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Exploration of Extreme Environments with Current and Emerging Robot Systems

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Abstract

Purpose of Review The discovery of living organisms under extreme environmental conditions of pressure, temperature, and chemical composition on Earth has opened up the possibility of existence and persistence of life in extreme environment pockets across the solar system. These environments range from the many intriguing moons, to the deep atmospheres of Venus and even the giant gas planets, to the small icy worlds of comets and Kuiper Belt Objects (KBOs). Exploring these environments can ascertain the range of conditions that can support life and can also identify planetary processes that are responsible for generating and sustaining habitable worlds. These environments are also time capsules into early formation of the solar system and will provide vital clues of how our early solar system gave way to the current planets and moons.

Recent Findings Over the last few decades, numerous missions started with flyby spacecraft, followed by orbiting satellites and missions with orbiter/lander capabilities. Since then, there have been numerous missions that have utilized rovers of ever-increasing size and complexity, equipped with state-of-the-art laboratories on wheels. Although current generations of rovers achieve mobility through wheels, there are fundamental limitations that prevent these rovers from accessing rugged environments, cliffs, canyons, and caves. These rugged environments are often the first places geologist look to observe stratification from geohistorical processes. There is an important need for new robot mobility solutions, like hopping, rolling, crawling, and walking that can access these rugged environments like cliffs, canyons, and caves. These new generations of rovers have some extraordinary capabilities including being able to grip onto rocks like NASA/JPL LEMUR 2, operate in swarms such as MIT's microbots, or have high-specific energy fuel cell power supply that is approximately 40-fold higher than conventional lithium ion batteries to Stanford/NASA JPL's Hedgehog which is able to hop and somersault in low-gravity environments such asteroids. All of these mobility options and supporting technologies have been proposed and developed to explore these hard-to-reach unconventional environments.

Summary This article provides a review of the robotic systems developed over the past few decades, in addition to new state-of-the-art concepts that are leading contenders for future missions to explore extreme environments on Earth and off-world.

Keywords Extreme environments · Hopping · Climbing · Autonomy · Planetary exploration

Introduction

Since the dawn of the space age, nearly 250 robotic spacecrafts have ventured or made flybys of every planet in the solar system. In 1966, Luna 9 became the first spacecraft to achieve soft landing on the Moon and to transmit photographic data to Earth from the surface of another planetary body. Later in 1970, Luna 17 carried Lunokhod 1, the first in the series of lunar rovers. Lunokhod 1 operated for 322 Earth days, travelled 10.54 km, and returned home more than

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20,000 images and 206 high-resolution panoramas. Five years later, the Soviet successfully launched the first lander to Venus onboard the Venera 9 mission. The orbiter was the first spacecraft to orbit Venus, while the lander was the first to return images from the surface of another planet. Venera 9 equipped with diamond windows lasted less than an hour in the extreme temperature and pressure of the Venus surface.

Planetary Science Using Landers and Rovers

In 1975, NASA's Viking 1 became the first lander returning complete data and pictures from the Martian surface which was followed by numerous successful surface missions to Mars. Viking 1 and 2 were also ambitious in carrying science laboratories to test the Martian regolith for life. A series of well-publicized experiments were conducted to ascertain existence of life on Mars. However, the experiments proved inconclusive. There were more questions raised than answers, and it was very clear that there were inorganic processes going on the surface of Mars that mimicked some aspect of microbial metabolism.

In 1997, Mars Pathfinder landed a lander and a microrover called Sojourner. Sojourner demonstrated the potential of using rovers to perform planetary science on an off-world environment. Sojourner famously carried an Alpha-Particle X-ray Spectrometer (APXS) and used to rove to a rock of interest and lay the spectrometer at the base of the rock to determine its elemental composition. The following years saw numerous successful surface missions: Cassini-Huygens became the first Saturn orbiter and first outer planet lander in 1997. Hayabusa I became the first sample return mission from an asteroid in 2003, and Rosetta/Philae became the first comet orbiter and lander in 2004. In most cases, these landers were targeted for relatively benign terrain which had minimal landing risks. The exception is Philae which landed on a comet surface covered by surface environment that was extremely rugged. The inability for Philae to hop or anchor on the surface had substantially shortened the surface mission.

In the last decade, the Outer Planets Assessment Group (OPAG) has organized an ambitious exploration strategy under the theme of "Making Solar Systems" and has identified three science goals under this theme: building blocks, interior secrets, and extreme environments [1]. Exploring the extreme environments across the solar system can address the question of habitability in these planetary environments and also determine the global mechanisms that affect the evolution of volatiles on planetary bodies. It should be noted that planetary landers and rovers have often exceeded all expectations and demonstrated the value of robotic mission to perform planetary science. They have become an integral part of a holistic surface exploration program for several major space agencies. Current generation of rovers have proven their merit but are large, in the order of several hundred kilograms and house state-of-the-art science laboratories. However, in order to meet increasingly ambitious scientific and programmatic goals, future rover missions will need to exhibit competencies far beyond those of the current rovers. Even the 2015 NASA Technology Roadmaps prioritize the need for next-generation robotic and autonomous systems that can explore extreme and rugged environments that are hard to reach even for expert human climbers [2]. The next section provides an overview of the past robotic platforms and the direction in which the future robotic platforms are progressing to explore these extreme environments.

Progressing from Wheeled Mobility

Mobility is a vital element for space missions due to valuable science return potential from different sites as opposed to static landers. With advancement in technological development over the years, numerous mobile systems have been developed, some of which are spin-offs from terrestrial applications like automobiles that use wheels and military tanks that use tracks and aerial balloons. Others have been developed purely for space application like hoppers and hybrid systems. Since 1970s, twelve surface missions have reported using mobile robots. Most of them used wheels as their mobility element for locomotion. However, there are numerous ways to achieve mobility on an extraterrestrial surface. Some of the important systems are wheel-enabled, leg-enabled, track-enabled, hoppers, wheel-leg hybrid, and hop-roll hybrid systems.

Wheels have been commonly used for years to enable motion on terrestrial applications as demonstrated for the first time during the Lunokhod 1 and 2 missions in 1970 and 1973 respectively on the lunar surface by former Soviet Union [3]. The Lunokhod rovers (Fig. 1e) were teleoperated from Earth but with great difficulty due to the 2–5 s latency. The latency had resulted in numerous instances of operator fatigue, near-misses, and outright accidents. The Lunokhod rover's suspension system consisted of eight active wheels that allowed the rover to move longitudinally. This eight-wheel enabled mobility systems are very heavy and no longer being used for space exploration. Numerous works on newer suspension concepts in recent years have led to the development of the six-wheel rocker-bogie suspension system at NASA Jet Propulsion Laboratory and California Institute of Technology (Fig. 1a–d) [4].

In the rocker-bogie suspension system, all six wheels are independently actuated by DC motors with additional capabilities of steering the front and rear wheels. This suspension system enables the rover to passively keep all wheels in contact with the ground even while travelling on severely uneven terrains; however, the rover can climb obstacles only up to 1.5 times its wheel diameter. Another limitation of this system is excessive wheel slippage which results in total rover immobility as observed on Mars [5]. For example, Spirit and

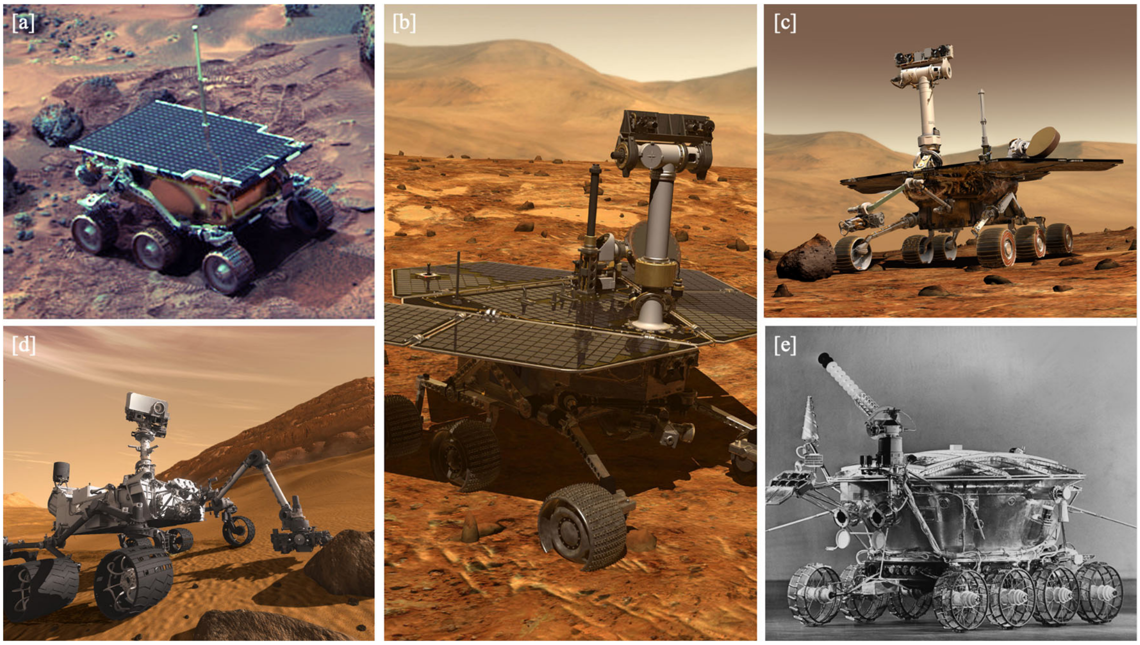

Fig. 1 Wheeled rovers for planetary exploration. **a** Sojourner rover (courtesy: NASA/JPL). **b** Spirit rover (courtesy: NASA/JPL). **c** Opportunity rover (courtesy: NASA/JPL). **d** Curiosity rover (courtesy: NASA/JPL). **e** Lunokhod 1 rover (courtesy: NASA/GSFC/Arizona State University)

Opportunity rovers (Fig. 1b, c) were trapped in loose soil for weeks. However, this rocker-bogie system has been used to develop rovers of different size and mass by geometrically scaling the system as can be seen in the Rocky7 testbed, Mars Pathfinder mission rover Sojourner, Mars Exploration Rovers (MERs) Spirit and Opportunity, and Curiosity (MSL) rover, all developed by NASA, JPL, and Caltech (Fig. 1).

Teleoperation of rovers on Mars is not possible due to latencies ranging from 9 to 18 min. In addition, it is always not possible to achieve direct line of sight from an Earth ground station to Mars surface assets. This has required use of the Deep Space Network and Mars orbiting relay assets such as Mars Reconnaissance Orbiter (MRO) to communicate message to rover on the Martian ground which results in operational delays lasting hours to a day. All of these factors require autonomy onboard the rovers. This includes autonomous navigation, path-planning, and control.

For close-range autonomous navigation, the Sojourner rover (Fig. 1a) performed proximity and hazard detection by using its laser striping and camera system to determine the presence of obstacles in its path. Distance travelled was measured using dead-reckoning approaches that involve estimating heading and distance travelled by averaging odometry and on-board gyro measurements [3]. Dead-reckoning is sufficient for short distance; however, the error accumulates exponentially. Hence, the ground operators on Mars Pathfinder developed a grid-based localization system using the lander's panoramic cameras. The panoramic cameras were able to constantly track the Sojourner rover and hence provide an external estimate of true position relative to the lander. These external position estimates could be used to correct for the error accumulation in dead-reckoning and enable a hybrid localization approach that is practical, providing a few centimeters of error. Localization was ultimately critical for performing science on the mission as Sojourner with its APXS can provide position/source location of a rock being examined for its elemental composition.

The rovers on the Mars Exploration Rover mission took one step forward by using an onboard software-based intelligence system for autonomous surface navigation that performs stereo vision-based perception, local terrain hazard mapping, traversability assessment, incremental goal-directed path selection, and vision-based pose estimation [6]. The Mars Exploration Rovers were also a lot larger than Sojourner, being the size of a small dining table. Importantly, Mars Exploration Rover was equipped with a power system and communication system that enabled it to traverse long distances away from its landing spot. In contrast, Mars Pathfinder had its primary communications system and cameras equipped on a static lander. Mars Exploration Rover each operated for 6 and 15 years, much longer than the 90 sols (Martian day) primary mission. The MERs made many important discoveries, which include ground evidence of sedimentary rock on the surface of Mars, evidence of "dust devils", evidence for an early Mars that was abundant with water, extensive deposits of "blueberry"-shaped/colored rock called "concretions" produced from salt-water deposits interacting with iron-rich hematite minerals, and evidence for ancient hydro-thermal systems.

While the MERs were able to travel tens of kilometers away from their landing site, driving them was a slow process that involved uploading new sets of driving commands over a 24-h cycle and for the rover stopping and waiting for the next batch of move commands. While the distances travelled and discoveries made were impressive, there was an important need to further increasing operational efficiency. Next, the Curiosity rover (Fig. 1d) implemented an autonomous navigation system called Autonav, for the first time, that led the rover to decide for itself how to drive safely on Mars. Using Autonav, the Curiosity rover analyzes images taken during its drive to calculate a safe driving path which is even safer than the human rover drivers on Earth that can evaluate ahead of time [3]. This has enabled Curiosity to constantly move with only daily check-ins from the human operators. The increased mobility of Curiosity has also been made possible thanks to a radioisotope thermoelectric generator (RTG) (nuclear battery) power system that provides constant power throughout the life of the rover. This too was a major advancement over the MERs that relied on photovoltaic solar panels for power. While the photovoltaic solar panels were thought to initially last less than 90 sols due to Martian dust accumulation, dust devils would periodically wipe clean the solar panels. However, extreme Martian dust storms would "dump" centimeters or more of dust that would bury the panels, thus ending the MER missions. RTGs however are impervious to these dust accumulations, and Curiosity has been able to withstand long-ranging dust storms of 2018 that lasted almost a year and had let to the loss of the one of the remaining Mars Exploration Rovers, Opportunity.

Even other space agencies like the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA) have also proposed their wheel-based mobility systems through ExoMars and SELENE-II missions. ExoMars employs longitudinal and transverse bogie systems [7] while SELENE-II uses the so-called Pentad Grade Assist Suspension or PEGASUS suspension system for their Micro5 testbed rover [8]. ExoMars is proposed to use an autonomous navigation system developed by the French Space Agency CNES, which uses a set of algorithms to construct a 3D model of the terrain surrounding the rover, which compares the model with respect to the rover's locomotion capabilities to compute a compatible path. Micro5 rover's navigation strategy is based on both teleoperation and autonomous behavior without any active steering mechanism. Steering is controlled by differential of left and right wheels with the help of special tires and spiral fin specially developed for the rover. Another rover designed by the Swiss Federal Institute of Technology—EPFL is the Shrimp architecture [9]. The rover has two bogies on each side where a couple of two wheels are mounted on a support which can freely rotate around a central pivot. Moreover, it has one wheel mounted on a fork in the front and one wheel in the rear. The spring mechanism on the front wheel guarantees optimal ground contact of all wheels at any time, and its parallel mechanism produces an elevation of the front wheel when an obstacle is encountered. The bogies provide lateral stability during the rover's motion even on very rough terrain.

Tracks and Legged Mobility

Robots equipped with track-enabled mobility systems use crawl units or tracks that make it suitable for motion on difficult terrains similar to military tanks. The Nanokhod rover developed based on Russian technology using a track-enabled system was supposed to be launched with Beagle 1 Lander by ESA on 2003 Mars Express Mission but was canceled [10]. The track-enabled robot for BepiColombo mission to Mercury was also unfortunately canceled, but since then, it has been studied for lunar and other planetary missions. The Advanced Space Technology research group in JAXA also proposed a tracker for SELENE-II lunar mission that consisted of four caterpillar crawl units with two on both sides [11].

Another mobility system for planetary exploration developed across the last few decades is leg-enabled robots based on biological designs and neurobiological controllers. One such example is an octopod (eight-legged) robot called SCORPION (Fig. 2a) developed by German Research Center for Artificial Intelligence—Bremen, Defense Advanced Research Projects Agency, and NASA for outdoor walking in dangerous, highly unstructured, rough terrain where mobility is crucial [12]. Another example is a hexapod (six-legged) robot called the DLR Walker (Fig. 2b), developed by the Institute of Robotics and Mechatronics of German Aerospace Center (DLR) adapted from DLR Hand-II [13, 14]. Different walking gaits for the robot have been developed to overcome any complex structured terrain and also have led to the development of the in-house Semi-Global Matching Method algorithm [15]. Using this algorithm, the robot can autonomously map a 3D environment, localize itself, and determine the next safe trajectory in the mapped environment.

The Legged Excursion Mechanical Utility Rover (LEMUR 3) (Fig. 2c) developed by NASA JPL is another four-legged robot, which has demonstrated climbing on cliff faces and smooth glass [16••]. Microspine grippers are used for climbing the rocky surface, and gecko adhesive grippers were used for the glass solar panels. The planning system for LEMUR 3 consists of a local footstep planner and a global body-level planner. The local footstep planner is assisted by a ring of infrared depth sensors that estimates the distance of the gripper to the surface, while a force-torque sensor detects gripper contact and grasping events. For the global body-level planner, an illumination-invariant actuated LiDAR system is used for reconstructing centimeter-scale geometry that extends from between the limbs up to tens of meters from

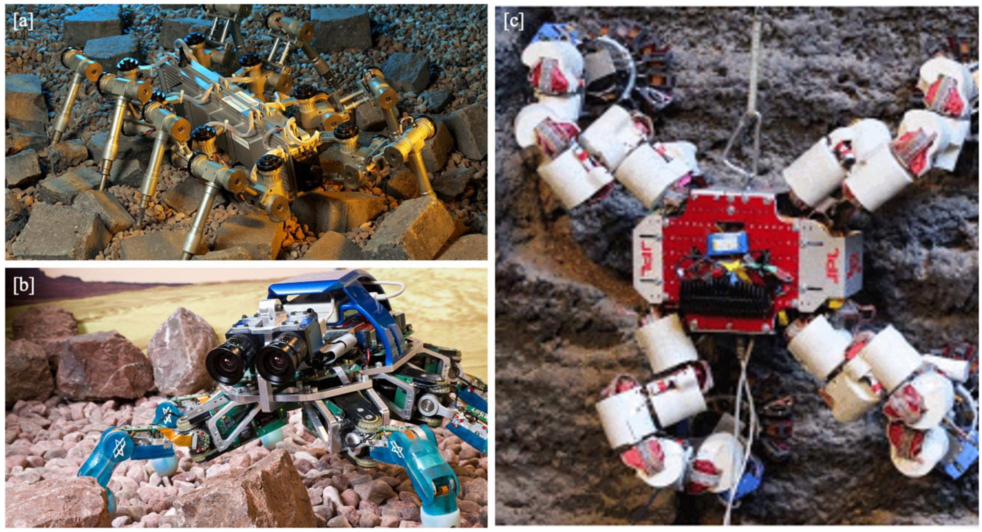

Fig. 2 Track-enabled and leg-enabled robots. **a** 8-legged system SCORPION (courtesy: University of Bremen/DARPA/NASA). **b** DLR Walker robot (courtesy: DLR/ESA). **c** LEMUR 3 robot (courtesy: Parness, 2017/NASA JPL)

the robot. These map patches generated are evaluated for graspability based on a classifier trained on previous grasping experiences [16••].

Spherical Robots for Unconventional Mobility

Several spherical shaped robots have also been proposed and developed over the years for planetary exploration using rolling and somersault mobility that includes spherical robots developed at University of Sherbrooke [17], Cyclops at Carnegie Mellon University [18], inflatable ball robots developed at North Carolina State University [19] and University of Toronto [20], and Kickbot developed at MIT [21]. Spherical robots offer several advantages thanks to their shape. First thanks to their round shape, they are ideal for free rolling especially in the wind or down a slope due to gravity. Second, the sphere encloses maximal volume for minimal surface area and thus is well designed for minimizing surface area for heat transfer and minimizing material for enclosing a pressurized internal volume. Thanks to the spherical shape, the internal cavities could be pressurized to increase storage of gasses, transport of liquids, and avoid stress build-up from sharp corners on a cube.

A typical drive system for a spherical robot consists of a pair of direct drive motors in a holonomic configuration. For the case of Cyclops and the inflatable robots, the center of gravity is moved by pivoting a heavy mass that results in rolling. There are other mobility techniques such as the Gyrover robot that uses spinning flywheels attached to a two-link manipulator and the Hedgehog spacecraft/rover hybrid system developed by Stanford and NASA JPL that uses a 3-axis reaction wheel system to spin-up and somersault [22••]. The use of reaction wheels by Hedgehog enables it to creep over steep and uneven obstacles. However, it is still unclear if a gyro-based system can overcome both steep slopes and large obstacles as even a gyro-based system is bound to slip on steep surfaces.

Hopping is another alternative to rolling and creeping. Typically, hopping is achieved by a hopping spring mechanism to overcome large obstacles. The microhopper for Mars exploration developed by the Canadian Space Agency [23] is one such example. At the end of each jump, the microhopper can land in any orientation because of its regular tetrahedron geometry. Shape memory alloy (SMA) actuator is used to design a novel cylindrical scissor mechanism–based hopping mechanism for the microhopper. However, the drawback of this design is that it allows only one jump per day on Mars. Another technique for hopping is developed by Plante and Dubowsky at MIT that utilizes a polymer actuator membranes (PAM) to load a spring. The system enables microbots (Fig. *3*) with a mass of 100 g to hop up to 1 m, although the mechanism weighs only 18 g [24, 25]. The microbots were configured to polymer electrolyte membrane (PEM) fuel cells that provided much higher specific energy than conventional batteries. A PEM fuel cell prototype has been developed that can achieve up to 5000 kWh/kg fuel-specific energy on Earth [26••] and around 2000 kWh/kg fuel/oxidizer-specific energy off-world [26••, 27]. A fuel cell power system offers many of the advantages of the RTGs, which provide high-energy power for months and years, instead of hours. However, unlike RTGs, PEMs are relatively clean and quiet; they can be started and stopped. Importantly, they can be used to power devices to access pristine environments and fragile natural ecosystems. Microbots are centimeter-scale spherical mobile robots equipped with power and communication systems, a mobility system that enables it to hop, roll, and bounce and an array of miniaturized sensors such as imagers, spectrometers, and chemical analysis sensors developed at MIT. Ideally, many hundreds of these robots would be deployed inside caves, lava tubes, canyons, and cliffs enabling large-scale in situ

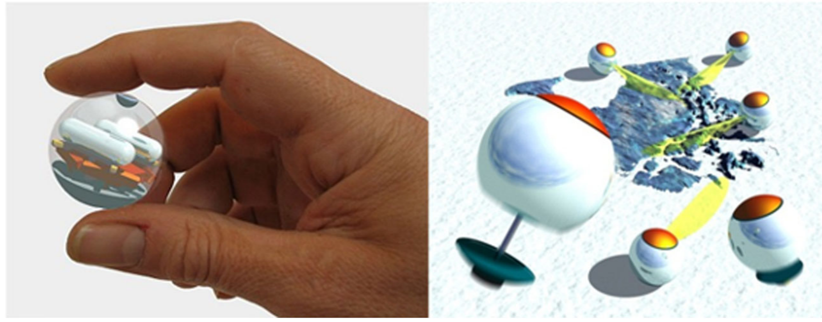

Fig. 3 (Left) Artistic view of the microbot concept. (Right) Microbots exploring the surface of an icy moon (courtesy: Dubowsky, 2005/Thangavelautham 2012)

exploration. The microbots would explore the advantages of mother-daughter architecture and communicate science data back to a central unit, such as lander for relaying it back to Earth.

The SphereX (Fig. 4) robot being developed at SpaceTREx laboratory of the University of Arizona is another example of spherical robot and is a direct descendant of the microbot platform [28]. SphereX has the same goals as the microbots, but with the goal of launching fewer robots, that are better equipped with science grade instruments. SphereX achieves both rolling and hopping mobility, with the help of chemical rockets for propulsion and a 3-axis reaction wheel system for attitude control. SphereX proposes to use a combined fuel-cell power supply and H_2/O_2 propulsion system, where the same fuel is used to power the fuel cell and is also used as a propellant for the propulsion system. The system uses lithium hydride and lithium perchlorate to extract hydrogen and oxygen for both the power system and the propulsion system.

Mapping and navigation for SphereX are performed with the help of a 3D LiDAR system that uses an ICP-based Pose-graph SLAM algorithm to perform simultaneous localization and mapping in unknown environments like caves, lava tubes, and pits [29]. Multiple hopping SphereX robots would be deployed from and work in collaboration with a large state-of-the-art planetary rover or lander to access extreme terrains canyons and underground pits (Fig. 4) [30•, 31]. The fully developed SphereX robots have a range of 5 km. To feasibly explore a cave or lava tube requires a team of SphereX robots that work collaboratively to map, navigate, and communicate the data back to the base station. Often, there will be no line of sight communication between the base station and the robot team. Hence, the robots need to act as relays to pass messages from the base station to individual robots along the cave much like a bucket brigade. Moreover, this team of robots can also be used to transmit power and light wirelessly in the form of laser from the base station to the robots inside the cave. Another way these SphereX robots could be used is by configuring multiple robots by connecting them with tethers with each robot equipped with microspine grippers [32] to climb inclined walls, cliffs, craters, canyons, and skylights. The multirobot system can work cooperatively much like a team of mountaineers to systematically climb a slope. Even if one robot were to slip and fall, the system would be held up with multiple attachment points [33].

An interesting alternative to hopping is flying. In theory, flight provides a unique point of view above a terrain of interest and minimizes concerns of bypassing large or impassible obstacles. A few mission concepts have proposed methods to fly off-world. This includes NASA JPL's helicopter for Mars [34] and NASA Langley's ARES rocket-powered aircraft [35]. Both systems have large footprints. Rockets are the most compelling option for flight in off-world environments with thin or no atmosphere.

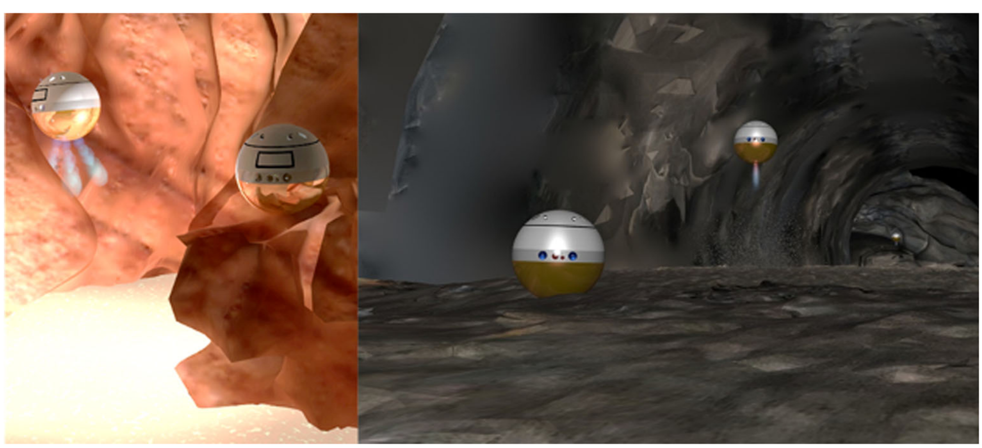

Fig. 4 Artistic views of SphereX robots cooperatively exploring (left) canyons on Mars and (right) underground pit on the Moon (courtesy: Thangavelautham, 2014)

Significant work has also been focused on developing tethered legged and wheeled robots for exploring crater walls and cliff faces. One realization of the mother-daughter architecture for such a robot is the DuAxel/Axel platform [36]. The rover is connected to a mother lander with the help of a tether, which enables exploration of extreme terrains, operating like a yoyo. Another similar example is the Teamed Robots for Exploration and Science on Steep Areas (TRESSA) used for climbing steep cliff faces with slopes varying from 50 to 90° [37]. TRESSA is a dual-tethered system and consists of three robots (one cliffbot and two anchorbots), where the cliffbot is connected to the anchorbots via tethers. The anchorbot and cliffbot exchange synchronization messages for the start and ending of a traverse and tether tension control are primarily achieved through varying the tether velocity based on tension feedback on the tether attachment assembly.

Conclusion

In this review article, we document the evolution of planetary missions that started with flyby spacecraft into orbiter and landers, followed by rovers. Rovers have advanced to become the primary surface vehicle of choice for most major space agencies. Rovers have also evolved in sophistication, carrying advanced instruments and laboratories onboard in addition to critical onboard instruments for localization, navigation, and path-planning. Rovers such as the MER operated for between 6 and 15 years on the surface of Mars and made numerous major geological discoveries that have totally transformed our understanding of Mars and showed an ancient Mars with abundance of water and conditions to sustain life. These rovers however relied heavily on humans in the loop to perform driving on Mars. Rover development evolved beyond MERs to present day rovers the size of SUVs such as Curiosity and the upcoming Mars 2020 rover, Perseverance. Curiosity has more advanced navigation cameras that enable for autonomous driving, albeit at slow speeds of 0.14 km/h. However, the increased size of these present-day rovers limits their mobility capabilities and now there are growing calls for developing a whole new generation of small, agile, and rugged robotic vehicles that can perform unconventional mobility including hopping, somersaulting, and climbing. These new generations of robots are under development and are leading concept for next-generation exploration missions to off-world environments. These robots, as we show, promise accessibility to rugged and extreme environment that can barely be reached by expert climbers but are also sites of great interest to planetary geologist and can get firsthand glimpses of rock formation, stratification, and fossilization. Importantly, these next-generation rovers are equipped with some of the latest navigational sensors, LiDAR, and vision cameras. They open the possibility of autonomously accessing isolated pockets of ecosystems in these extreme environments that can harbor life. Numerous such ecosystems have been found on Earth, and hence, it raises the possibility of finding such places on the subsurface of Mars, icy moons such as Europa and Enceladus.

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Compliance with Ethical Standards

Conflict of Interest Himangshu Kalita and Jekan Thangavelautham report a pending patent on Spherical Robots for Off-World Surface Exploration.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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