HISTORY OF SPACE ROBOTICS

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Abstract: *The history of space robotics is a fascinating and critical aspect of space exploration, highlighting the technological breakthroughs, challenges, and advancements that have occurred since the early days of remotely controlled probes to the current generation of autonomous rovers and landers. Through the study of the history of space robotics, we can gain a deeper understanding of the role that robotics has played in space exploration and how it has expanded our knowledge of the universe.*

Keywords: *Robotics, Space exploration, Autonomous systems, Planetary exploration, Robotics control, Space operations*

1 Introduction

The human race has always been captivated by space exploration, constantly pushing the boundaries of what is achievable in this challenging domain. A fundamental factor contributing to this accomplishment is space robotics. From the initial remotely operated space probes to the present-day autonomous landers and rovers, space robotics has been a significant technology in space exploration. The development of space robotics has been influenced by both technological breakthroughs and challenges, and has greatly contributed to our comprehension of the cosmos. By studying the history of space robotics, we can gain insight into the future of space exploration and the evolving role that robotics will continue to play in expanding our knowledge of the universe. In this paper will be discussed different types of uses of robots and their specific functionalities in space mostly focused on historical point of view.

1.1 Planetary exploration robots

The current state of art of planetary surface exploration could be exemplified by Sojourner, which was deployed from Pathfinder lander on the Mars in the late 1990s. Sojourner's movements were determined by human controllers. While the robot had the capacity to autonomously avoid obstacles, it was mostly teleoperated. The Mars Exploration Rovers (MERs) that landed on Mars in 2004 were an improvement in terms of size, power, communication, and instrumentation, but they were also teleoperated like Sojourner. On the other hand, exploration robots that have been tested on Earth have demonstrated significantly greater capabilities. These robots have traversed multi-kilometer distances autonomously and operated in the polar desert of Antarctica to seek and identify meteorites. Robots like K9 and FIDO have approached targets and placed instruments in contact with them autonomously, operating in service of remote science teams. These advancements have demonstrated the ability to traverse long distances, conduct extensive investigations, and perform autonomous investigations with minimal human oversight. However, even with these capabilities, human scientists remain responsible for interpreting the data collected by the robots. Over the next years, navigation and mobility will no longer be significant barriers to planetary exploration. Highly capable mechanisms with autonomous navigational capabilities will be able to traverse most locations on a planetary surface, with specialized robots used for certain situations. Sensor fusion and path planning in multidimensional spaces will be a focus of development, as will robot self-awareness for monitoring and responding to system health and safety, as well as resource management. In the future, robots will execute complete missions with contingencies and innovation, but they will not independently design their missions. While humans will still be in the loop with remote surface exploration, they will not provide moment-to-moment commands. Instead, they will receive and interpret data while robots act collaboratively to seek information. However, robots will still perform within narrowly defined areas of expertise and lack the perceptual and cognitive abilities of human field scientists.

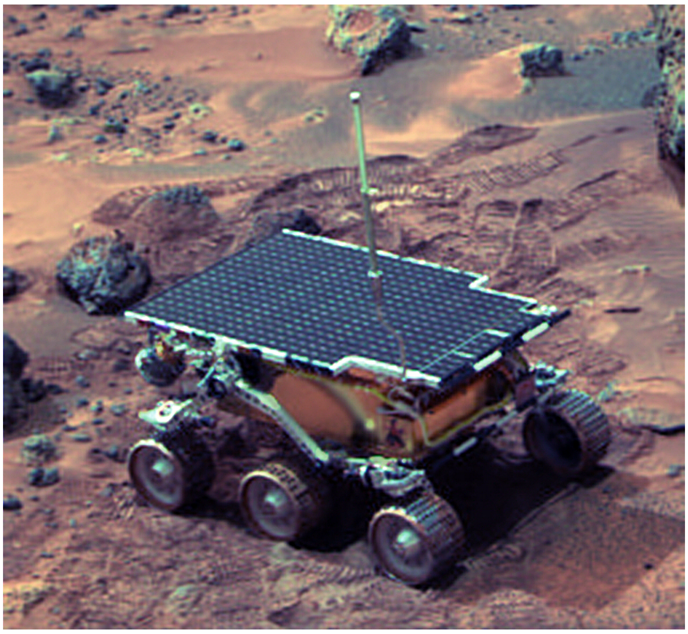

Figure 1: Sojourner - exploration robot [11]

1.2 Robots for operations in space

The focus of in-space operations is on assembling, inspecting, and maintaining components, including their replacement. Currently, robots used in space are limited to gross component assembly and are directly teleoperated on the Space Shuttle and the International Space Station (ISS) remote manipulator systems. However, ground testbeds like Ranger and Robonaut, as well as in-space experiments like ROTEX, have shown more dexterity, such as connecting cables and opening panels, still under teleoperation. Autonomous assembly of carefully designed components has been demonstrated on ground testbeds such as Skyworker and the ASAL robot. Remote inspection tasks have been demonstrated with the AERCam Sprint, which was teleoperated in that case. In the upcoming years, it is believed that the mechanical dexterity of assembly and maintenance robots should approach or even exceed that of a space-suited human. However, achieving the same level of dexterity as a human hand that is not restricted by pressurized gloves is more difficult. This capability is likely to be fully realized only under teleoperation, which requires high-bandwidth and low-latency communication between the human and the robot. To achieve autonomous assembly and maintenance in space, careful systems engineering will be necessary to ensure the compatibility of the robots and the facility being constructed. Automated inspection, on the other hand, seems well within near-term robotic capability, and safety assurance is the only barrier to broader use.

Figure 2: Robotic arm [12]

2 Specific functionalities

In this section will be discussed different types of specific functionalities of robots in space.

2.1 Science Planning and Perception

Currently, autonomous rover planners are used in terrestrial systems for maintaining prioritized lists of science goals with multiple constraints between them, enabling fully autonomous operations for short durations (hours) in relatively simple environments. However, over the next ten years, we expect to see significant improvements in the robustness of these systems, allowing fully autonomous operations for up to a day in desert-like environments. Additionally, there will likely be advancements in the ability of these systems to seek patterns and anomalies, generate discovery plans, and collect interesting scientific data with dramatically reduced operational effort. Despite these advancements, achieving performance at the level of a human scientist in the field remains a challenge. Unless there are significant breakthroughs, the best autonomous systems will still only perform well within narrowly defined areas of expertise, lacking the general cognitive and perceptual abilities of a human field scientist.

2.2 Surface Instrument Deployment

The current flight systems for planetary rovers, such as Sojourner and MER, use supervised autonomy to approach rocks and place instruments on their surface. While these systems require multiple cycles to approach a single rock, there are no fundamental obstacles to developing highly autonomous sample approach and instrument placement capabilities that would allow a rover to autonomously track and navigate to multiple rocks 10 meters away, and place instruments in contact with them within a few centimeters of the requested point. In recent years, terrestrial robots have made significant progress in autonomous instrument placement against nearby large rock targets. In the next ten years, these systems are expected to demonstrate sufficient robustness for deployment on missions. However, dealing with more complex situations such as extreme terrain, occlusions, and operations in highly confined areas will require intense effort. Developing coordinated sensor and manipulator systems that can intelligently and robustly interact with objects in an outdoor environment, beyond simple manipulation and sensor placement, is at least a decade away. Qualifying such systems for use in space will present significant difficulties beyond the usual obstacles to space qualification. It will be challenging to characterize autonomous systems with complex behaviors to ensure that minimal performance criteria are met under all reasonable circumstances.

2.3 Surface Mobility

The achievement of safe and effective navigation in an environment is a complex task that requires the interaction of various robotic capabilities. As the degree of autonomy increases, the complexity of the task also increases significantly. With limited autonomy, robots have been able to accomplish tasks such as localizing in the environment, navigating while avoiding obstacles, and collecting scientific information. To achieve longer durations and distances and greater science returns, enhanced robotic capabilities and increased autonomy are needed. These capabilities include monitoring system state and health, reactively planning complex operations, acting efficiently, building maps, and conducting science data collection. Mechanical capabilities, energy, and thermal issues are also important. In the next years, planning capabilities, obstacle avoidance, and visual servoing are expected to improve significantly. Automatic mapping is also expected to improve, enabling high-resolution map fusion and more global map creation. Simultaneous localization and mapping is well understood in theory, but intense development is required to make it reliable in practice. Autonomous exploration is expected to reach basic levels of competence in the next decade, with the ability to collect anomalous data opportunistically. However, breakthroughs in fundamental problems are required for competencies such as mechanism stability and self-repair and self-recovery. In terms of overall rover performance, reliable systems capable of traveling hundreds of meters per command cycle are expected in the next decade. Breakthroughs in autonomy are needed for multi-year missions, and extreme terrains such as cliff faces still present challenges. Teleoperation with high-bandwidth and low-latency is mature, and nominal development over the next decade will deliver autonomous execution of human prescribed plans. Truly independent rovers are still a decade or more away.

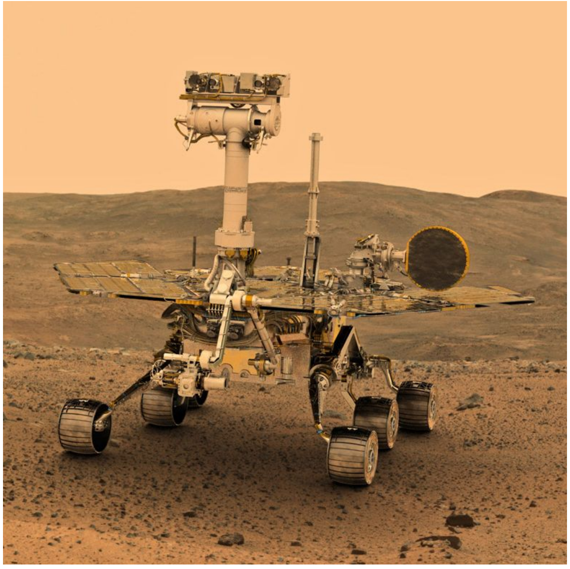

Figure 3: Opportunity rover [13]

2.4 Surface and In-Space Human Assistance

Through field tests with astronauts, the Robotic Assistant has demonstrated its ability to carry tools, follow humans, and assist in the deployment of equipment such as solar panels and cables. The Space Shuttle and ISS remote manipulators have also been used to move crewmembers and components. In the coming years, it is expected that robots will be able to work in close proximity to crewmembers with safety considerations dictating the level of physical interaction. With continued development, these robots may become increasingly integrated with natural language and gesture interfaces, approaching the level of limited teammates.

2.5 In-Space Maintenance

The remote manipulator systems of the space shuttle and station are capable of moving large objects, but they lack the ability to perform complex maintenance tasks. In-space experiments, including ROTEX and ETS-VII, have been conducted to demonstrate teleoperated robots performing maintenance tasks. However, within the next decade, we can expect the development of more dexterous robots, such as the Space Dexterous Robotic Manipulator (SPDM), which will be able to perform routine maintenance tasks under teleoperation. Through intense effort, these robots may eventually be able to autonomously access and replace obstructed components, but significant breakthroughs are required to achieve autonomous diagnosis and repair of arbitrary faults that even astronauts are currently unable to accomplish in space.

2.6 In-Space Assembly

Example of robots capable of in-space assembly are the Space Shuttle and ISS remote manipulator systems (RMS), which can move and mate large components under human supervision. However, ground testbeds have shown that robots can autonomously transport and mate large components, and perform fine assembly tasks such as mating connectors. In the next years, robots are expected to gain the ability to perform delicate assembly tasks autonomously, approaching the dexterity of a space-suited human. However, complex robotic assembly with little or no human supervision will require breakthrough technologies. Even with intense effort, robotic assembly of complicated structures in space will still require some degree of human supervision and guidance, including occasional teleoperation from space or ground-based humans.

3 Common Challenges

The assessment of space robotics uncovered recurring themes identified by the participants, which can be classified into categories such as whole-system design, mission capability, robustness, and virtual presence.

3.1 Virtual Presence

The ultimate aim of space robotics is to enable human cognitive interaction with space environments without the need for physical presence. This could allow for activities like planetary exploration and space assembly to be performed remotely, with operators sitting comfortably in a lab or control room. While some technologies needed for this goal are not solely dependent on robotics, replicating the dexterity and sensing capabilities of a human are critical challenges that require significant advancements in robotics. Although the development of high-bandwidth, low-latency communication could aid in achieving virtual presence.

3.2 Mission Competence

The involvement of humans in space exploration is indispensable. While robots can gather data and perform tasks, they still require human direction and supervision. The challenge is to transition humans from controlling the robot's every move to focusing on mission objectives and scientific strategies, while still maintaining the ability to take direct control when needed. Robots are limited to completing basic goals, such as reaching a specific location or manipulating an object in a certain way. In the future, robots must be able to process complex mission objectives, such as exploring a particular area and reporting any significant findings or assembling complex structures. This will require significant advancements in robot cognitive abilities, including planning, diagnosis, and adaptation. Robots must be capable of interpreting ambiguous instructions based on an understanding of both the task and human intentions in order to be truly mission competent.

3.3 Whole-system Design

The success and reliability of any robotic mission heavily rely on whole system design. Robots cannot work alone and are ineffective if added to a system not originally designed for them. Expecting adequate performance from a robot in a situation crafted for humans is unrealistic. Therefore, when designing a mission, it is important to consider the entire system, including the robot, supporting infrastructure (such as power, communications, navigation, and maintenance), and the human component. These considerations are far more critical to the success of robotics than any robot-specific technology, such as mobility, dexterity, or intelligence. System engineering that accounts for all these factors can greatly enhance the reliability and robustness of robot operations. For instance, for in-space operations, it may require designing specialized components and attachment mechanisms, while for surface operations, it might entail centralized power generation or a GPS-like infrastructure.

3.4 Robustness

The ability of a system to function despite faults or unexpected circumstances is known as robustness. However, this is a major challenge in robotics since robots may interact in ways that cannot be verified and validated using conventional methods. Currently, robots are not as adaptable as humans and their systems are often prone to brittleness. Achieving robustness in robots that can diagnose and recover from faults and operate efficiently in harsh environments is a major challenge for the coming decade. Robustness can also be achieved by incorporating human intelligence and flexibility when needed. However, since there is a lack of experimental data on the interactions between robots and their environment, validation and characterization are difficult to accomplish. Therefore, extensive experimentation is needed to validate and characterize these interactions and achieve robustness in robotic systems.

4 Conclusions

To summarize, the assessment of space robotics has identified several scenarios where robots can be effectively used, such as dexterous assembly, human-robot collaboration, planetary surface access, and comprehensive surface investigation. In order to achieve success in these scenarios, research and investment in infrastructure and experimentation are necessary to advance the state of the art. Although few fundamental breakthroughs are required, sustained effort focused on developing methodologies and gaining experience in the use of robots in space exploration is crucial. By doing so, robotic systems can be made more capable and effective, and the boundaries of exploration can be pushed further. The potential of space robotics is promising, but it requires investment and effort to achieve the desired outcomes.

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