Robotics for Space Exploration: From Mars Rovers to Lunar Missions

1st Babar Hussain University of Electronic Science and Technology China Email: bhussain.cs@gmail.com

2nd Guo Jiandong University of Electronic Science and Technology China Email: jdguo@uestc.edu.cn

3rd Sidra Fareed University of Electronic Science and Technology China Email: sidramalikk124@gmail.com

4th Subhan Uddin University of Electronic Science and Technology China Email: subhanuddinkhan@gmail.com

Abstract

Robotics has become an indispensable element in the exploration of ex- traterrestrial environments, enabling scientific discoveries in domains that are otherwise inaccessible or hazardous to human presence. This survey paper provides a comprehensive overview of the development, deployment, and future direction of robotic systems specifically designed for space ex- ploration, with a focus on missions to Mars and the Moon. Beginning with a historical perspective, the paper explores early robotic missions that laid the foundation for current technologies. It then highlights the technical advancements and scientific achievements of iconic Mars rovers such as Spirit, Opportunity, Curiosity, and Perseverance, examining their mobility mechanisms, autonomous navigation systems, power sources, and onboard scientific instruments. Parallel to Martian exploration, the pa- per discusses lunar robotics, including legacy missions like Lunokhod and Apollo Lunar Rovers, as well as emerging robotic platforms planned un- der NASA's Artemis program and VIPER rover mission aimed at lunar surface exploration and resource prospecting.

The survey further investigates key innovations in space robotics in- cluding autonomous decision-making, advanced locomotion systems adapted to extreme terrains, communication strategies under signal delays, and energy efficiency in harsh environments. It also addresses the major chal- lenges faced in designing robots for space missions, such as radiation ex- posure, mechanical reliability, and communication latency. Finally, the paper explores future trends in robotic space exploration, including the integration of robotic systems in long-duration human missions, in-situ resource utilization (ISRU), and robotic construction of extraterrestrial habitats.

By synthesizing past, present, and emerging trends, this paper aims to serve as a detailed resource for understanding the critical role of robotics in advancing humanity's reach beyond Earth. The insights gained from this survey will aid future research and mission planning by identifying technological gaps and highlighting successful robotic design strategies for upcoming planetary exploration initiatives.

1 Introduction

Space exploration has always posed immense challenges due to the harsh, re- mote, and unpredictable environments beyond Earth's atmosphere. In response, robotics has emerged as a critical enabler of extraterrestrial missions, allowing scientists to extend their reach to distant planetary bodies while overcoming limitations in human spaceflight, such as cost, safety, and physical endurance. Robotic systems offer the ability to operate autonomously or semi-autonomously in extreme conditions, perform complex scientific tasks, and relay invaluable data back to Earth, making them indispensable tools in the ongoing quest to explore the cosmos.

Over the past few decades, robotic missions have significantly contributed to our understanding of the Moon, Mars, and other celestial bodies. From the Soviet Union's Lunokhod lunar rovers to NASA's highly sophisticated Mars rovers such as Curiosity and Perseverance, each generation of robotic explorers has advanced in terms of mobility, intelligence, endurance, and scientific capa- bility. These robots are not only designed to navigate rugged and unknown terrain, but also to perform precise measurements, collect and analyze sam- ples, and support long-term scientific observation under extreme environmental conditions.

This survey paper aims to present a comprehensive overview of the develop- ment and deployment of robotic systems in space exploration, with a particular emphasis on Mars and lunar missions. It explores the historical evolution of robotic platforms, the core technologies that drive their performance, and the significant scientific outcomes achieved through their deployment. Furthermore, it highlights ongoing technological innovations and the future role of robots in supporting human exploration, in-situ resource utilization, and sustainable pres- ence on other planets.

By reviewing both the successes and challenges encountered in past and present missions, this paper provides valuable insights into the current state and future potential of space robotics. It serves as a foundational reference for researchers, engineers, and mission planners working toward the next generation of robotic explorers.

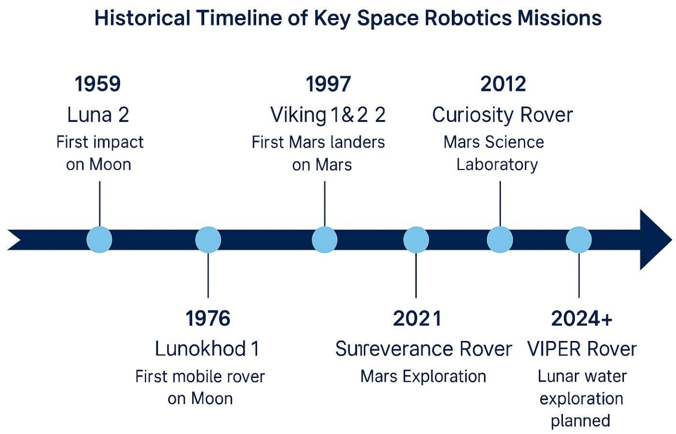

Figure 1: Historical Timeline of Key Space Robotics Missions

2 Historical Background of Robotics in Space

The integration of robotics into space exploration represents one of the most transformative advancements in human history. From the earliest missions to contemporary endeavors, robotic systems have played a pivotal role in extending the frontiers of scientific discovery beyond Earth. Understanding the historical progression of robotics in space provides critical insights into how technolog- ical innovations have evolved to meet the unique demands of extraterrestrial environments.

2.1 Early Robotic Space Missions

The first successful use of robotics in space exploration dates back to the 1960s, during the height of the space race between the United States and the Soviet Union. The Soviet Luna program marked a significant milestone with Luna 2 becoming the first human-made object to impact the Moon in 1959, followed by Luna 9, which achieved the first successful soft landing on the lunar sur- face in 1966. These missions, while limited in autonomy, laid the groundwork for robotic exploration by demonstrating the feasibility of remotely operated systems on other celestial bodies.

One of the most notable achievements of early space robotics was the Lunokhod program by the Soviet Union. Lunokhod 1, deployed in 1970, was the first re- motely controlled rover to traverse the lunar surface. Equipped with cameras, scientific instruments, and powered by solar panels, Lunokhod 1 operated for 11 months, providing critical data on lunar soil properties and environmental conditions. Its success proved the value of mobility and remote operation in planetary exploration.

Concurrently, the United States developed the Surveyor program (1966– 1968), which involved a series of robotic spacecraft designed to perform soft landings on the Moon. These landers collected crucial data on lunar soil me- chanics, which later supported the planning of the Apollo human missions.

2.2 Robotic Missions to Mars

Following the success of lunar robotics, attention shifted toward Mars, a planet of great scientific interest. NASA's Viking 1 and Viking 2 missions, launched in 1975, were landmark achievements as the first missions to successfully land on Mars and transmit images and scientific data back to Earth. Although the Viking landers were stationary, they introduced more sophisticated scientific instrumentation and advanced autonomy in robotic space systems.

The concept of mobility was reintroduced with the Mars Pathfinder mission in 1997, which carried the small rover Sojourner. Weighing only 11.5 kilograms, Sojourner demonstrated the feasibility of semi-autonomous rover operations on the Martian surface, using hazard avoidance systems and remote-controlled nav- igation. Its successful mission opened new possibilities for future mobile robotic exploration.

2.3 Evolution of Robotic Technologies

From the early landers and rovers to modern sophisticated systems, robotic technologies have undergone dramatic evolution. Advances in miniaturization of electronics, development of lightweight and durable materials, improvement in communication systems, and the introduction of semi-autonomous and au- tonomous control mechanisms have all contributed to the enhanced capabilities of space robots.

The increasing complexity of mission objectives from simple terrain imaging to complex geological sampling and atmospheric analysis demanded innovations in robotic mobility, navigation, power management, and artificial intelligence. These advances have been pivotal in enabling more ambitious missions, such as the long-term operation of rovers on Mars and future plans for lunar robotic exploration supporting human return missions.

3 Mars Exploration Rovers

Mars has been one of the prime targets for robotic exploration, given its po- tential for past or present life, its similarity to Earth in many respects, and its potential as a future site for human habitation. Robotic rovers have revolu- tionized Mars exploration by providing mobility, flexibility, and the ability to conduct complex scientific investigations across diverse terrains. This section provides a detailed review of the key Mars exploration rovers that have shaped our understanding of the Red Planet.

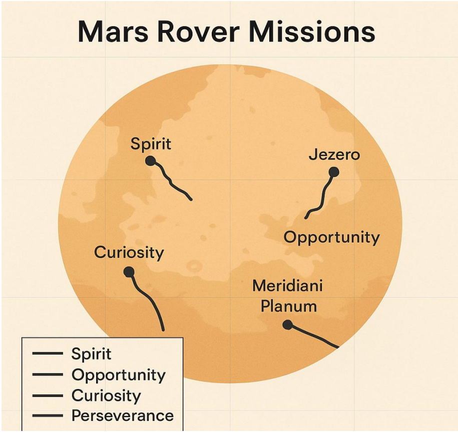

Figure 2: Mars Rover Missions Map (Landing Sites and Routes)

3.1 Spirit and Opportunity Rovers (Mars Exploration Rovers– MER)

Launched in 2003 as part of NASA's Mars Exploration Rover program, Spirit (MER-A) and Opportunity (MER-B) were twin robotic rovers designed to study the Martian surface and search for evidence of past water activity. They landed on Mars in January 2004, with Spirit arriving in Gusev Crater and Opportunity in Meridiani Planum.

Both rovers were equipped with an array of scientific instruments, including panoramic cameras, microscopic imagers, Mössbauer and alpha particle X-ray spectrometers, and rock abrasion tools. Their primary mission objectives were to:

- Search for and characterize a wide range of rocks and soils for clues to past water activity.
- Determine the distribution and composition of minerals, rocks, and soils.
- Validate environmental conditions to assess whether they were ever con- ducive to life.

Spirit operated successfully until 2010, far exceeding its original 90-sol (Mar- tian day) mission. It covered a distance of approximately 7.7 kilometers, dis- covering evidence of ancient hot springs and past volcanic activity.

Opportunity, often described as one of the most successful Mars missions, operated for nearly 15 years until June 2018. It traveled over 45 kilometers, uncovering compelling evidence that liquid water once existed on Mars' sur- face. One of its most significant discoveries was the identification of hematite "blueberries," small spherical mineral formations that form in the presence of water.

3.2 Curiosity Rover (Mars Science Laboratory - MSL)

Launched in November 2011 and landing in August 2012, **Curiosity** represents a major advancement in Mars rover technology. Curiosity is about the size of a small car, weighing approximately 900 kilograms, and was designed to explore Gale Crater and study the planet's climate and geology.

Key features of Curiosity include:

• **Power System**: Unlike previous solar-powered rovers, Curiosity uses a radioisotope thermoelectric generator (RTG), providing a reliable power source and allowing operations during dust storms and nighttime.

• **Scientific Payload**: It carries the most sophisticated suite of instruments ever sent to Mars, including the Sample Analysis at Mars (SAM) labora- tory, the Chemistry and Mineralogy (CheMin) instrument, high-resolution cameras, and a robotic arm equipped with a drill.

• **Mission Goals**: Curiosity's primary mission is to determine whether Mars ever had conditions suitable for microbial life, study the climate and geology of Mars, and prepare for future human exploration.

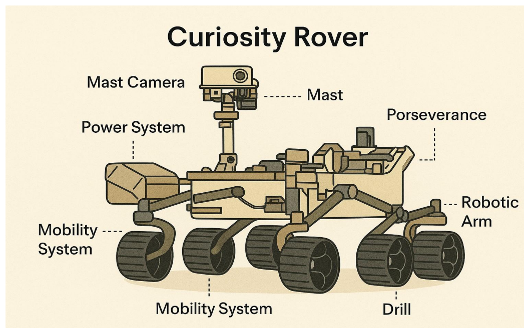

Figure 3: Diagram showing Curiosity Rover's main systems

3.3 Perseverance Rover (Mars 2020 Mission)

Building on Curiosity's success, NASA launched the **Perseverance** rover in July 2020, which landed in Jezero Crater in February 2021. Perseverance is tasked with searching for signs of ancient microbial life and collecting samples for possible future return to Earth.

Distinctive innovations in Perseverance include:

• **Sample Caching System**: Perseverance is the first rover designed to collect and store Martian rock and soil samples in sealed tubes.

• **MOXIE (Mars Oxygen In-Situ Resource Utilization Experiment)**: A technology demonstration aimed at producing oxygen from the Martian atmosphere.

• **Helicopter Scout (Ingenuity)**: Perseverance carried a small drone he- licopter, Ingenuity, which successfully completed the first powered flight on another planet.

• **Enhanced Autonomy**: Perseverance features improved autonomous nav- igation capabilities, allowing it to travel greater distances and make more complex decisions without direct input from Earth.

Perseverance's exploration of the ancient river delta within Jezero Crater provides critical insights into Mars' hydrological past and its potential for life.

3.4 Comparative Analysis of Mars Rovers

Table 1: Comparative Analysis of Mars Rovers

Feature	Spirit/Opportunity	Curiosity	Perseverance
Landing Year	2004	2012	2021
Power Source	Solar Panels	RTG	RTG
Main Mission	Water evidence search	Habitability study	Life detection and sample collection
Mobility Range	˜45 km (Opportunity)	˜30 km (ongoing)	˜20+ km (ongoing)
Key Innovation	Twin long-duration rovers	Mobile laboratory	Sample caching and aerial scouting

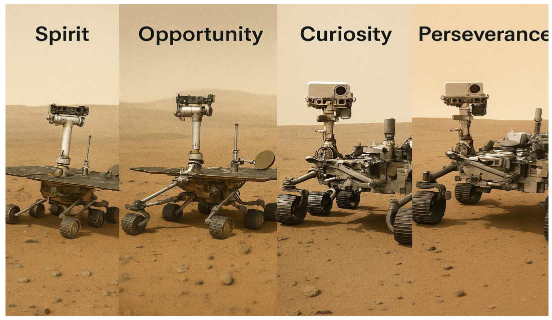

Figure 4: Side-by-side images of Spirit, Opportunity, Curiosity, and Persever- ance

4 Lunar Robotics: Pioneering Exploration Be- yond Earth

The Moon, Earth's closest celestial neighbor, has long served as a proving ground for robotic space exploration. Lunar robotics has evolved from early sample-return missions to complex autonomous systems capable of conducting extended scientific investigations. As preparations for sustained human pres- ence on the Moon progress, robotic systems continue to play an indispensable role in advancing technological capabilities, performing scientific research, and supporting future manned missions.

4.1 Early Robotic Lunar Missions

The history of lunar robotics began during the Cold War-era space race, with the Soviet Union and the United States leading pioneering efforts. The Soviet Luna program (1959–1976) was the first to successfully deliver robotic probes to the lunar surface. Luna 2 was the first human-made object to impact the Moon, while Luna 9 achieved the first successful soft landing in 1966, transmitting panoramic images back to Earth.

In parallel, NASA's Surveyor program (1966–1968) conducted a series of landings to characterize the lunar surface, assess landing conditions, and support the Apollo program. These missions tested critical technologies such as soft-landing propulsion, remote control operations, and soil sampling, laying the groundwork for human exploration.

4.2 Lunokhod Rovers: The First Mobile Robots on An- other World

One of the most significant achievements in lunar robotics was the deployment of the Lunokhod rovers by the Soviet Union.

• **Lunokhod 1** (1970) and **Lunokhod 2** (1973) were remotely operated vehicles designed to traverse the lunar surface, analyze soil properties, and conduct environmental measurements.

• Each rover was equipped with solar panels, chemical analyzers, panoramic cameras, and spectrometers.

• Lunokhod 1 traveled over 10 kilometers during its mission, while Lunokhod 2 set a long-standing record of 39 kilometers driven on another celestial body.

These missions demonstrated the feasibility of remote surface mobility, nav- igation, and sample analysis without direct human presence—an essential capa- bility for future planetary exploration.

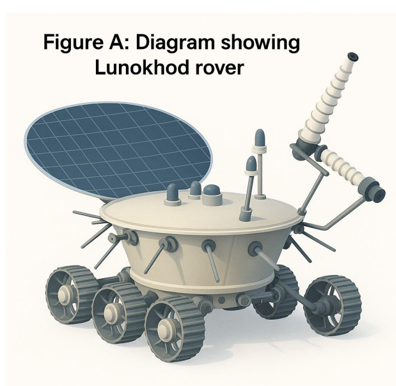

Figure 5: A diagram showing Lunokhod rover

4.3 Modern Lunar Robotic Missions

The 21st century has witnessed a renewed interest in lunar exploration, driven by international collaboration and advancements in autonomous robotics.

Notable modern missions include:

4.3.1 China's Chang'e program

• Chang'e 3 (2013) successfully deployed the **Yutu (Jade Rabbit)** rover, which operated for over two years despite initial technical setbacks.

• Chang'e 4 (2019) achieved the first soft landing on the far side of the Moon, deploying the **Yutu-2** rover, equipped with ground-penetrating radar and spectrometers.

4.3.2 NASA's Artemis program

As part of its **Artemis** initiative, NASA has developed robotic precursors like the **Volatiles Investigating Polar Exploration Rover (VIPER)**, scheduled for deployment at the lunar south pole to search for water ice resources.

4.3.3 International contributions

• Japan's **SLIM** mission (Smart Lander for Investigating Moon) aims to demonstrate precision landing technologies.

• India's **Chandrayaan-3** mission successfully landed a rover near the Moon's south pole in 2023, making India the fourth nation to achieve a lunar land- ing.

These missions mark a new era of lunar robotics, emphasizing resource prospecting, long-term durability, and scientific exploration in preparation for sustained human activities.

4.4 Technological Advances in Lunar Robotics

Modern lunar robots integrate advanced technologies to operate in the harsh lunar environment:

• **Autonomous Navigation**:

– Rovers now incorporate artificial vision, path-planning algorithms, and hazard avoidance systems to traverse uneven and unpredictable terrain.

• **Energy Management**:

– Robots employ enhanced solar power systems, radioisotope thermo- electric generators (RTGs), and advanced battery storage to survive prolonged lunar nights (up to 14 Earth days).

• **Thermal Regulation**:

– Specialized materials and internal heating systems protect delicate instruments from extreme temperature fluctuations, ranging from

+127°C in sunlight to -173°C at night.

• **Scientific Instrumentation**:

– High-resolution cameras, spectrometers, neutron detectors, and drilling equipment enable sophisticated geophysical, chemical, and environ- mental studies.

5 Robotics for Future Space Missions

As space exploration advances toward more ambitious goals, robotics is posi- tioned as a critical enabler. Future missions envision robots as autonomous pioneers, tasked with preparing environments for human exploration and con- ducting complex scientific operations.

5.1 Robotic Missions to Mars: Preparing for Human Ar- rival

Robotic systems will pave the way for human missions to Mars:

• **Mars Sample Return Mission**: NASA and ESA aim to retrieve Mar- tian samples through a series of coordinated robotic efforts, including a Sample Retrieval Lander, a Fetch Rover, and a Mars Ascent Vehicle.

• **Robotic Construction**: Autonomous robots will build habitats, landing pads, and infrastructure using 3D printing technologies with local mate- rials like Martian regolith.

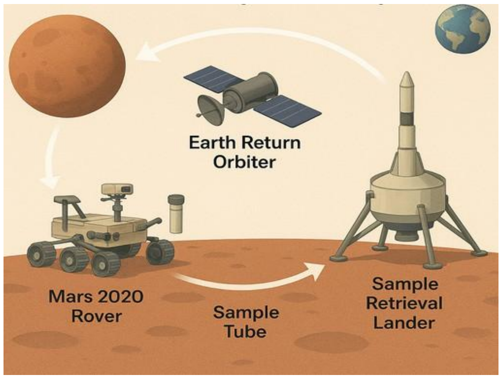

Figure 6: A simple conceptual image of Mars Sample Return plan

5.2 Lunar Gateway and Deep Space Robotic Operations

The **Lunar Gateway** will utilize advanced robotic systems:

• **Canadarm3**: A highly autonomous robotic arm for module inspection and repair.

• **Autonomous Logistics**: Cargo delivery and unloading handled by au- tonomous systems, validating key technologies for future Mars missions.

5.3 Asteroid Exploration Robots

Robots are expanding exploration beyond planets:

• **OSIRIS-REx**: Used a robotic arm to collect asteroid samples from Bennu.

• **Hayabusa2**: Deployed small landers across asteroid Ryugu to gather material.

Future robotic missions may focus on asteroid mining and planetary defense.

5.4 Technologies Shaping Future Space Robotics

Key innovations include:

• **Advanced Autonomy**: Self-guided navigation and decision-making ca- pabilities.

• **Modular and Reconfigurable Robots**: Adaptable systems that can adjust to mission needs.

• **Swarm Robotics**: Teams of small robots working collaboratively.

• **Human-Robot Collaboration**: Robots assisting astronauts with tasks like construction and science operations.

5.5 Challenges Ahead

Critical challenges remain:

• **Harsh Environments**: Surviving radiation, dust, and extreme temper- atures.

• **Communication Delays**: Demanding highly autonomous systems.

• **Energy Management**: Sustaining reliable power during extended mis- sions.

6 Challenges and Limitations in Space Robotics

Space robotics faces numerous challenges that significantly impact mission suc- cess. Robots must endure extreme environmental conditions, including drastic temperature swings, intense radiation, abrasive lunar and Martian dust, and rough, low-gravity terrains that accelerate system wear and tear. Communi- cation delays, especially for missions to Mars, require robots to operate au- tonomously with limited real-time guidance, while restricted bandwidth further complicates data transmission. Energy management remains critical, with solar power limitations and the complexity of alternative systems like RTGs affect- ing mission longevity. Mechanical reliability demands highly durable designs, but redundancy increases mass and cost. As missions move farther from Earth, robotic systems must adapt independently to unpredictable conditions, making autonomous decision-making essential. Finally, high development and launch costs, combined with mission risks, impose strict constraints on design, reliabil- ity, and operational planning for future space exploration.

7 Technological Innovations in Space Robotics

Technological innovations have greatly expanded the capabilities of space robotics, making it possible to explore more distant and challenging environments than ever before. Advances in mobility systems, such as rocker-bogie suspension de- signs and adaptive wheels, have enabled rovers to traverse rocky, uneven, and hazardous terrains with increased stability and durability. Robotic arms have become more sophisticated, featuring high degrees of freedom, force feedback, and tool-changing mechanisms that allow for precise scientific sampling, drilling, and equipment deployment. Progress in autonomy and onboard intelligence has empowered robots to navigate independently, detect faults, and adapt mission plans dynamically without requiring constant human supervision, which is crit- ical given the long communication delays in space. Miniaturization technolo- gies have led to the development of small robots like CubeSats, nano-rovers, and swarm systems, allowing cost-effective and flexible exploration strategies that can cover larger areas and perform distributed experiments. Energy sys- tems have also seen major improvements, with the development of lighter, dust-resistant solar panels, more efficient radioisotope thermoelectric genera- tors (RTGs), and experimental energy-harvesting methods to extend mission lifespans. Furthermore, advances in communication and onboard data process- ing have allowed space robots to transmit larger volumes of scientific data back to Earth more efficiently while making real-time assessments and prioritizing in- formation independently. Together, these technological breakthroughs are not only enhancing the success of current missions but are also laying the foundation for future exploration of the Moon, Mars, asteroids, and beyond.

8 Future Prospects and Missions in Space Robotics

Space robotics is at a turning point, with new missions and technologies set to transform exploration. As humanity targets Mars, asteroids, and deep space, robots will be key to success.

8.1 Upcoming Mars Missions

- **Mars Sample Return** (NASA & ESA): A multi-mission effort to collect and return Mars samples to Earth, involving complex robotic coordina- tion.

- **Mars Ice Mapper**: A joint project to map water ice deposits, vital for future human missions.

8.2 Lunar Exploration Initiatives

- **Artemis Program & Lunar Gateway** (NASA): Robots will help build the Lunar Gateway and support a sustainable lunar presence.

- **VIPER Rover** (NASA): Launching in 2025 to search for water ice at the Moon’s south pole.

- **European and Chinese Missions**: ESA and China are advancing lunar robotics for exploration and resource use.

8.3 Robotic Exploration of Asteroids and Outer Planets

- **Psyche Mission** (NASA): Studying a metal-rich asteroid with autonomous systems.

- **JUICE** (ESA): Exploring Jupiter’s icy moons with advanced robotic tools.

- **DART** (NASA): Successfully tested asteroid deflection using autonomous targeting.

8.4 Technological Frontiers in Space Robotics

- **In-Situ Resource Utilization (ISRU)**: Robots extracting local re- sources for survival.

- **Self-Replicating/Repairing Robots**: Researching robots that can main- tain themselves using space materials.

- **AI and Machine Learning**: Enhancing robot autonomy and adaptabil- ity.

- **Soft Robotics**: Flexible robots for extreme terrains like caves and lava tubes.

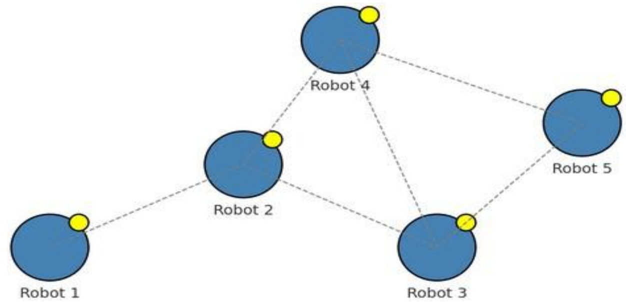

Figure 7: Swarm robotics concept

8.5 Human-Robot Collaboration in Space

Robots will prepare sites, assist astronauts, perform hazardous tasks, and enable telepresence operations, making space exploration safer and more efficient.

9 Conclusion

The field of space exploration has been profoundly transformed by the evolution of robotics, from the earliest lunar rovers to today's sophisticated Martian ex- plorers and orbital robotic systems. Throughout this survey, we have explored how robotic platforms have expanded humanity's reach beyond Earth, enabling critical scientific discoveries, technological advancements, and preparation for future human presence on other celestial bodies.

Robots such as the Mars Rovers Spirit, Opportunity, Curiosity, and Per- severance—have demonstrated exceptional capabilities in surface exploration, autonomous navigation, and scientific experimentation under challenging ex- traterrestrial conditions. Similarly, early lunar rovers like Lunokhod and Apollo Lunar Roving Vehicles pioneered the way for mobile surface operations, offering vital experience that informs current and future designs.

The increasing sophistication of robotic autonomy is reshaping mission strate- gies. Autonomous decision-making, onboard scientific analysis, and real-time hazard avoidance are no longer experimental but are mission-critical features, enabling robots to operate efficiently despite communication delays and environ- mental unpredictability. Robotic technology continues to evolve with emerging trends like swarm robotics, human-robot collaboration, and in-situ resource uti- lization (ISRU), promising to revolutionize the way future missions are designed and executed.

As we look to the future, robotics will play an indispensable role in human- ity's ambitious goals: establishing a sustainable presence on the Moon, initiating crewed missions to Mars, and exploring the outer planets and their moons. The development of lighter, more resilient, and more intelligent robotic systems will be crucial for overcoming the unique challenges of deep-space missions.

Nevertheless, significant challenges remain. The need for higher reliability, energy efficiency, and robust autonomous operations continues to drive research and innovation. Ethical considerations, particularly regarding planetary pro- tection and autonomous decision-making, must be thoughtfully addressed as robotic systems gain greater independence.

In conclusion, robotics stands at the forefront of space exploration, bridging the gap between human aspiration and technological capability. As we enter a new era of exploration, robots will not only serve as our scouts and scientists but also as essential partners in the quest to unlock the mysteries of the solar system and beyond. The continued advancement of robotics will be key to transforming science fiction visions into reality, expanding the horizon of human achievement into the vast expanse of space.

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