A Survey of Space Robotics

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Abstract

In this paper we summarize a survey conducted by NASA to determine the state-of-the-art in space robotics and to predict future robotic capabilities under either nominal and intensive development effort. The space robotics assessment study examined both in-space operations including assembly, inspection, and maintenance and planetary surface operations like mobility and exploration. Applications of robotic autonomy and human-robot cooperation were considered. The study group devised a decomposition of robotic capabilities and then suggested metrics to specify the technical challenges associated with each. The conclusion of this paper identifies possible areas in which investment in space robotics could lead to significant advances of important technologies.

1. Introduction

Robotic systems began the era of space exploration with series of spacecraft including Mariner, Ranger, Surveyor, and Lunakhod. Robotics enables current missions on planetary surfaces, on orbit and in deep space, and is essential in all conceptions of future space exploration and operation. Assessing 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) is chartered with determining NASA's exploration priorities and the technologies needed to attain them. For this purpose, the Human-Robotic Working Group (HRWG) commissioned an assessment of the current and projected state of the art of space robotics. This paper summarizes that study.[12]

We address what robots and robotic systems can currently do, what the major space-related challenges are, and what we can plausibly expect in a decade, by sustaining the current development efforts (nominal condition) or by increasing the level of research effort (intensive condition). We also identify those capabilities requiring technological breakthroughs, which by their very nature are unpredictable.

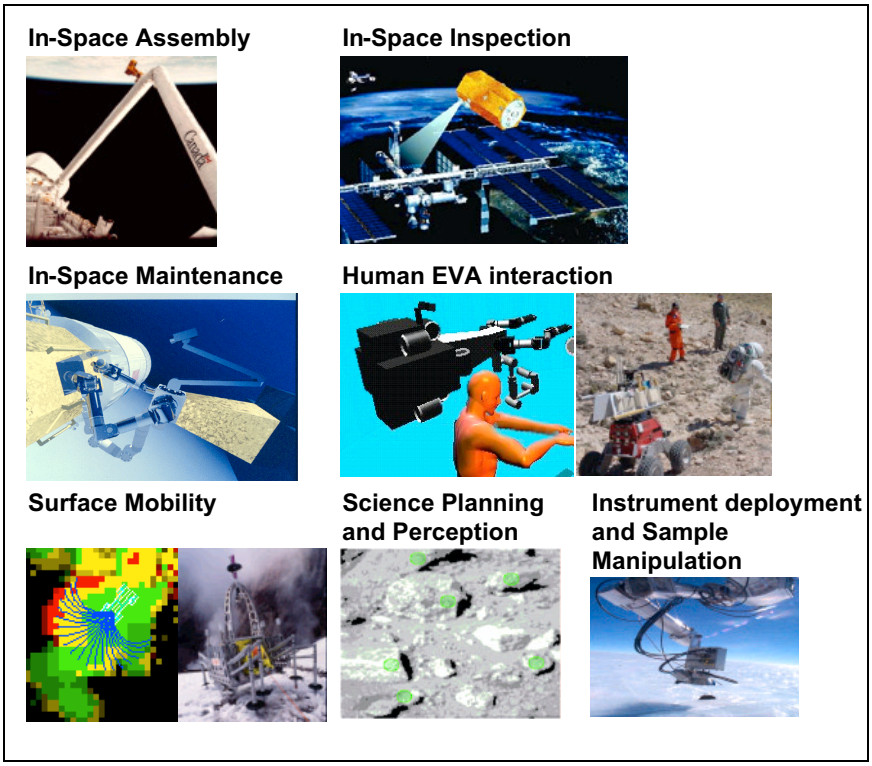

Figure 1: Space Robotics was decomposed into in-space and surface environments and into autonomous and human-assistance applications. In-Space autonomous capabilities considered assembly, inspection, and maintenance tasks and astronaut-assistance for orbital extravehicular activity (EVA). On the surface, EVA as also considered along with autonomy for mobility, instrument and sample operations and science investigations.

Figure 2: Sojourner on Mars with wheels configured to turn in place to orient for sensor placement, as imaged by the Pathfinder lander. Sojourner received detailed command sequences each communication cycle and exhibited only rudimentary autonomy.

We consider a broad range of space robotics functionalities (*Figure* 1) spanning planetary surface exploration and in-space operations. Inputs were received from the 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.

1.1. Robots for Planetary Surface Exploration

The current state of the art in flight demonstrated planetary surface exploration is exemplified by Sojourner (*Figure 2*), which deployed from the Mars Pathfinder lander in July-September 1997. Sojourner executed detailed command sequences determined by human controllers and uploaded each command cycle, two or three times per sol. Sojourner had unused capability for autonomously avoiding obstacles in its path. Sojourner's maximum speed was 0.01 m/s and it traveled several hundred meters in the course of its 83 sol mission Sojourner's capabilities are surpassed by the Mars Exploration Rovers (MERs) destined for Mars landing beginning in January 2004. (*Figure 3*) Although both possess some degree of automatic navigational and instrument capability, they are essentially teleoperated by command sequence with telemetry and images downloaded from Mars each communication opportunity and a sequence of robot actions uploaded for the following cycle (about two per day). Scientists guided Sojourner only through rover engineers and even simple operations such as placing an instrument against a rock took several days. The MER rovers will be more capable due to greater size and power, and better communication and instrumentation, but will be operated in a manner similar to Sojourner.

In contrast, terrestrially demonstrated exploration robots have significantly greater capabilities. Robotic vehicles have performed multi-kilometer traverses autonomously [14] and have operated in the polar desert of Antarctica to autonomously seek and identify meteorites [2]. Robots including K9 and FIDO can autonomously approach targets and place instruments in contact with them and have demonstrated autonomous operation in the service of remote science teams.[4][7] Taken together these demonstrate the ability to traverse long distances between sites, intensively investigate them and perform autonomous investigation in less time and with less human oversight for the next generation of planetary rovers. Although advanced rovers demonstrate capabilities for automating science data collection, none are significantly involved in science data interpretation; this remains the purview of human scientists, who guide the investigation and use the rovers as tools in their exploration.

In a decade navigation and mobility will diminish as barriers to planetary exploration. Long traverses and access, sometimes with specialized robots, to most locations on a planetary surface will be possible.

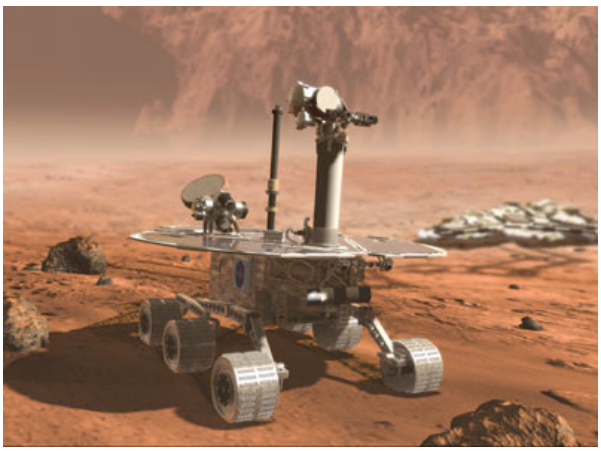

Figure 3: Mars Exploration Rover illustrated departing its lander. MERs can navigate and avoid obstacles an may utilize this capability during their 2004 missions.

In ten years, we expect that highly capable mechanisms will rove most compelling areas of the Earth with autonomous navigational capability well established. Development will likely focus on sensor fusion, from numerous and diverse sources, and path planning in this multidimensional space. Real-time characterization of obstacles as well as terrain features will be established. Development is also likely in robot self-awareness, the capability for monitoring and responding to system health and safety as well as attention to resources including time and power. Robots will travel tens of kilometers autonomously.

We still expect humans to be in the loop with remote surface explorers but not providing moment-to-moment commands. Humans will receive and interpret the data provided and robot will act collaboratively to seek information. We expect that robots will execute complete missions with contingencies and innovation but not to independently design their missions. The ability to accomplish mission objectives with high reliability over great distances will not be limited by localization, perception or reasoning technologies. Fundamental limitations will remain specific to only physical properties, like power storage.

Our study participant consensus indicated it likely that scientists will be able to interact directly with rovers with high-level goals rather than actions prescribed at a low-level. However, performance with the skill of a human scientist in the field, particularly in terms of observation, interpretation and prioritization, is and will continue to be a significant challenge. Barring a breakthrough in the theory or practice of data understanding, rovers will perform within narrowly defined areas of expertise but will lack the perceptual and cognitive abilities of a field scientist.

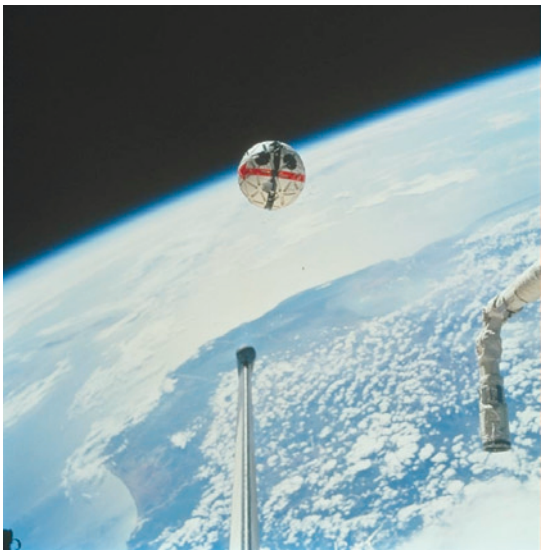

Figure 4: AERCam Sprint during a flight test from the Space Shuttle cargo bay (with tail in view). Free-flying robots could pose a collision risk to the shuttle or station but also reduce risks by offering comprehensive routine inspection.

1.2. Robots for In-Space Operations

In-space operations focus on component assembly, inspection and maintenance, typically component replacement. Currently deployed in-space robots are confined to the Space Shuttle and International Space Station (ISS) remote manipulator systems, which are directly teleoperated and perform only gross component assembly [9]. Ground assembly testbeds such as Ranger [1] and Robonaut [6]as well as in-space experiments like ROTEX [8] have demonstrated more dexterous operations, including connecting cables and opening panels, still under teleoperation. Ground testbeds such as Skyworker [13]and the ASAL (NASA Langley) robot have demonstrated autonomous assembly of carefully designed components. In-space experiments such as AERCam Sprint [16] have demonstrated the usefulness of robots (teleoperated in this case) for remote inspection tasks. (*Figure 4*)

In the next decade our study consensus opinion was that 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 require careful systems engineering to ensure the compatibility of robots and the facility they are constructing. Automated inspection, on the other hand, seems well within near-term robotic capability, and safety assurance is the barrier to broader use.

2. Detailed Functionalities

2.1. In-Space Assembly

Current in-space capabilities for robotic assembly consist of the Space Shuttle and ISS remote manipulator systems (RMS). These teleoperated robot

arms can move large components and mate those components under careful human supervision. Ground testbeds have demonstrated autonomous transport and mating of large components, for example Carnegie Mellon's Skyworker and NASA Langley's Automated Telescope Assembly. Ground testbeds have demonstrated teleoperated robots performing fine assembly such as mating connectors for example NASA JSC's Robonaut (*Figure 5*) [6] and University of Maryland's Ranger [1].

In a decade, 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 with supervision and guidance (including occasional teleoperation) from space or ground-based humans. Complex robotic assembly with little or no human supervision will require breakthrough technologies.

2.2. In-Space Inspection

Currently there are no inspection robots in operation in space. A test of a free-flying camera, AERCam Sprint 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 [4].

Study participants concluded that in ten years autonomous robotic inspection of exterior surfaces will be feasible and that limited autonomous screening of the sensor data is likely. With intense effort, a robot could autonomously inspect most exterior surfaces and detect anomalies on the Space Shuttle and ISS.

2.3. 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 [6].

In the next ten years more dexterous robots, such as the Space Dexterous Robotic Manipulator (SPDM), [7] that can perform routine tasks such as changing out components under teleoperation are likely. With intense effort, these robots may be able to autonomously access and change-out obstructed components. Breakthroughs are needed to achieve autonomous diagnosis and repair of arbitrary faults (that currently even astronauts cannot achieve on orbit).

Figure 5: Robonaut at NASA Johnson Space Center is a teleoperated robot with the full range of motion of the human upper body. It is directly teleoperated by a human operator who can see through Robonaut's "eyes" and affect hand and arm position with instrumented gloves.

2.4. Surface and In-Space Human Assistance

Robotic concepts for assisting humans during surface EVA are being explored by the EVA Robotic Assistant [5]. In field tests with suited astronauts, the Robotic Assistant has demonstrated the ability to follow humans while carrying tools, and to help them deploy a solar panel and cables.

The Space Shuttle and ISS remote manipulators have been used to move crewmembers 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 next decade we expect robots to possess the capability to work in physical proximity to EVA crewmembers. Safety considerations will likely dictate the extent of the physical interaction. With intense effort, these robots may be able to approach being limited teammates, with natural language and gesture interfaces and frequent physical interchange.

2.5. Surface Mobility

Mobility is results from 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 widely accomplished. 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.

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 needed. Significant capabilities include monitoring system state and health, reactively planning complex operations, acting in a resource-efficient manner, building maps, opportunistically conducting science data collection. 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 [3] and FIDO have demonstrated long-distance autonomous navigation, extreme terrain mobility, and relevant science operations, respectively.

According to assessment results, a number of important advances in competency will occur within the next decade even at nominal research effort. Planning capabilities will enable exploration of unknown terrain, with coverage patterns adapting on-line based on the terrain being explored. Similarly, 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. Obstacle avoidance is also expected to mature significantly. Current state-of-art is limited to diverting local paths based on obstacle detection but in 10 years we can expect to see overall path optimization wherein a rover makes fine distinctions to maximize local traversability. Visual servoing will also see significant improvements if current trends continue. Today this competency is limited to direct in-view motion, in 10 years respondents expect significant improvements, leading to the ability to servo toward visual features continuously while avoiding obstacles and otherwise optimizing path control. Automatic mapping will also benefit from significant improvements where today, the state-of-art is mostly limited to local terrain maps that are, at best, naively co-registered. In 10 years, the state-of-art will enable high-resolution map fusion and thus more global map creation.

Another set of competencies is not expected to be available within 10 years unless a deliberate, intense development effort is initiated. Simultaneous localization and mapping is well understood in theory with remaining problems and methods for data association being advanced. Intense development will, according to respondents, lead to solutions to the map-building problem, wherein a rover will be able to construct a global, consistent map of natural terrain by fusing its local sensor readings together with information based on orbital data. There is optimism that simultaneous localization and mapping will progress sufficiently on the data association problem to make localization of planetary rovers reliable in practice. Autonomous exploration is expected to reach only basic levels of competence this decade, including the ability to collect anomalous data opportunistically. However, with intense effort, reviewers believe that robots would be able to seek out anomalies and generate discovery plans and thereupon collect relevant data autonomously.

A number of desirable competencies are unlikely in the coming decade without unexpected breakthroughs on fundamental problems, often tied to physical limitations such as power. In the area of mechanism stability, the ability to self-right from upset conditions is unlikely to be a solved problem regardless of the intensity of effort devoted. In the case of health monitoring, competencies of self-repair and self-recovery are beyond the 10 year timeline.

In our survey assessment of metrics for specific capabilities for surface mobility was followed by metrics of overall rover performance. With respect to distance, 10 years should provide reliable systems able to 100's of meters per command cycle, more intense effort does not improve this as the participants believe a breakthrough in self-reliance was need to reach 1000m per command cycle. The duration of missions will continue to be governed by available power but beyond that intensive effort is required to develop rovers capable of surviving for a single year, with breakthroughs in autonomy needed for multi-year missions. Survey respondents considered a wide variety of environments from soft, dune terrains to boulder fields to hard, steep slopes an concluded that in almost any terrain specialized rovers have been conceived or even demonstrated that could sometimes

Figure 6: NASA's K9 rover can approach a designated location then automatically determine the best measurement site, deploy its instrument to a rock, and collect science data in a single command cycle.

succeed at traversal, however extreme terrains such as cliff faces still defy any reliable solution. In terms of autonomy, teleoperation with high-bandwidth and low-latency is mature and supervisory teleoperation with medium bandwidth and latency, such as applied for the MERs, is the state-of-the-art. Nominal development over the decade will deliver autonomous execution of human prescribed plans (over medium bandwidth). With intensive effort rovers will generate and execute plans needing only human assistance. Rovers that are truly independent, that derive their actions from mission objectives and operate with a minimum of human guidance are a decade or more away.

2.6. Surface Instrument Deployment

Flight systems (Sojourner and MER), using supervised autonomy, require several cycles in order to approach a single rock several meters distant and place a compliantly mounted instrument in contact with its surface (Sojourner could, however, place its APX spectrometer against the ground in a single cycle). Nevertheless, there are no fundamental obstacles to developing robust, highly autonomous sample approach and surface instrument placement capabilities sufficient for a rover to autonomously track multiple rocks 10m away, and navigate to them to place instruments in contact with them within a few centimeters of the requested point. The emerging consensus is that by 2009 a rover could have this capability, provided that nominal research and development effort continues.

Recently terrestrial robots have demonstrated autonomous single cycle instrument placement against nearby large rock targets. For example K9 (*Figure 6:*) 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.

Marsokhod, Rocky 7, and FIDO have demonstrated autonomous approaches to targets using visual means. [15] In ten years, such systems will demonstrate sufficient robustness for deployment on missions. Intense effort is needed to deal with more complex situations involving extreme terrain, occlusions, and operations in highly confined areas.

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. Space qualifying such systems will entail 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.

2.7. 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 environments. In ten years we expect steady improvements in robustness allowing fully autonomous operations for up to a day 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 challenge. Without significant breakthroughs, the best systems will perform well only within narrowly defined areas of expertise and lack the general cognitive and perceptual abilities of a field scientist.

3. Common Challenges

The space robotics assessment revealed themes that emerged repeatedly from the participants. These themes can be categorized as: robustness, whole-

system design, mission competence, and virtual presence.

3.1. Robustness

Robustness is the property of a system to continue to function in the presence of faults or anomalous, unexpected conditions. Robustness is a significant challenge because robots must interact in ways that may not be amenable to standard approaches of verification and validation. Robots achieve much less than the human degree of adaptability and so robustness remains largely beyond our technological grasp; robotic systems are brittle in too many regards. Robots that are self-reliant, meaning able to address faults through self-diagnosis and recovery, and long-lived despite the physical challenges of power, temperature, wear, and stability, will remain a challenge in the decade to come.

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

Robotics is 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, without sufficient experimentation, robustness cannot be achieved.

3.2. Whole-system Design

Whole 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.

3.3. Mission Competence

Humans will always be in involved in space exploration, whether as consumers of the data gathered by the robot or as directors of robot activities. There is no point to completely autonomous space exploration.

The challenge is to shift the human from directing the minute-to-minute activities of the robot to allow the human to concentrate on the mission objectives and scientific strategies, while at the same time allowing for direct control when necessary. Currently robots work on goals that are primitive like “go to this exact location,„ or “put your manipulator in this configuration.„ Humans string together these primitive goals to accomplish mission objectives. This can be tedious and inefficient. Future success of robotics will be dependent on the ability of robots to process mission objectives such as “explore that area 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. Mission competent robots interpret ambiguous instructions that can only be resolved through intimate knowledge of both the task and humans intentions.

3.4. Virtual Presence

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, examining them with all her physical senses and better, but without leaving her lab. Or imagine an engineer overseeing the assembly of 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 like 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 decade. However, robots such as Robonaut demonstrate the future potential for virtual presence.

4. Conclusions

In conclusion, the space robotics assessment pointed to application scenarios for effective robots. We summarize these as follows:

- Dexterous assembly: To *build anything* requires systemic design, dynamic control, assembly planning, sliding autonomy and integrated experimentation.
- Human/robot collaboration: To *help people* requires human models and language, collaborative skills, sliding autonomy and integrated experimentation
- Planetary surface access: To *go anywhere* requires mechanism design, terrain perception, localization, mobility planning and integrated experimentation.
- Comprehensive surface investigation: To conduct science survey requires science models and evaluation, multi-modal sensing, science autonomy and integrated experimentation

Investment in research will enable space robotics for these scenarios and provide returns in productivity.

The space robotics assessment report paints a promising picture of the potential of space robotics by those working most closely on the problems. For this picture to be realized, investment in infrastructure and experiments that will advance the state of the art are needed particularly for those capabilities identified as requiring intensive effort. Few of the necessary future robotic capabilities require fundamental breakthroughs; most require only a sustained 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 and effectiveness of robotic systems in space and pushing the boundaries of exploration.

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