SPACE ROBOTS

Review on space robotics: Toward top-level science through space exploration

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Robotics and autonomous systems have been instrumental to space exploration by enabling scientific breakthroughs and by fulfilling human curiosity and ambition to conquer new worlds. We provide an overview of space robotics as a rapidly emerging field, covering basic concepts, definitions, historical context, and evolution. We further present a technical road map of the field for the coming decades, taking into account major challenges and priorities recognized by the international space community. Space robotics represents several key enablers to a wide range of future robotic and crewed space missions as well as opportunities for knowledge and technology transfer to many terrestrial sectors. In the greater humanitarian context, space robotics inspires both current and future generations to exploration and critical study of science, technology, engineering, and mathematics.

INTRODUCTION

Space exploration of our solar system and distant galaxies in the furthest reaches of the universe is important to top-level science and to answer many fundamental scientific questions, including the formation of the universe, the origin of Earth, the evolution of life, and the existence of life beyond Earth. Space robotics plays a critical role in current and future space exploration missions and enables mission-defined machines that are capable of surviving in the space environment and performing exploration, assembly, construction, maintenance, or service tasks. Modern space robotics represents a multidisciplinary emerging field that builds on and contributes to space engineering, terrestrial robotics, and computer science, as well as related specialties such as materials and mechanisms (*1*).

Robotics improves humanity's ability to explore and to operate by providing access beyond human limitations in the harsh environment of space and supporting operations that extend astronauts' capabilities. Autonomous systems are capable of reducing the cognitive load on humans given the abundance of information that has to be reasoned in a timely fashion and are critical for improving human and system safety. Robotics can also enable the deployment and operation of multiple assets without the same order-of-magnitude increase in ground support. Given the potential reduction in cost and the risk of spaceflight, both crewed and robotic, space robotics and autonomous systems are deemed relevant across all mission phases, such as development, flight system production, launch, and operation.

Space robotics covers all types of robotics for the exploration of a planet surface, as well as those used in orbit around the bodies, and the sensors needed by the platform for navigation or control. Orbital robots can be envisaged for repairing satellites, assembling large space telescopes, capturing and returning asteroids, deploying assets for scientific investigations, etc. Planetary robots play a key role in surveying, observation, extraction, and close examination of extraterrestrial surfaces (including natural phenomena, terrain composition, and resources); constructing infrastructure on a planetary surface for subsequent human arrival; mining planetary resources; etc.

Two attributes are often deemed essential for a spacecraft to be classified as a space robot, namely, locomotion and autonomy (*2*). Depending on its application (either orbital or planetary), a space robot is designed to have locomotion (or mobility) to manipulate, grip, rove, drill, and/or sample. Driven similarly by the nature of the mission and distance from Earth, the robot is expected to have varying levels of autonomy, ranging from teleoperation by a human to fully autonomous operation by the robots themselves (*3*, *41*). Depending on the level of autonomy, a space robot can act as (i) an agent (or human proxy) in space to perform various tasks using teleoperation up to semi-autonomous operation; (ii) an assistant that can help human astronauts perform tasks quickly and safely, with higher quality and cost efficiency using semi-autonomous to fully autonomous operation; or (iii) an explorer that is capable of exploring unknown territories in space using fully autonomous operation (*4*).

Here, we survey past, current, and planned robotic spacecraft missions as well as describe some developmental work targeting future mission concepts. Because of the breadth and depth of the field, we acknowledge that this cannot be a comprehensive technical survey; it is rather intended to provide the reader with the flavor of this diverse and rapidly evolving field. We acknowledge previous surveys by Yoshida (*5*) in 2009 and Flores-Abad *et al.* (*6*) in 2014 that focus on on-orbit robotic servicing. In addition, for a more technically detailed coverage of space robotics, we refer the reader to (*7*, *8*).

HISTORY AND EVOLUTION OF SPACE ROBOTICS

Past and current space exploration using robots

Outer space has provided real, new exploration frontiers for mankind since the 1950s. With the capability and the irresistible attraction to go beyond our planet Earth, minimizing the impact of mankind on other extraterrestrial bodies (be it a planet, a moon, a comet, or an asteroid) is paramount. The onset of space exploration in the late 1950s to early 1960s focused on sending humans into Earth's orbit and to the Moon as a result of the space race between the Soviet Union and the United States. In parallel to the expensive development of crewed space programs, the use of cheaper robotic proxies was critical to understand the space environment where the astronauts would be operating and to further explore our solar system. Across the existing robotic missions, a range of mobility or locomotion systems has played a substantial role, including the surface rovers, robotic arms or manipulators, subsurface samplers, and drills.

For example, the first genuine robotic locomotion system successfully operated on an extraterrestrial body was a scoop (i.e., a manipulation

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cum sampling device) onboard the Surveyor 3 lander launched in 1967 to the Moon. After that, Luna 16 succeeded with the first planetary robotic arm–mounted drill in 1970, and Luna 17 succeeded with the first planetary rover called Lunokhod 1 in 1970. These "firsts" led to incredible mission successes and science discoveries as a result of unabated and relentless launch attempts during the space race between the superpowers (*4*).

Table 1 summarizes the missions and robots successfully flown on Earth's orbit, the Moon, Mars, and small bodies as of 2017. Within the orbital missions, robotic arms have been the major mechanism for extended mobility. For the planetary case, most existing missions have used either wheeled rovers or stationary landers but equipped with a robotic arm, a drill, or a sampler to achieve mobility. Many of the existing missions, particularly for planetary exploration, have achieved remarkable science; for example, much of what we know about the Moon and Mars has been the direct result of robotic in situ exploration.

National Aeronautics and Space Administration (NASA) has been at the frontier of Mars science through a series of successful planetary rover missions, for example, Mars Pathfinder (MPF), Mars exploration rovers (MERs), and Mars Science Laboratory (MSL) as introduced in Table 2. Instrumentation carried by the NASA Mars rovers has been substantially increasing with time. As a reference point, the MPF rover Sojourner was a relatively small, limited-lifetime mobile robot, yet its key discoveries in geology (i.e., likelihood of previous water on Mars, magnetic properties of Martian dust, and current Mars climate) rewrote our understanding of Mars (*9*). The two identical MERs were much larger and hence could carry a much more capable science payload, including enhanced remote sensing, and a more advanced robotic arm carrying instruments for close-in/surface measurement including the

Table 1. Successfully flown robots on Earth's orbit, the Moon, Mars, and small bodies as of 2016.

Launch year	Mission name	Country	Target	Rover	Arm	Sampler	Drill
1967	Surveyor 3	United States	Moon			x	
1970/1972/1976	Luna 16/20/24	Soviet Union	Moon		x	x	x
1970/1973	Luna 17/21	Soviet Union	Moon	x			
1975	Viking	United States	Mars		x	x	
1981/2001/2008	Canadarm1/2/Dextre	Canada	ISS		x		
1993	Rotex	Germany	Earth's orbit		x		
1996	MPF	United States	Mars	x			
1997	ETS-VII	Japan	Earth's orbit		x		
2003	Hayabusa	Japan	Asteroid			x	
2003	MERs	United States	Mars	x	x	x	
2004	ROKVISS	Germany	ISS		x		
2007	Orbital Express	United States	Earth's orbit		x		
2008	JEMRMS	Japan	ISS		x		
2008	Phoenix	United States	Mars		x	x	
2012	Robonaut	United States	ISS		x		
2011	MSL	United States	Mars	x	x	x	
2013	Chang'E 3	China	Moon	x			
2004 (arrived in 2014)	Rosetta	Europe	Comet		x	x	x
2016	Aolong-1	China	Earth's orbit		x		

Table 2. Growing science capabilities of NASA's Mars robotic missions as exemplified by each generation of Mars rover.

Mars rover	Mass (kg)	Lifetime (sol)	Distance traveled (km) (as of April 2017)	Maximum traverse speed (cm/s)	Science payload mass (kg)	Science results reported
MPF's Sojourner	10	83	0.1	0.6	<1	(*9*)
MER's Opportunity	185	4500*	>44	1	6	(*10–12*)
MSL's Curiosity	899	1667*	>15.98	5	75	(*13*)

*Still in operation as of 2017.

Rock Abrasion Tool, the Microscopic Imager, the Alpha Proton X-Ray Spectrometer, and the Mossbauer Spectrometer. The rovers also had significantly more advanced mobility and navigation capabilities that enabled the Opportunity rover to travel more than 44 km in more than 4700 sols (i.e., Martian days) as of 2017. The MER rovers achieved even more impressive scientific progress in the fields of geology, atmospheric science, and much more (*10*–*12*). The MSL rover Curiosity is the largest among the three rover missions and is more capable, with the help of next-generation instruments, of studying geology, the atmosphere, environmental conditions, and potential biosignatures. From a robotic perspective, Curiosity has a number of instruments that use the robotic arm to take close-in measurements, namely, the Mars Hand Lens Imager, the Alpha Particle X-ray Spectrometer, and sample acquisition analysis (*13*).

Another notable project is the Japanese Hayabusa robotic mission that studied and sampled the near-Earth asteroid Itokawa in 2005 and returned these samples to Earth in 2010. The Hayabusa mission received considerable attention with special issues in *Science* on Itokawa (*14*) and the findings from the returned sample (*15*).

As an alternate data point, the Rosetta mission of the European Space Agency (ESA) made an extremely bold attempt for a controlled landing on a comet nucleus. The Rosetta lander called Philae (Fig. 1) had a number of remote sensing and in situ instruments for compositional/gas analysis (e.g., Cometary Sampling and Composition and Ptolemy), drilling and sample retrieval (i.e., SD2), and surface measurement (i.e., Surface Electrical Sounding and Acoustic Monitoring Experiment). Unfortunately, the lander bounced, and its subsequently canted resting location prevented application of the arm, sampler, and drill and limited Philae's measurements and lifetime. Despite these challenges, Philae made possible numerous scientific achievements, including the discovery of organic molecules on the nucleus of 67P/Churyumov-Gerasimenko (*16*, *17*).

Fig. 1. Artistic depiction of Philae lander at landing (courtesy of ESA).

FUTURE SPACE ROBOTIC MISSIONS

Mid-term planned missions

A list (Table 3) of upcoming robotic missions planned by various international space agencies in the medium term makes evident that what was historically the domain of relatively few nations/organizations now includes a much greater rate of launches and diversity of players. Space-faring nations like China and India are more active in promoting robotic missions, targeting the Moon first as a test-bed. NASA and ESA have their focus on Mars and small bodies and are also advancing space robotics to tackle sample return missions.

Orbital robotic missions

A number of on-orbit applications envisaged for the 2025 to 2035 time frame require advanced robotics capabilities.

Table 3. Medium-term space robotic missions in the pipeline.

Launch year	Mission	Country	Target	Rover	Arm	Sampler	Drill
2017	Chang'E 5	China	Moon	x	x	x	x
2018	Chandrayaan 2	India	Moon	x			
2018 (to arrive)	OSIRIS-REx Sample Return	United States	NEA		x	x	
2018	InSight	United States	Mars		x	x	x
2018	Chang'E 4	China	Moon (farside)	x			
2019	SLIM	Japan	Moon	x	x	x	x
2020	Mars 2020	United States	Mars				
2020	ExoMars 2020	Europe	Mars	x		x	x
2020+	Chinese Space Station	China	Earth's orbit		x		
2025	Phobos sample return	Europe and Russia	Phobos		x	x	

Mission operators may range from space administrations to national governments to businesses. The following mission foci are envisaged: space debris removal, rescue, planned orbit raising, inspection and support to deployment, deployment and assembly aid, repair, refueling and orbit maintenance, mission evolution and adaptation, lifetime extension, and re- and deorbiting. The International Space Station (ISS) continues to represent an excellent opportunity for scientific experiments to be conducted in space, amid the unique characteristics, constraints, and pressures that environment brings. China is also actively developing its own space station program that will be gradually established in the next decade, providing a new space platform for robotic solutions. These orbital robotic missions can directly and indirectly support scientific exploration from Earth's orbit.

Planetary robotic missions

Newly planned planetary missions typically aim to deliver more exciting, ambitious scientific goals, building on the results gained from past missions to the Moon, Mars, and small bodies. In particular, missions planned by NASA and ESA in the medium term will demonstrate advanced science and robotic technologies compared with past missions.

NASA's OSIRIS-REx mission. OSIRIS-REx (Fig. 2) was launched in 2016 and will arrive at the near-Earth carbonaceous asteroid 101955 Bennu in 2018. It will map the target for 500 days and then approach and capture a small sample (<2 kg) to return to Earth in 2023. Its Touch-and-Go Sample Acquisition Mechanism (TAGSAM) uses a sampler head on the end of a robotic arm. When the sample head detects impact, it uses a nitrogen system to acquire a sample. TAGSAM can be used up to three times when attempting to acquire a sample. When the spacecraft returns to Earth in 2023, it will use a Sample Return Capsule (Stardust heritage) with reentry heat shield and parachute to land the sample.

NASA's InSight mission. InSight (Fig. 3) is a Mars lander that is scheduled for launch and landing on the surface of Mars in 2018. InSight uses many of the same concepts as the previous Phoenix lander mission but uses different instruments to study the Martian interior. Its Instrument Deployment Arm and Instrument Deployment Camera will deploy two instruments: (i) the Seismic Experiment for Interior Structure (led by Centre national d'études spatiales, the French national space agency), a seismographic instrument used to study the Martian interior and seismic activity, and (ii) the Heat Flow and Physical Properties Probe (led by Deutsche Zentrum für Luft- und Raumfahrt, the German national space agency), a self-burrowing mole that penetrates up to 5 m below the planetary surface to measure heat escaping from the Martian interior (*18*).

Fig. 2. OSIRIS-REx spacecraft with the TAGSAM robotic sampling arm (courtesy of NASA).

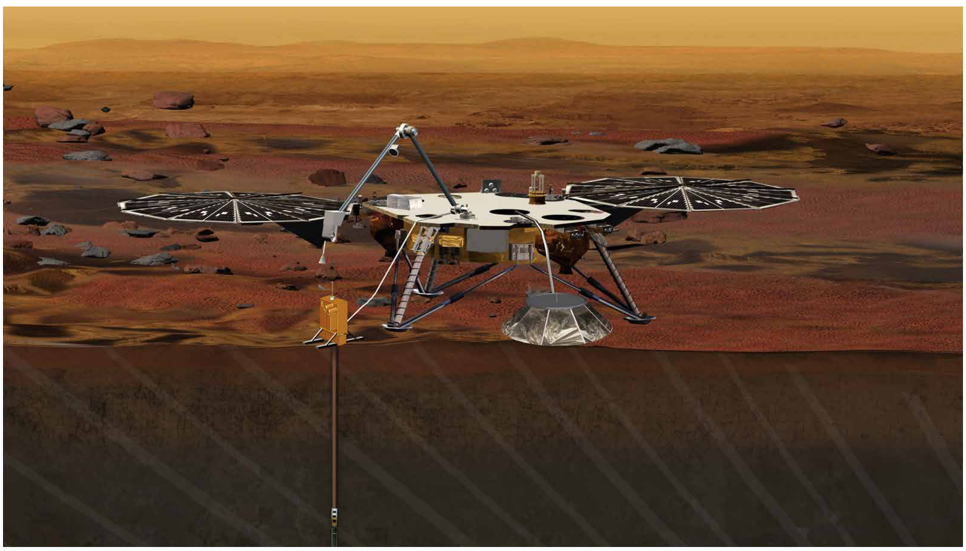


Fig. 3. InSight lander with a robotic instrument deployment arm and a seismic sensor and a heat flow sensor deployed (courtesy of JPL/NASA).

NASA's Mars 2020. The United States' next rover to Mars, Mars 2020, shares considerable heritage with the MSL rover but carries entirely new instruments. The mission will use the Skycrane deployment method (Fig. 4), which uses a rocket-powered hovering carrier to lower the rover to the surface of Mars with a tether. However, the delivery method is enhanced with Terrain Relative Navigation to enable the system to avoid hazardous terrain in selecting a location to lower the rover. Another substantial improvement is that the rover will carry a drill that is capable of coring and caching samples for potential future retrieval to return to Earth. The new rover will also have increased autonomy, including (i) an onboard scheduler to better use available time, energy, and data volume (*19*) and (ii) the ability to autonomously target instruments, such as SUPERCAM, based on scientist-provided criteria, which is an evolution of the AEGIS system currently on MER (*20*) and MSL (*21*).

Fig. 4. Mars 2020 rover being deployed by Skycrane (courtesy of JPL/NASA).

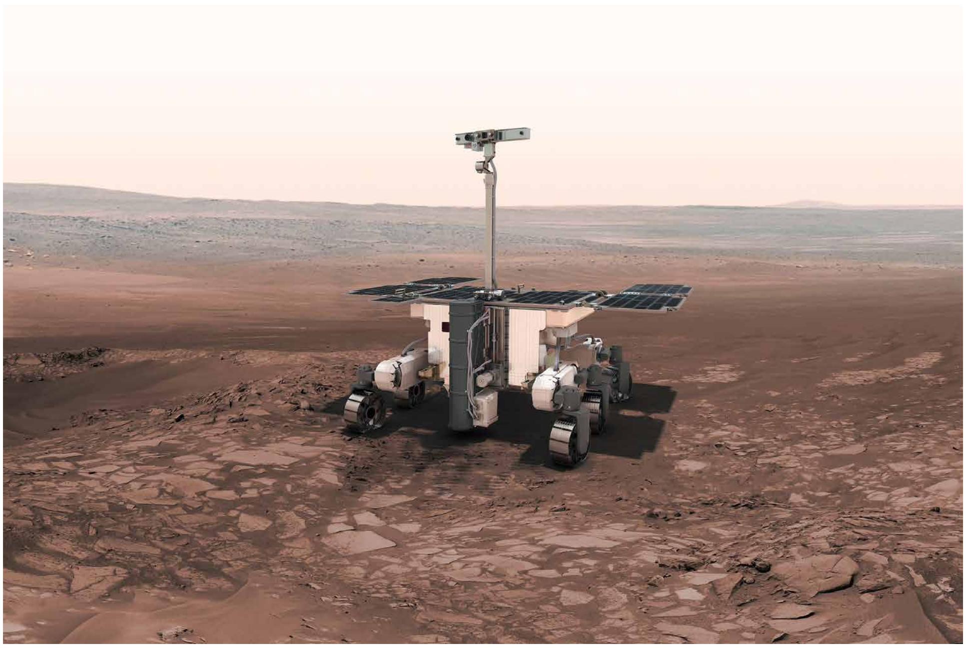


Fig. 5. ExoMars 2020 with rover and deep drill assembly (courtesy of ESA).

ESA's ExoMars 2020. Presently, ExoMars (Fig. 5) is the only European-funded mission to make substantial use of robotics in the form of an autonomous rover, an automated exobiology laboratory, and a robotic drilling system; it is due to be launched in 2020 to complement the ExoMars Phase 1 launched in March 2016. Data from the novel suite of instruments onboard the ExoMars rover will help conduct accurate visual and spectral characterization of the surface of Mars, ranging from panoramic (meter) scales and smaller (submillimeter) studies to the molecular identification of organic compounds. The surface study is complemented by electromagnetic and neutron subsurface investigations, which will further help understand the depositional environment (e.g., sedimentary, volcanic, and Aeolian). The unique contribution on exobiology from ESA's Mars robotic mission constitutes a step forward in the search for traces of past or present signatures of life on Mars.

ESA-Roscosmos' Phobos sample return. Another robotic mission in study is PHOOTPRINT (Fig. 6), which aims at the return of surface samples from Phobos (Mars' moon). The mission would make use of robotic elements to sample the surface in low gravity. The mission has been initially assessed in two ESA concurrent design facility (CDF) studies, in one industrial study, and, more recently, under the assumption that it could become a joint mission with Roscosmos (Russian Space Agency), by a further CDF study. The mission would need the relevant technologies by about 2022.

Long-term mission concepts

To meet the long-term need for exploration and science, a variety of robotic mission concepts, encompassing efforts from both academia and industry, have been proposed and studied by the international space community. Table 4 attempts to summarize these ideas in an organized manner without having an exhaustive list.

EVOLUTION OF SPACE ROBOTICS

The new generation of space exploration has traveled further into the solar system to tackle more ambitious scientific and exploration goals. Hence, it is anticipated to require more capable space robots with diversified locomotion (Table 5) and increased level of autonomy (Fig. 7). Most existing, successfully flown space robots are considered robotic agents that act as human proxies in space. Future space missions with increasingly challenging goals will require higher levels of autonomy, evolving toward robotic explorers and robotic assistants.

Diversified mobility and access

Despite successful exploration performed to date, space robotic systems have literally only scratched the surface. To further advance our knowledge of Earth and other destinations, a cornucopia of robotic mobility solutions have been proposed by the space community to explore the vast swathes of unexplored landscapes. The exciting new work underway is intended to provide access to more extreme terrains, caves, and aerial exploration of extraterrestrial surfaces or to tackle challenging tasks in orbit. Table 5 gives an organized view and summary of many proposed ideas to date, examples from which are further described in Table 6 based on a number of NASA-funded studies.

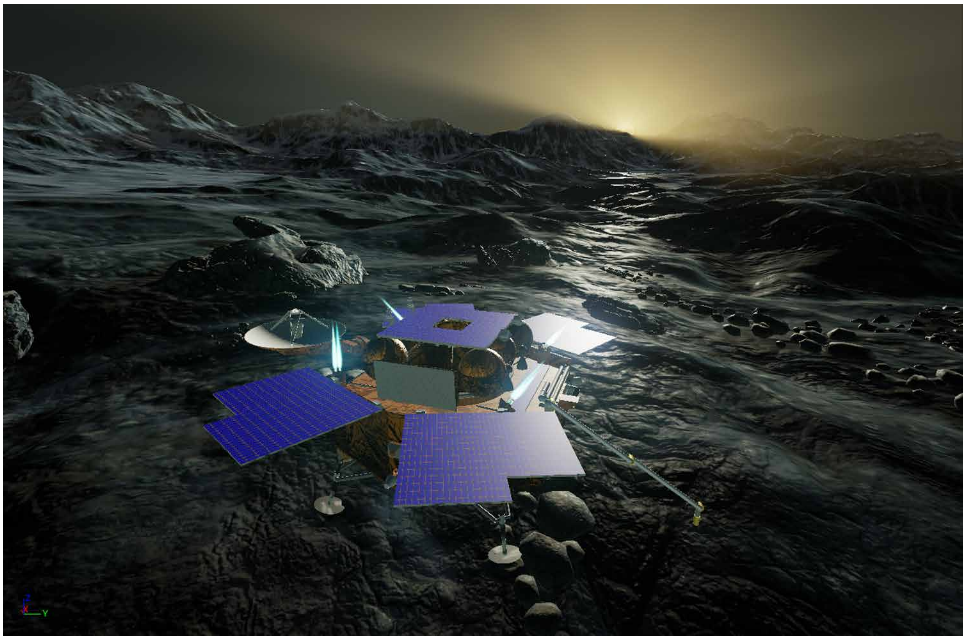


Fig. 6. Phobos sample return mission concept (courtesy of Airbus DS Ltd.).

Table 4. Long-term space robotic mission concepts (*4*). ISRU, in situ resource utilization.

Destination	Proposed mission concepts	Proposed robotic locomotion
Earth's orbit	Space debris removal, on-orbit servicing, and assembly	Arm, hand/gripper, harpoon
Moon	Sample return, ISRU, exploration of permanently shaded craters, prepare for manned base	Rover, arm, sampler, drill
Mars	Sample return, ISRU, crewed base	Aeroshell, airplane, helicopter, balloon, hopper, swarms
Venus	Exploration	Balloon
Mercury	Exploration	Rover
Asteroid	Sample return, ISRU	Rover, hopper, arm, harpoon
Titan	Exploration	Aeroshell, aerobot, balloon, lake lander, submarine, ship, cooperative robots
Europa/Enceladus	Exploration	Subsurface, submarine, hopper
Gas giants	Exploration	Balloon

A more comprehensive and system-level mobility concept is humanoid robotics, particularly in the context of human exploration space missions and human-robot interaction. Extremely prominent in this area is NASA's Robonaut program, which has been used onboard the ISS. The mobile Robonaut Centaur participated in the human-robot Desert Rats demonstrations (*22*), which has also included the ATHLETE nonhumanoid limbed robot (*23*). DLR's Justin platform (*24*) is another humanoid example.

Increased level of autonomy

Increasing robotic autonomy enables human interaction with or usage of robots at a greater level—as assistants/peers in mixed human-robot teams or goal-oriented fully autonomous explorers. Planning, scheduling, and resource management enable robotic agents to manage their own actions within resource limitations. Robust task execution systems allow autonomous robots to persist in uncertain execution environments. Navigation, mode, and state estimation and situational awareness capabilities, also called integrated vehicle health management and prognostics, enable autonomous robots to track their own state as well as their state within their locale and immediate environment to operate appropriately. These technologies together enable space robots to have increased survivability, increased ability to achieve their desired missions, and more effective support for science.

Many research and development (R&D) efforts have focused on increasing the efficiency of traditional science measurements using new forms of closed-loop science (*25*), scientific goal-oriented planning (*26*), and reconfigurable autonomous onboard control (*27*). Spacecraft applications already flown on real-world missions include tracking dust devils on Mars (*28*); retargeting of Mars rover measurements for MER (*14*) and MSL (*15*); and monitoring of active volcanism (*29*), cryosphere (*30*), and flooding (*31*) from orbit (*32*). Future proposed applications include detection and tracking of plumes (*33*) or surface volatiles at primitive bodies (*25*).

Advancement in general artificial intelligence techniques (e.g., machine learning and adaptation) is relevant for improving autonomous functions of space robots in many areas. For example, machine learning is often applied to sensing and perception (e.g., machine vision) tasks. It has also been applied to locomotion to improve locomotion strategies, policies, and navigation. System-wide autonomy, planning, scheduling, and resource allocation are also areas of continuing work for machine learning. In human-robot interaction, learning for adaptation to individual users or specific tasks is an area of active work. Furthermore, in multi-agent systems, coordination and control, as well as data assimilation, are viable applications for machine learning.

TECHNICAL DEMANDS AND CHALLENGES

The current desire to explore space is as strong as ever. Past space powers have been gradually joined by a flurry of new nations eager to test and demonstrate their technologies and to contribute to an increasing body of knowledge. Commercial endeavors also have eyes on space and actively promote the Moon and Mars as possible destinations for long-term human presence or habitation. Whether future exploration missions be crewed or robotic, space robots are always desired to deliver the robotic avatars and to perform in situ tasks to proxy, assist, or explore through their "eyes," "ears," "noses," and "hands" (*4*).

In particular, the technical goals of robotics are to extend human's reach or access into space, to expand our abilities to manipulate assets and resources, to prepare environments for human arrival, to support human crews in their space operations and the assets they leave behind, and to enhance efficiencies of mission operations across the board. Advances in robotic sensing and perception, mobility and manipulation, rendezvous and docking, onboard and ground-based autonomous capabilities, and human-robot integration will help achieve these goals.

NASA's 2015 technology road map has identified several robotics areas needed by 2035 (*34*). Similarly, ESA has been developing technology road maps in space robotics through various European Commission–funded projects, such as PERASPERA and SpacePlan2020.

Table 5. Diversified locomotion for future space robots (*4*).

Robotic platform	Robotic locomotion
Land surface	- Wheeled rover - Tracked rover - Legged rover - Rolling (e.g., ball or sphere) rover - Hopper - Hovercraft
Airborne	- Quadcopter, helicopter, or ornithopter - Plane or glider - Balloon, montgolfier, aerobot
Subsurface	- Drill (e.g., ice drilling or melting, rotary drilling, percussive drilling, dual reciprocating drilling) - Submarine, submersible
Manipulation	- Arm - Hand, gripper - Sampler (e.g., corer, scoop)
Water surface	- Vertical profiling float - Boat, ship

Other space-faring nations like Russia, China, India, and Japan have also announced their individual plans for future missions involving space robotics. Besides differences in mission timetables by different space players, there are numerous technological needs or challenges in robotics that are widely acknowledged by the international space community (see Table 7).

NEW OPPORTUNITIES

Commercial entry into space robotics

The competitive landscape of space robotics is changing. Traditionally, national space agencies have been the principal entities. More recently, commercial enterprises have declared their intent and are entering the area. Commercial enterprises are investigating and developing the means to exploit resources in the Moon and asteroids. Moon Express, Deep Space Industries, and Planetary Resources are working toward the long-term goal of exploiting key elements in the Moon and beyond. In the near term, exploitation of resources beyond Earth could include water-bearing substances to enable in situ production of rocket fuels (e.g., at the Moon or at Mars for a return vehicle). In the more distant future, the mining of helium-3 from the Moon and elsewhere could provide valuable fuel for fusion reactors. Last, rare metals (such as iron, nickel, cobalt, platinum, and titanium) can be found in many extraterrestrial bodies. As a nearer-term goal, some of these teams are competing for the Google Lunar X prize worth $30 million for operating a rover on the lunar surface.

Knowledge/technology transfer to nonspace sectors

Exploration and Robotics is an area of the space industry that is driven heavily by technology and faces huge challenges to achieve the mission science goals. It is mainly concerned with upstream activities with very little direct downstream benefits to the space industry. However, it does have excellent potential for spin-along activities, allowing the spinning in of terrestrial technologies from other sectors and then spinning out the resulting technology advances. Early findings have revealed that current advances being made in R&D projects on space robotics could have significant knock-on effects in many sectors, including the following:

(1) Nuclear facility decommissioning: for post-operational clearout, initial decommissioning, interim decommissioning, and final demolition.

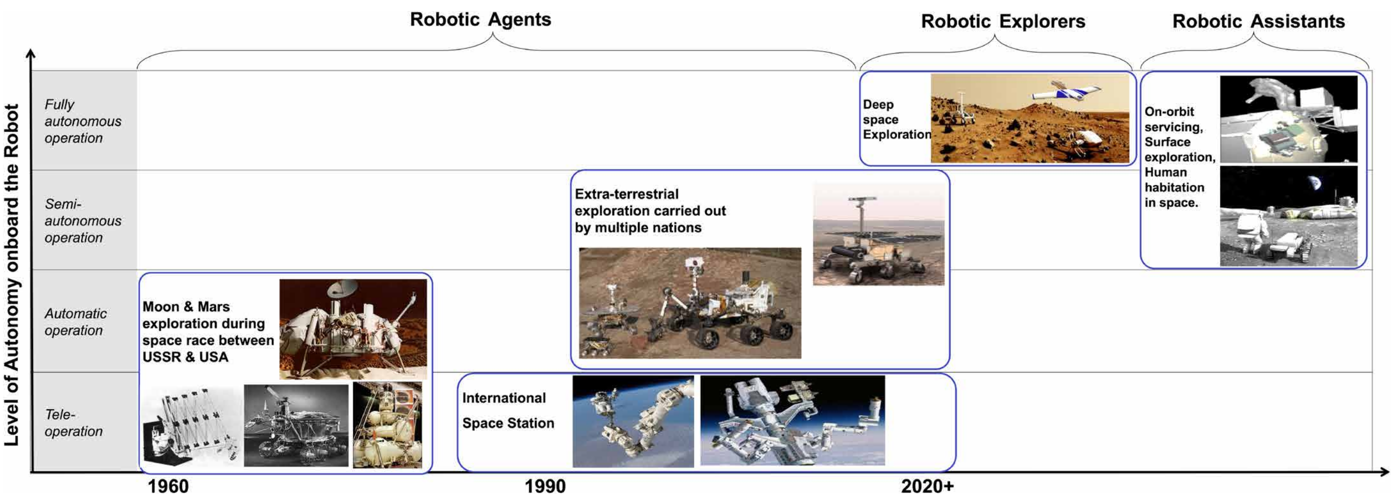


Fig. 7. Evolution of space robots in terms of level of autonomy (*1*).

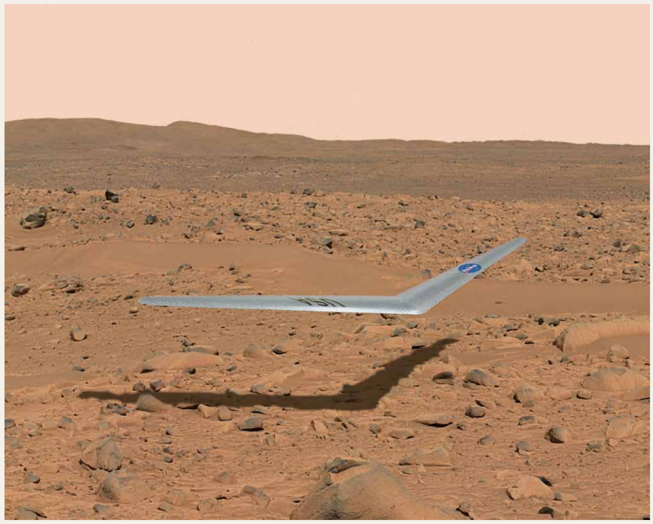
Table 6. Examples of novel robotic locomotion concepts for future space exploration (all images courtesy of JPL/NASA).

Mars helicopter (*36*)

Mars helicopter is proposed to facilitate surface rover operations. Despite the thin Martian atmosphere (only 0.6% that of Earth), the solar-powered Mars helicopter at 1 kg in mass and with a 1.1-m-long rotor, would scout ahead of a surface rover, providing critical imagery to enable the rover to drive up to three times as far per sol.

Mars airplane (*37*)

Whereas the extremely thin Martian atmosphere makes air vehicles challenging, a Mars airplane is proposed as the Preliminary Research Aerodynamic Design to Land on Mars (or Prandtl-m). A Mars airplane could be released as part of the entry, descent, and landing ballast for a future Mars-landed mission to acquire unique airborne imaging of the Martian surface.



Test flight in the Mojave Desert, CA, USA

Titan aerobot (*38*)

With a dense methane atmosphere providing strong lift and weak gravity, an aerobot is an ideal vehicle to explore Titan, a moon of Saturn. Titan is of great interest to scientists because of its abundant methane as a possible ingredient for life and its liquid methane lakes on the surface. Aerobots and montgolfiers have been proposed and tested to develop technologies for this ambitious robotic mission.

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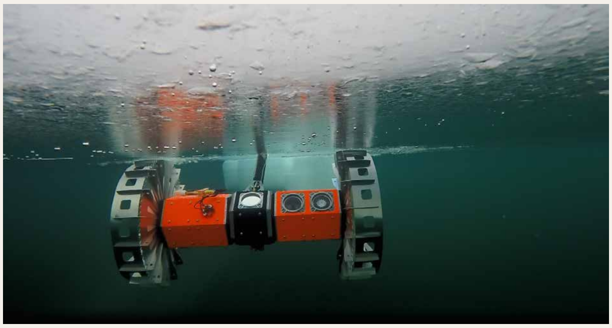
Table 6. Continued

Mars dual-axel rover (*39*)

Recent interest in recurrent slope linnae as liquids on the surface of Mars has spurred interest in robotic access to extreme slopes to study these science phenomena. The axel robot is a single axle with tether designed to rappel down steep slopes. In a dual-axel rover configuration, one axel would remain at the top of the slope as an anchor to allow the other axel to rappel down the slope.



Underwater vehicle (*40*)

Scientists now believe that there are at least eight ocean worlds in our solar system. These liquid oceans may provide the best chance for life outside Earth in our solar system. BRUIE, Buoyant Rover for Under Ice Exploration underwater vehicle, is a rover designed to roam the underside of the icy shell at the top of an ocean (such as on Europa, Enceladus, or other ocean worlds). BRUIE could rove along the underside of ice—adjusting its buoyancy to maintain contact or hop at will. Its position at the water-ice interface offers it a great position to explore this unique surface where evidence of life may exist.

BRUIE Field trials in Alaska, USA

Table 7. Technological needs and challenges for space robotics in the coming decades.

Areas	Goals	Technological needs or challenges	Relevance to achieving top-level science
Sensing and perception	To provide situational awareness for space robotic agents, explorers, and assistants	- New sensors - Sensing techniques - Algorithms for 3D perception, state estimation, and data fusion - Onboard data processing and generic software framework - Object, event, or activity recognition	The sensors provide the vast bulk of the direct science: -Increases in instruments, both remote sensing and in situ enable more precise measurements (e.g., spatial, spectral resolution, while reducing volume, mass, and power). - New types of instruments are emerging. Imaging spectroscopy to determine composition; lidar for 3D mapping; interferometric radar for change detection, structure; sample processing for life detection and astrobiology to enable new measurements for new types of science.
Mobility or locomotion	To reach and operate at sites of scientific interest on extraterrestrial surfaces or free space environments	- Mobility on, into, and above an extraterrestrial surface using locomotion like flying, walking, climbing, rappelling, tunneling, swimming, and sailing - Melting through the kilometers-thick ocean worlds' ice shells of Europa, Enceladus, or Pluto - Manipulations to make intentional changes in the environment or objects using locomotion like placing, assembling, digging, trenching, drilling, sampling, grappling, and berthing	Locomotion represents the ability to explore an environment, such as rovers, aerobots, and submarines. Melting through ocean worlds' ice shells enables access to habitable oceans underneath. Digging, trenching, and coring enable access to materials without atmospheric contamination (e.g., Mars geology) or radiation (e.g., Europa astrobiology).

(Continued on next page)

Table 7. Continued

High-level autonomy for system and subsystems	To provide robust and safe autonomous navigation, rendezvous, and docking capabilities and to enable extended-duration operations without human interventions to improve overall performance of human and robotic missions. To enable closed-loop science for more efficient, novel science (e.g., tracking a dynamic plume at a comet)	- GNC algorithms - Docking and capture mechanisms and interfaces - Planning, scheduling, and common autonomy software framework - Multi-agent coordination - Reconfigurable and adjustable autonomy - Automated data analysis for decision-making, fault detection, isolation and recovery/IVHM, and execution	- Enhanced guidance navigation and control means higher precision navigation for better science measurements. Scheduling, execution, and integrated vehicle health management enable more productive science time for vehicles. - Automated science analysis and scheduling enable closing the loop without ground in the loop, enabling more science cycles per mission (i.e., higher productivity and unique, opportunistic science).
Human-robot interaction	To enable humans to accurately and rapidly understand the state of the robot in collaboration and act effectively and efficiently toward the goal state	- Multimodal interaction; remote and supervised control - Proximate interaction - Distributed collaboration and coordination - Common human-system interfaces	Virtual reality and augmented reality allow more natural interfaces to analyze vast acquired data streams. Virtual reality and augmented reality also allow for natural means of vehicle controlling such as by reach, touch, and gesture.
System engineering	To provide a framework for understanding and coordinating the complex interactions of robots and achieving the desired system requirements	- Modularity, commonality, and interfaces - Verification and validation of complex adaptive systems - Robot modeling and simulation - Software architectures and frameworks - Safety and trust	High stakes in billions require a reliable mission. As systems become increasingly complex, being able to characterize robotic behavior (especially for multivehicle swarms) becomes increasingly challenging.

(2) Health and care: for robotic surgery, diagnostics, independent living, nursing systems, prosthetics, and analysis and therapy.

(3) Emergency services: for improved responsiveness, reduced risk to life, and more efficient deployment.

(4) Deep mining: for exploration, excavation, and refinement in wind energy for turbine inspection and maintenance.

(5) Seabed robotics: for exploration and exploitation of oil, gas, and mineral resources on the ocean floor.

(6) Water industry: for asset inspection, maintenance, and health condition monitoring.

(7) Agriculture industry: for crop inspection and precision farming.

The markets associated with each of these sectors are expected to undergo huge growth in the coming years, and the adoption and insertion of robotics-based products and services into these applications are expected to deliver economic benefits of at least $1.9 trillion by 2025 (*35*).

CONCLUSIONS

Robotics has demonstrated novel access capabilities for humans to extend their reach in space. Past robotic missions have enabled unique science, increasing our knowledge in a wide range of science disciplines. Future robotics missions will continue to change the way space is explored in even more fundamental ways, enabling exploration more frequently, at a reduced cost, and in ever more challenging and dynamic environments. These missions will both continue our robotic exploration beyond Earth and play a key role in furthering human exploration beyond Earth.

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2. Noting this paper does not consider regular orbiting satellite or flyby spacecraft that only have mobility in their orbital trajectory. In addition, although these spacecrafts are technically “robotic,” they typically do not have intimate, unpredictable interactions with their environment that is more typical of the “robotics field,” such as driving mobility, sampling, manipulation or assembly, or atmospheric interactions as with an airplane, a helicopter, or an aerobot.
3. Level of autonomy onboard spacecraft defined by European Cooperation for Space Standardization (ECSS) [42]: Level E1: Execution mainly under real-time ground control, that is, remote or teleoperation; Level E2, execution of preplanned mission operations onboard, that is, automatic operation; Level E3, execution of adaptive mission operations

onboard, that is, semi-autonomous operation; Level E4, execution of goal-oriented mission operations on board, that is, fully autonomous operation.

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