Akin (UMd), Chris Culbert (JSC)

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References

1. Wilcox, B., and T. Nguyen, “Sojourner on Mars and Lessons Learned for Future Planetary Rovers”, in *ICES*, 1997.
2. D. Wettergreen, M.B Dias, B. Shamah, J. Teza, P. Tompkins, C. Urmson, M.D. Wagner, and W. L. Whittaker, “First Experiment in Sun-Synchronous Exploration,” International Conference on Robotics and Automation, pp. 3501—3507, 2002.
3. Apostolopoulos, D., M.D. Wagner, B.N. Shamah, L. Pedersen, K. Shillcutt, W.L. Whittaker, “Technology and Field Demonstration of Robotic Search for Antarctic Meteorites” in *International Journal of Robotic Research*, special Field & Service Robotics issue, November 2000.
4. Pedersen, L., M. Bualat, D.E. Smith, R. Washington, “Integrated Demonstration of Instrument Placement, Robust Execution and Contingent Planning”, in *International Symposium on Artificial Intelligence and Robotics in Space (i-SAIRAS) 2003,* Nara, Japan, 2003.
5. Huntsberger, T., H. Aghazarian, Y. Cheng, E.T. Baumgartner, E. Tunstel, C. Leger, A. Trebi-Ollennu, and P.S. Schenker, (2002) “Rover Autonomy for Long Range Navigation and Science Data Acquisition on Planetary Surfaces”, in *proc. IEEE International Conference on Robotics and Automation*, Washington, D.C. May 2002.
6. Nesnas, I., M. Maimone, H. Das (2000), “Rover Maneuvering for Autonomous Vision-Based Dexterous
7. David L. Akin, “Science Planning for the Ranger Telerobotic Shuttle Experiment,” in Proceedings of the 6th International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS), 2001.
8. Robert Burridge and Jeffery Graham, “Providing Robotic Assistance,” SPIE 2001.
9. M. A. Diftler and Robert O. Ambrose, “Robonaut: A Robotic Astronaut Assistant,” in Proceedings of the 6th International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS), 2001.
10. L. Kerstein, F. Seinsiek and E. Graf, “Inspector and the International Space Station,” *Space Technology*, 16(2), 1997.
11. Rod McGregor and Layi Oshinowo, “Flight 6A: Deployment and Checkout of the Space Station Remote Manipulator System (SSRMS),” in Proceedings of the 6th International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS), 2001.
12. Oda Mitsushige, “ETS-VII: Achievements, Troubles and Future,” in Proceedings of the 6th International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS), 2001.
13. Raja Mukherji, Daniel A. Ray, M. Stieber, J. Lymer, “Special Purpose Dexterous Manipulator (SPDM) Advanced Control Features and Development Test Results,” in Proceedings of the 6th

International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS), 2001.

14. P. Staritz, S. Skaff, C. Urmson, and W.L. Whittaker, Skyworker: a robot for assembly, inspection and maintenance of large scale orbital facilities, *Proceedings of the 2001 IEEE International Conference on Robotics and Automation (ICRA '01)*, Vol. 4, May, 2001, pp. 4180 – 4185.

15. T. Williams and S. Tanygin, “On-orbit Engineering Test of the AERCam Sprint Robotic Camera Vehicle,” *Advances in the. Astronautical Sciences*, 99(2), 1001-1020, 1998.

16. Nesnas, I., R. Volpe, T. Estlin, H. Das, R. Petras, D. Mutz, (2001) “Toward Developing Reusable Software Components for Robotic Applications,” in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2001.

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14. ABSTRACT
This report summarizes an extensive survey done in 2002 to determine the then state-of-the-art in space robotics and to predict future robotic capabilities. It looks at both in-space operations (e.g., assembly, maintenance, inspection) and planetary exploration operations (e.g., mobility, manipulation, science perception). The conclusion of the report presents several possible areas in which investment by the space robotics community can lead to breakthrough technologies.

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