Current Robotics Reports (2021) 2:239–249
https://doi.org/10.1007/s43154-021-00056-3

SPACE ROBOTICS (Y GAO, SECTION EDITOR)

Planetary Surface Mobility and Exploration: A Review

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Accepted: 6 May 2021 / Published online: 25 May 2021

Abstract

Purpose of Review With the continued interest in scientific space exploration and rapid development of the commercialized space sector, there have been a wide array of exploration technologies proposed for planetary mobility. This paper aims to survey these new technologies, explain the motivations and challenges of traversing different space environments, and describe why certain approaches will be more ubiquitous.

Recent Findings A continued dominance by four- and six-wheeled vehicles for lunar and Martian exploration due to reliability, simplicity, and efficiency is observed. However, there is an emergence of alternative wheeled vehicle kinematics, other legged locomotion, and flying, climbing, or hopping robots when these designs confer specific advantages.

Summary The engineering maxim "form follows function" is strongly represented within the array of robotic planetary explorer designs. The limitations of an irradiated, dusty, vacuous, remote operating environment which prioritizes efficiency and robust operation often lead to small iterations on working designs because deviations from the status quo are simply not feasible or deemed too risky. Those proposed designs which do deviate have clear justifications driven by their particular environments or intended purpose. Engineers developing future planetary exploring robots for space environments may find these considerations useful.

Keywords Space exploration · Planetary rovers · Lunar robots · Robotic platforms · Autonomous robotics

Introduction

The field of space robotics has many unique challenges unlike those found in Earth environments. These challenges include a total or near vacuum (zero atmosphere), various types of radiation, remote operation with no chance of repair or return, dust ingress to moving parts, and strict mass, volume, power, and thermal engineering budgets or requirements. Many times, gravity can also become a factor as robotic motion is sometimes unintuitive in low-gravity environments. These challenges often preclude what seem to be obvious solutions when roboticists enter the space sector; if someone has not done it, there is probably a good reason. In particular, there are some material limitations which preclude common power transfer mechanisms such as belts (elastomers degrade due to radiation and outgassing) or other polymers due to radiation. The terrain is primarily composed of regolith, a very fine but generally abrasive rocky material, which creates a deformable environment which often wears components. The thin or absent atmosphere generates new challenges for entry and landing, and the use of any system which requires fluids or gases such as hydraulics or pneumatics must contend with external pressure variations. Finally, a planetary rover must adhere to all the above requirements, survive the vibrations of launch and entry, and survive the impact of landing before it can begin operation. This has led to a general form factor for space robotic exploration.

Despite differences in suspension or wheel construction, every successfully landed Martian or lunar rover is a variation of a 4-, 6-, or 8-wheeled vehicle. The first remote-operated robotic rovers on an extraterrestrial body belonged to the Soviet space program (Lunokhod 1 and 2) [1] and drove on an eight-wheeled system, landing in 1970 and 1973, respectively. An impressive feat for its time, a robotic rover would not set wheel on extraterrestrial ground again for almost 25 years until 1997 when Sojourner deployed. All Martian and lunar explorers from either the National Aeronautics and Space Administration (NASA) (Opportunity [2], Curiosity [3], Spirit [2], Sojourner [4]) or China National Space

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This article is part of the Topical Collection on *Space Robotics*

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Administration (CNSA) (Yutu [5], Yutu-2) are six-wheeled. All three human transport vehicles (the Lunar Roving Vehicles from Apollo 15, 16, and 17) [6] are four-wheeled. This core blueprint has held up for a reason: wheels are a very efficient way to reliably traverse distances in a conventional manner.

While there are certainly advantages to the distribution of load under six wheels compared to four, some studies have highlighted unintuitive results. For example, a trade study [7] examined simulations whereby a six-wheeled vehicle with 20-cm-diameter wheels was compared to a four-wheeled vehicle with 30-cm-diameter wheels. The six-wheeled vehicle would result in greater sinkage, more resistance, less drawbar pull, and shallower maximum slope ascension. However, the study also used a rigid suspension. The main advantage of the six-wheeled approach is most easily seen in the rocker-bogie and the effect of keeping as many wheels in contact as possible. It allows for greater stability and redundancy (always a planetary robotics concern). In fact, Spirit rover continued its mission for 5 years after one of its front wheels broke thanks to this redundancy. This is seen as an acceptable trade-off for the slightly increased rolling resistance and complexity. Among the advantages to some of these passive systems, beyond stability, are a better distribution of vehicle load among wheels and driving contact between the wheel and ground to maintain tractability.

When designing the locomotion of planetary robots, the concerns are always the same: minimize mass and mechanical complexity while maximizing traction and reliability. But what would be the characteristics of traveling in an *unconventional* manner during planetary exploration then? We explore these areas of space robotics development defined as follows:

1. Conventional planetary robot design is defined as wheeled mobility intended for uninterrupted ground contact, traversing the environment by rolling and using passive suspension. This has been the typical historical design for space robotic exploration.
2. Modified wheeled travel means modifications to typical wheeled surface travel such as stance-changing actuators. This involves actively changing suspension characteristics or linkage characteristics between wheel and chassis while keeping the core end-effector (a wheel) and generation of motion (wheel rolling) the same.
3. Alternate surface mobility means an approach which deviates from wheeled travel due to the inability for wheels to provide an adequate reaction force; these include amphibious or aquatic targets and low-gravity surface travel in either unconsolidated or rocky media. In both cases, the terrain is not suitable for wheels to react against even with active suspensions, and thus, other locomotive methods are required.
4. Vertical mobility is designated in this paper as a primary or sole focus on robotic exploration and travel which includes a significant motion in the vertical plane. Scaling, jumping, and flying are all ways of achieving this, and the robots in this section demonstrate approaches appropriate to gravity, atmosphere, and surface conditions which the previous wheeled and unwheeled surface mobility systems are not able to achieve.

Modified Wheeled Travel

The typical six-wheeled, rocker-bogie, or similar suspensions have been discussed at length in the literature with optimization studies [8] and traverse characterization [3]. Linkage differential mechanisms are fixed on either side of a rover to balance the angle of the left and right sides. Each side has a rocker which mounts one wheel in front and bogie with two wheels pivoting on the back end of the rocker. The differential averages the two rockers for the pitch angle of the rover, keeping it in better balance. Rodriguez et al. [9••] summarizes the motivations quite well when discussing higher-speed rover designs. One area given attention is novel active suspensions. These can vary in the number of actuators and degrees of freedom.

A good example of recent and novel modified wheeled travel is the SCARAB rover [10–12]. Precursors to the Scarab's inchworming or crawling motion include the Lama rover [13] and the Hylos robot [14]. Using a novel active 5-bar suspension setup on each side, the rover possesses two unique capabilities. The first is the ability to traverse a cross-slope path with less slippage thanks to the ability to raise one pair of wheels independently, adapting to the slope and lowering the center of mass. This creates less sinkage and less disturbance of the soil, resulting in reduced motion resistance. Indeed, the slippage (deviation from the commanded path) of conventional stance was × 2.5 higher than that of the split stance [11]. El-Dorado-II-B [15–17] shows an approach with linear actuators to cross-slope traversal with similar success. The SCARAB robot also has a secondary mode of travel. The second capability of SCARAB is unique to the design and known as an "inch worming" or push–pull motion [18]. During this motion, the rover is static while retracting its wheels close together on each side. Then, while rotating the front wheel to the direction of travel, and holding the back wheel static, the wheel linkages are simultaneously expanded out. The result is a motion in which the rolling wheel pulls the center of the craft forward, while the back pushes against accumulated material behind it. This is a capability not seen in other rovers. Key findings included the result that push–pull generated 30–40% more thrust than rolling alone. In high sinkage material, it was able to continue in situations where traditional wheeled motion resulted in entrapment. Finally, this approach was also able to return the rover from a starting entrapped position to one with movement. As a secondary mode of transport, it would only require two additional actuators if less complexity was desired for a rover. Contrasted with modifying the stance, another idea explored by the now defunct Resource Prospector project [19] is that of a sweeping and lifting motion. The lunar prospecting idea was continued under the VIPER rover [20, 21] moniker, although the lifting dynamics were converted to a tilting motion which still allows for vertical travel of the wheels. The idea of lifting and sweeping was recently explored with greater attention given to the granular mechanics to understand the principles of success [22]. The Mini RP15 was tested on a variety of slopes using its unique gait composed of spinning the wheel, lifting it, and sweeping loosely consolidated material from the slope in front of it. Removal of the lifting motion caused the greatest detriment to progress during direct slope traversal of a 15° incline of unconsolidated material, even greater than stopping wheel spin. Examining granular mechanics can provide many valuable insights for rover design; for example, only after looking at granular imaging analysis was it determined that the increase in tractive force from grousers is most likely due to a pre-clearing of front material, not from generation of paddle thrust [23].

A related system to the previously discussed stance modification can be seen on the Rosalind Franklin Rover (previously known as ExoMars [24, 25]), which is a six-wheeled rover with triple bogies and 3-DOF (degree of freedom) wheels [26, 27].

Notably, the bogies balance the rover such that the rear two wheels are connected and balance about a center pivot bogie assembly, while the remaining pair of left wheels and right wheels do the same. Traditionally, six-wheeled Mars rovers have used the rocker-bogie system described earlier in this paper. Each wheel on this rover possesses 3 DOF: wheel rotation to travel, rotation about the vertical axis (sweep), and a rotating "knee" joint to articulate up and down.

This diverts from the other six-wheeled rovers by eliminating the passive differential to balance the two sides. Instead, the combination of the rear bogie and active DOF can compensate for uneven terrain. It is notable that while Perseverance, the successor of Curiosity, uses the same traditional rocker-bogie setup (with steering motors on the front and back four wheels), these rover designs with planned launches (VIPER in 2023 and Rosalind Franklin in 2022) include more active suspensions than previously flown rovers. While one is part of the "NewSpace" commercial sector and one is traditional public research, they both share similar design changes in their 3 DOF per wheel and emphasis on individual wheel actuation capabilities when compared to traditional rovers. Yet the designs are also notably different; VIPER is four-wheeled with an entirely active suspension to traverse the moon, and Rosalind Franklin is six-wheeled with a mixed passive and active suspension for traversing Mars. This may signal a new set of pathways forward for planetary rover design.

As discussed with SCARAB, slope traversal is one of the reasons a planetary rover may include complexity in the design. This, combined with a desire to escape high slip entrapment such as the terrain which ended Spirit's mission, motivates research into these extra degrees of freedom. At the extreme end of the modification spectrum is a rover design with no passive suspension. The SherpaTT [28–30, 31•] uses an actively articulated suspension system with 5 DOF in each of four-wheeled legs. There is a motor to drive the wheel, to rotate about the vertical wheel axis (for steering) and the vertical axis at the rover body (for panning the leg). Two linear actuators inside the leg joints allow the robot body to travel vertically and fully manipulate the center of gravity. This resulted in the successful traversal of a 28° slope of loose soil and duricrust using a purely force-reactive approach without visual sensors. For a visual comparison of the differences in these systems, please see Fig. 1. It is also meant to be used in conjunction with other robots, such as Coyote III [35] which use an unusual wheel shape. Wheel-leg systems, or "whegs" as they are sometimes called, can combine the advantages of feature climbing from legged locomotion with the efficiency advantages of wheeled locomotion. On a rocky planetary surface with a relatively stable environment media, it would provide advantages over wheeled mobility by generating greater grip and climbing torques.

The range of actuated chassis are beneficial under different circumstances. For a 20 DoF system such as SherpaTT, the control approach is based on force measurements at each wheel mounting point and roll–pitch measurements of the rover's main body, allowing active adaption to sloping terrain, active shifting of the center of gravity, active roll–pitch influencing, and body-ground clearance control. This led to 28° slope ascension of loose soil and duricrust during tests. In less extreme cases, the locomotive gaits of robots such as VIPER or MiniRP15 are designed to slowly crawl and ascend hills or remove the robot from entrapment when traversing unconsolidated media. While they contain less DoF, they are also decidedly less complex, and VIPER is a good example of compromise between classic rover design and newer designs. They are designed for bodies such as the moon with unconsolidated surfaces, and the added complexity of one DoF per wheel has been accepted as a trade-off to allow greater flexibility in exploration and avoiding entrapment.

Modified wheeled mobility continues to develop for missions where the technology will be most advantageous: gravity within an order of magnitude of Earth's (lunar and Martian), traversal of large aggregate amounts of land distance (most efficiently done by wheels), and an anticipated need for slope ascension, entrapment escape, and other similar

Fig. 1 Modified wheeled travel. **A** SCARAB; **B** El-Dorado-II-B; **C** RP15, the precursor to VIPER; **D** Mini-RP15, **E** Rosalind Franklin Rover; **F** SherpaTT. **A** Adapted with permission. Copyright 2019, NASA. **B** Adapted with permission [16]. Copyright 2013, Wiley Periodicals, Inc. **C** Adapted with permission [32]. Copyright 2015, NASA. **D** Adapted with permission [22]. Copyright 2020, Science Publishing Group. **E** Adapted with permission [33]. Copyright 2009, Mike Peel. **F** Adapted with permission [34]. Copyright 2020, MDPI Publishing Group

challenges in partially or fully deformable terrain. In these environments, wheeled mobility provides an opportunity to react vehicle forces against the ground in an energy-efficient manner while adding additional degrees of freedom to counteract the above obstacles. As described in this section, wheeled travel has proven successful in planetary environments. The wheel is an efficient way to travel, engineers are experienced designing around it, and it is versatile in application. The addition of active suspensions and DOF's in this section highlights the ways in which it can be improved, including some rovers with close launch dates. However, sometimes an environment or terrain may require more specialization, and thus, we will discuss alternative surface mobility strategies next.

Alternative Surface Mobility

The above developments have resulted in fundamental changes to wheeled planetary rover technology which will actually be launched or are at higher technology readiness levels. In a different category are mobility approaches which use a fundamentally different locomotion than wheeled travel altogether as seen in Fig. 2. While most of these have not been selected for a launch or launched yet, they represent possible developments for the planetary robotics community in the future. The first of these research thrusts is the category of screw-propelled vehicles [37–45], which are ground or amphibious vehicles which use helical geometries and blades to generate thrust rather than wheel traction. These have been developed further for Earth-based applications but are currently in the experimental stage for space. Although the above research has shown that a screw-propelled vehicle can mobilize in lunar simulant in Earth gravity, there remain several questions before the form is adopted for space applications. Aside from mass and volume considerations, the locomotion is relatively inefficient in a heavily frictional environment such as that of the moon or Mars. The large amount of surface contact is less advantageous than in an amphibious or colloidal environment like clays which are the typical environment of a screw-propelled vehicle (SPV) on Earth. This large contact patch also raises questions about thermal management, as it would provide a quick pathway for heat loss. However, keeping the planetary rover design philosophy in mind (form follows function), there are several cases in which this form of mobility would be attractive.

One proposed use of screw propulsion is not as a substitute for wheels but instead concentrically located around a snake-like body [36, 46]. In this case, it is likely that a combination of wheel-like movements, screw propulsion, and body manipulation would be more energy-efficient than snake movement alone. The Exobiology Extant Life Surveyor (EELS) program intends to use such a robot to traverse unconsolidated snow/ice on Enceladus (one of Saturn's moons), fall or anchor down a crevasse, and eventually swim through the water below the surface

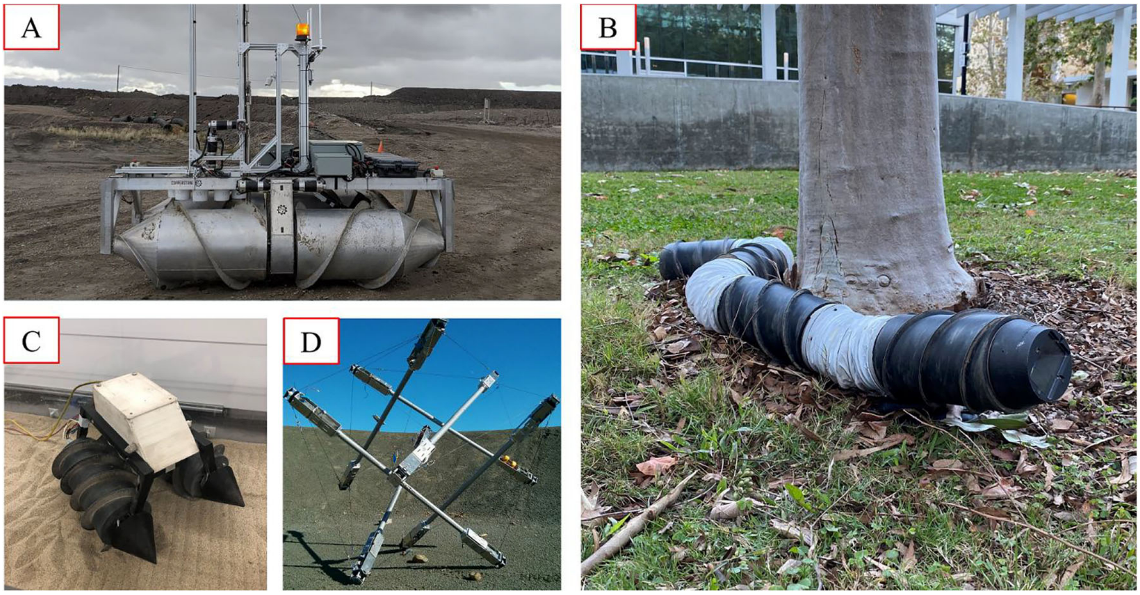

Fig. 2 Alternative surface mobility. **A** Copperstone Technology's AR-0, **B** ARCSnake, **C** Lunar SPV Prototype, **D** NASA Superball Tensegrity Lander. **A** Adapted with permission. Copyright 2020, Copperstone Technology. **B** Adapted with permission [36] from UCSD Advanced Robotics and Controls Lab. Copyright 2020, IEEE. **C** Adapted with permission. Copyright 2020, Andrew Thoesen. **D** Adapted with permission, Copyright 2017, Vytas Sunspiral . Copyright 2017, ASME

to look for microbial life or the precursors thereof, such as thermal venting. The desire for using the screws as aquatic propulsion gives them an advantage in this case, and the thermal balance has been accounted for. This proposed mission is also of relatively short duration. The characteristic of short duration is one of the most important. If long-term thermal maintenance is not required, there is flexibility if the propulsion conveys an advantage. In the case of the EELS robot, we see a compelling case for the use of the screw propulsion on Enceladus.

One of the more radical ideas to gain recent traction is that of tensegrity locomotors on planetary surfaces. Tensegrity structures are a collection of *n* axial elements suspended in either compression or tension, composed into a designated structure. Using a controller on this network, it is possible to create poses for effective impact absorption [47], transporting a 1 kg package over 1 km on the moon by means of "walking" and hopping [48], or even as an all-encompassing descent, landing, and maneuvering system for the ocean worlds of our solar system [49]. A full discussion of the "SUPERball" form of these types of systems is provided by NASA [50, 51]. An advantage of these systems is the ability to centrally locate important payloads and protect them with the active suspension (of which the entire robot is comprised). They also have a potentially advantageous robot mass-to-payload ratio and flexible configurability; in the ocean world's example [49], the proposed structure acts as the descent vehicle (supporting a heat shield), lander (providing the structure for impact), and locomotor robot (using a jellyfish-like motion). Such a reconfigurable robot would conserve significant mass and resources over a rover which required these additional systems for a safe delivery to the surface.

Finally, purely legged locomotion is not often considered for unconsolidated planetary surfaces because of energy intensity and deformable terrain instability. Nevertheless, it is a fundamentally important robot form and could provide a blueprint for robots which crawl along the surface of rocky low-gravity bodies such as asteroids. One such robot is JPL's Robosimian [52], an advanced platform which could be a candidate for crawling across low-gravity rocky surfaces due to its high degree of freedom and grippers. It is also a candidate for microspine end effectors, which will be discussed in the next section.

Alternate surface mobility techniques which deviate from traditional wheeled reaction forces will continue to emerge for environments with different challenges; these include amphibious or aquatic targets and low-gravity surface travel in either unconsolidated or rocky media. In both cases, the terrain is not suitable for wheels to react against, and other locomotive methods are required. We have examined various approaches to planetary surface locomotion. Some of these have flavors of bioinspired movement, such as the principles of an earthworm, snake, or jellyfish. Others adapt a different way of interacting with the terrain, like the screw or tensegrity walking. Regardless, they are all designed with their environment in mind. However, some environments are better traversed off the ground, and for that, we will next examine vertical mobility.

Vertical Mobility

Historically, robotic exploration of other worlds has only been concerned with the locomotion of ground craft from point A to point B. As technology advances, shrinks in mass, volume, and price and accumulated experience start to influence design, and thus, this mode of space exploration will undoubtedly change. The last decade has seen proposed systems which rappel down or climb up cliffs, fly, and hop to explore their environments.

Although climbing robots have been developed for both Earth and space applications, their complexity has been sometimes seen as a hurdle to implementation in space. One possible solution is that of a repelling robot. The proposed Moondiver mission [53, 54], using the Axel rover system [55–57], suggests using this method as a means of exploring underneath the lunar mare, using a pit in Mare Tranquillitatis, and performing the first subsurface exploration. Details of the tether are covered in a recent paper [58], but the core concept involves a lander on the surface using a tether which acts as an anchor and a means for power delivery and communications. The Axel rover would then travel from this lander, with the stored tether and instrumentation, taking measurements along the descent into the lava tubes. This could reveal valuable secrets about the formation of the moon and its chemical and geologic makeup using measurements and an evaluation of the measurements as a function of depth.

Another interesting development with regard to robotic climbing technology in recent years has been the microspine [59–62]. The kinematics are designed such that passive pulling away from a gripped surface causes a reaction force which tightens the grip, ensuring anchoring. They have been shown to climb at inverted angles, reaching 116° [63] in experiments. This has been proposed for use in a variety of forms, including the now defunct Asteroid Redirect Mission, as a way to anchor, drill, and extract samples or entire boulders from an asteroid [64]. It is currently being explored for use in deep underwater missions [65] and is the main end-effector of the robot LEMUR 3 [66]. LEMUR 3 is the latest iteration of a robotic design going back to the original LEMUR in 2000 through LEMUR 2B in 2005 [67]. It was intended to use a different adhesive end-effector for external ISS use and use microspine grippers to climb caves on the moon and Mars. Among the most complex of the discussed designs, it uses four arms with seven serially replicated motors, giving it seven DOF per arm.

This was done with the intent to traverse any arbitrary surface from any approach vector. More recent tests have focused on hunting for astrobiological signs using instrumentation [68] on mock Mars lava tube caves and Mars canyon walls. This included a 4.2-m climb in approximately 7 h, although the potential maximum speed of the robot is not discussed.

However, the spines have been shown to have other novel planetary rover uses. PUFFER [69, 70] is an origami-inspired foldable robot which aims to enhance missions by providing a low-volume, low-mass, two-wheeled rover which integrates the electronics into the foldable chassis itself. Notably, the robot only uses 3 motors, one in each wheel and one to perform the folding motion. Designed for Mars lava tubes and potentially other environments, it is composed of spaceflight-tolerant materials and has tested microspines [71, 72] attached to the wheels, allowing it to climb steep inclines (47–49° depending on design). A similar robotic form factor based on the DROP robotic family [73] has shown the ability to climb vertical walls with the microspines as well. Unlike prior microspine systems, which use multiple materials, the main portion of each leg slice is constructed of laser cut high-impact acrylic in a cassette of nine stacked leg slices, rigid outer plates, and thin spacers separating each slice to allow independent movement. The microspines protrude only from the tip of each leg and do not interfere with the ground during normal forward walking, which prevents harm to the surface and stops the dulling of the spines when not in use

The Mars Helicopter *Ingenuity* [74–79] is a drone helicopter launched in 2020 to demonstrate the technology performance of flying robots in Mars atmosphere. Unlike the moon, which has no atmosphere to speak of, Mars possesses a very thin atmosphere (less than 1% of Earth pressure). This will be the first planetary powered flight beyond Earth. With a maximum altitude of 10 m and a maximum range of 300 m planned, combined with the orders of magnitude increase in speed and decrease in mass (see Table 1) compared to ground rovers, it represents a potential expansion in the approaches to scientific research on atmospheric bodies. Up to five flights are planned in the span of 30 days during the early stages of the Mars 2020 mission. A successful technology demonstration would likely lead to further development of larger craft, potentially up to 15 kg. This would enable direct communication to an orbiter and create a lander-independent robot, along with the addition of science payloads to the craft.

A New Frontiers mission in the same vein but with much larger scope is the proposed Dragonfly [80] architecture. This 8-rotor quadcopter would investigate Saturn's moon Titan for clues as to the development and origin of early life. Since the launch is set for 2027, the design continues to develop at the time of this review so the items in Table 1 are based upon current information. Notably, the mass has been nominally designed at 420 kg. This, contrasted with *Ingenuity*, highlights an important aspect of planetary robotics and a key insight to take away from this review: design for the environment. Mars has < 1% of the Earth's atmospheric pressure and roughly one-third of its gravity. Titan has 4 times the atmospheric density with one-seventh of the Earth's gravity. This is why a system of 1-m rotors can theoretically achieve enough thrust for flight of a 400+ kg vehicle. As we can see in Fig. 3, the differences in these robots is the greatest of the three categories.

Table 1 Planetary surface mobility styles, configurations, masses, and travel speeds

Name	Planetary body	Mass (kg)	Locomotion style	Appendages	Suspension or actuation	Speed (cm/s)	Reference
SCARAB	Moon	312	Wheeled	4 wheels	Passive differential rocker; 2 DOF five-bar stance and height adjustment	6.0	[10–12]
El-Dorado-II-B is	Moon	35	Wheeled	4 wheels	No passive, active linear actuators	5.0	[15–17]
VIPER	Moon	430	Wheeled, articulation	4 wheels	No passive, 3 active DOF per wheel with lift and rotation along vertical axis	22.0	[20, 21]
Mini-RP15	Moon	n/a	Wheeled, sweeping	4 wheels	No passive, 3 active DOF per wheel with lift and rotation along vertical axis	1.5	[22]
Rosalind Franklin	Mars	310	Wheeled, articulation	6 wheels	Passive triple bogie, 3 DOF per wheel	2.0	[24, 25]
SherpaTT	Mars	166	Wheeled, articulation	4 wheel-legs	No passive, 5 DOF per wheel-leg	10.0	[28–31]
ARCSnake	Enceladus	6.1	Screw propulsion	4 screw-wheels	3 active DOF per section	23.0	[36]
Tensegrity	Moon	10	Walking, hopping	6 bars	6 structural actuators, cold gas thrusters	n/a	[47, 48]
Tensegrity	Ocean World	20	Swimming	12 bars	3 structural actuators	n/a	[49]
Ingenuity	Mars	1.8	Rotary craft	2 rotors	None	1000.0	[74–79]
PUFFER	Mars	0.15	Wheeled	2 wheels	1 DOF folding mechanism	n/a	[69, 70]
Dragonfly	Titan	420	Rotary craft	8 rotors	None	1000.0	[80]
3 DOF Flywheel Hopper	Phobos	25	Hopping cube	None	3 internally actuated flywheels for hopping	20.0	[81•]
Axel (Moondiver)	Moon	39	Wheeled, rappel	2 wheels, 1 tether	Suspended on a tether	10.0	[55–57]
LEMUR 3	Mars, moon	35	Articulating arms	4 arms	7 DOF serial actuation per arm	n/a	[66, 67]

All previously discussed designs have targeted a variety of environments but contain a gravitational field within one order of magnitude of Earth's. In these environments, we have presumed that we are allowed to continually react against the ground; that is, if we push against the ground, we will remain there and the ground will remain there. Or, if we spin a wheel, there is enough gravitational force to give us tractive force forward. On an asteroid, this is not the case. To take our review to one of the more extreme environments for robotic exploration, the final proposed robotic explorer of this review, Hedgehog, is a hopping robot designed for asteroid or micro-moon (Phobos) surfaces. Hockman et al. [81•] provide an interesting argument for why hoppers make sense in a microgravity environment. Thrusters have limited propellant and operational complexity. Wheeled surface traction, as discussed above, presumes a strong enough gravitational field which is largely absent on bodies an order of magnitude less massive than the moon or Titan that we have discussed. The wheels will often lose contact with the surface or dislodge a loosely held-together media and engage in uncontrolled tumbling. For legged systems, critical surface properties of the granular media (such as density, cohesion, and strength) are often unknown, and this introduces uncertainty to end-effector design. Anchoring has also shown to be challenging in the past [85]. It has therefore been convention to use hoppers or tumblers on asteroids which bounce across the surface [86, 87]. An item of note is the EELS design for Enceladus, which has roughly 2% of Earth's gravity. In the case of screw propulsion, the screw has a large contact patch and is embedded in the media, and the direction of force is parallel to the rotation axis. With balanced reaction forces from counter-rotating screws, this opens an opportunity to do more controlled surface mobility of low-gravity bodies, although this option has not been frequently discussed.

The HEDGEHOG robot orients three internally located flywheels about its primary axes. This allows for complete enclosure of the design in a sealed cube, which is then protected by structural "spikes" located at its corners. It can apply either abrupt torques (using brakes) or slower controlled torques using motors. This allows hopping for large distance travel on a low-gravity body or tumbling on spikes by use of a weaker torque. Using a unique test bed to simulate microgravity, the robot hopped 30 times at a 50° angle with standard deviation of 3°. The target hop distance of 1 m resulted in an average of 0.94 m and 0.07 m standard deviation, and the average deviation in heading was only 1.5°. While hopping may appear to be random, it is fairly controlled. A notable deviation from target environment is the use of tile instead of granular media, but this was likely done for greater control to emphasize the microgravity results. This is a promising form factor for future tumbling and hopping explorers.

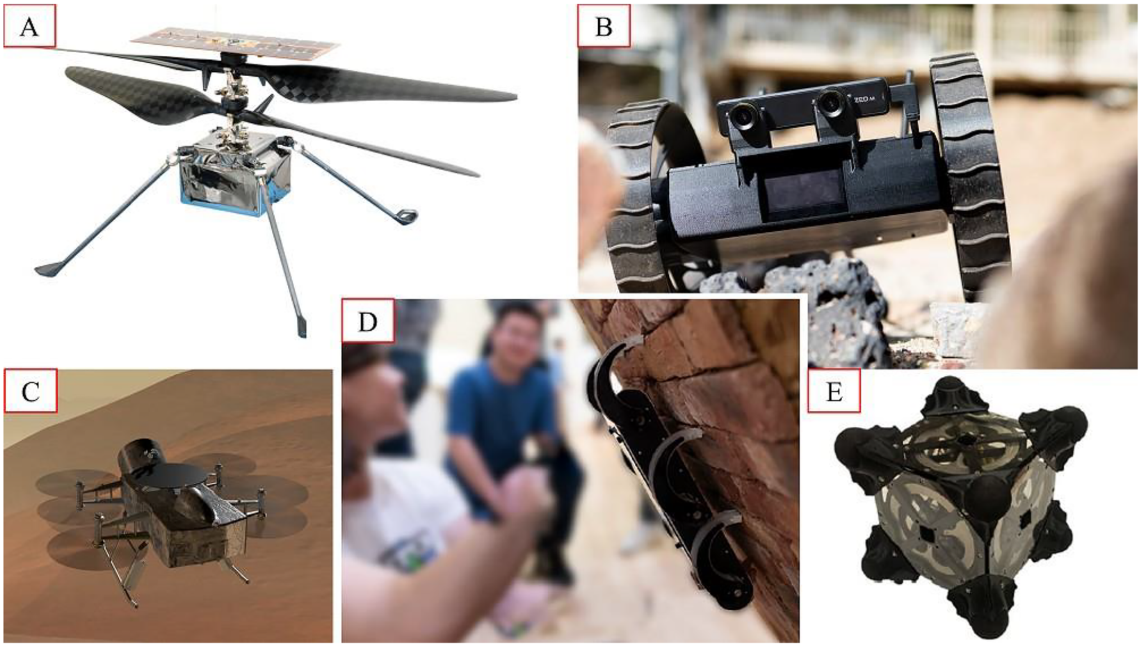

Fig. 3 Vertical mobility. **A** Ingenuity (Mars Helicopter), **B** A PUFFER prototype, **C** Dragonfly, **D** T-RHex microspine robot, **E** 3-DOF internal flywheel hopper. **A** Adapted with permission [82]. Copyright 2020, NASA/JPL-Caltech. **B** Adapted with permission [83]. Copyright 2020, NASA/JPL-Caltech. **C** Adapted with permission [84]. Copyright 2017, NASA. **D** Adapted with permission [63]. Copyright 2020, Authors. **E** Adapted with permission [81•]. Copyright 2016, Wiley Periodicals, Inc.

Vertical mobility will necessarily be different than traversing horizontal differences. The criteria for this technique are a primary or sole focus on robotic exploration and travel which includes a significant motion in the vertical plane. Scaling, jumping, and flying are all ways of achieving this, and the robots in this section demonstrate approaches appropriate to gravity, atmosphere, and surface conditions. Whether it is hopping on a low-gravity body, scaling a rocky cliff, or taking advantage of atmospheric conditions and flying, planetary robots which leave the ground convey certain advantages if the environment permits it. One rotorcraft has already launched, with a second planned for the last half of the decade. It is a testament to the innovation occurring in the design space, the advancement of technology, and challenging our assumptions about what might be the most effective way of exploration. While there are many planetary robots, these new forms will boldly go where no robots have gone before.

Conclusion

Planetary exploration robots take a variety of forms which are driven by the functional needs of some unusual environments and mission goals. In the past, and for most of the present, they have used similar locomotive characteristics on the ground even with impressive advancements in suspension and linkage design. The evolution of these robots continues by adding incremental changes to wheeled locomotion and adding extra degrees of freedom to conquer steeper slopes or avoid entrapment. Further developments introduce non-wheeled locomotion and gaits like walking, inchworming, and screw propulsion. In addition, the idea of a vertical climber or descent along a tether has matured in recent years, and it is likely we will see a flight-ready explorer in the next decade. Finally, aerial exploration has seen the first flight-ready craft in the Mars Helicopter (Ingenuity) with several other rotorcraft proposed for future missions, along with a leap forward in hopping and tumbling robotic design.

The conservative design decisions of planetary rover engineering for previous planetary explorers should make more sense to an outside roboticist in this context. The priority of reliability and mitigating risk encourages reuse as much as possible. It is impressive that the first half of this decade will see two unique rovers with distinctly novel wheel actuation schemes launch and land on planetary bodies. It is equally impressive that the same time frame will also see the first extraplanetary aerial explorer. Based upon that success, a rotorcraft of similar mass to the newly launched rovers will hopefully follow. The launch of such different designs in the present signals a willingness in the commercial and public research sector to open up new avenues for space exploration in the future.

Declarations

Conflict of Interest Andrew Thoesen and Hamid Marvi have a patent pending (systems and methods for a multi-modal screw-propelled excavation; 17/105,011).

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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