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Report on Robotics Technology for NASA's Planetary Science Exploration

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This study was commissioned by NASA's Science Mission Directorate's Planetary Exploration Science and Technology Office to identify high-priority robotics technologies to be developed for future planetary science missions.
It is not intended to represent NASA policy or planning.

Study Contents

Executive Summary

NASA's Planetary Exploration Science and Technology Office (PESTO) initiated this study to obtain recommendations for robotics technology investments and mission infusion. These robotics recommendations will be an input to the new Planetary Science Directorate (PSD) strategic technology plan as recommended by the 2023 Decadal Survey, "Origins, Worlds, and Life (OWL): A Decadal Strategy for Planetary Science and Astrobiology 2023–2032."

The study team convened to provide these recommendations consisted of 25 participants from 18 institutions around the country, including robotics subject matter experts (SMEs) and planetary scientists from NASA, industry, and academia who represent a diverse set of perspectives, expertise, and career levels.

The scope of the report includes surface, sub-surface, and aerial planetary robotics, while deferring some related fields to other dedicated efforts and reports. The result of the study is a list of high priority robotics technologies that, if matured through targeted investments, could enable high-priority missions highlighted in the planetary science decadal survey, or have potential to provide breakthrough advances this decade and beyond. The decadal survey does not make specific recommendations for missions smaller than New Frontiers, but it does outline compelling science questions that these missions could address. Hence, technology that could impact Discovery, Small Innovative Missions for Planetary Exploration (SIMPLEx)-class and smaller is included. The decadal also recommends science payloads to the Moon such as via PRISM (Payloads and Research Investigations on the Surface of the Moon) and CLPS (Commercial Lunar Payload Services) programs. With this scope, the study team identified top areas where NASA should invest in robotics technology development and infusion.

The first theme in the robotics technology recommendations is to go farther and sample more. The ability to sample and place instruments in-situ at a large number of locations on a planetary body is enabled by robotics. There is a tremendous opportunity for achieving this while acquiring science at relatively low cost given the synergy with the Moon to Mars program. With dedicated technology investment Endurance-A could achieve more than its baseline by driving even farther and robotically deploying in-situ instruments and autonomously sampling. The technology recommendations were selected so that if we're successful in infusing capability into science missions on the Moon and Mars, it could enable long-range missions in the future such as to Enceladus and Europa.

The second theme is small scale science robots. Small scale mobile robots and manipulators capable of deploying small science payloads could revolutionize small-class programs such as Discovery. They could extend the science reach of lander missions. Prior flight planetary science robots would not fit on small-scale missions. The Ingenuity flight technology demonstration weighed just 1.8 kilograms. Probes and lander missions are often the frontline for the first planetary exploration of a surface. The surface of previously unexplored planetary bodies can vary substantially from what is expected. Instruments onboard the OSIRIS-REx mission to asteroid Bennu revealed a surface littered with boulders instead of the smooth sandy surface that was expected based on observations from Earth and space-based telescopes. If flight maturity is demonstrated via CLPS payloads to the Moon, small mobile robots capable of accessing multiple locations could mitigate the risk of missions to unexplored surfaces and transform lander missions to Mars, small bodies, and beyond by increasing science return.

The third theme is to access extreme terrain and deep under the surface. Some technologies need investment over a long period to mature. Developing extreme terrain robots to access central peaks and rims of craters on the Moon and Mars will allow the capability to be ready for exploring caves and for missions farther from the Sun. Sub-surface access enables accessing samples from key science locations the Moon, Mars, and ocean worlds. They are enabled by components with low mass and power requirements that are capable of high performance in extreme conditions.

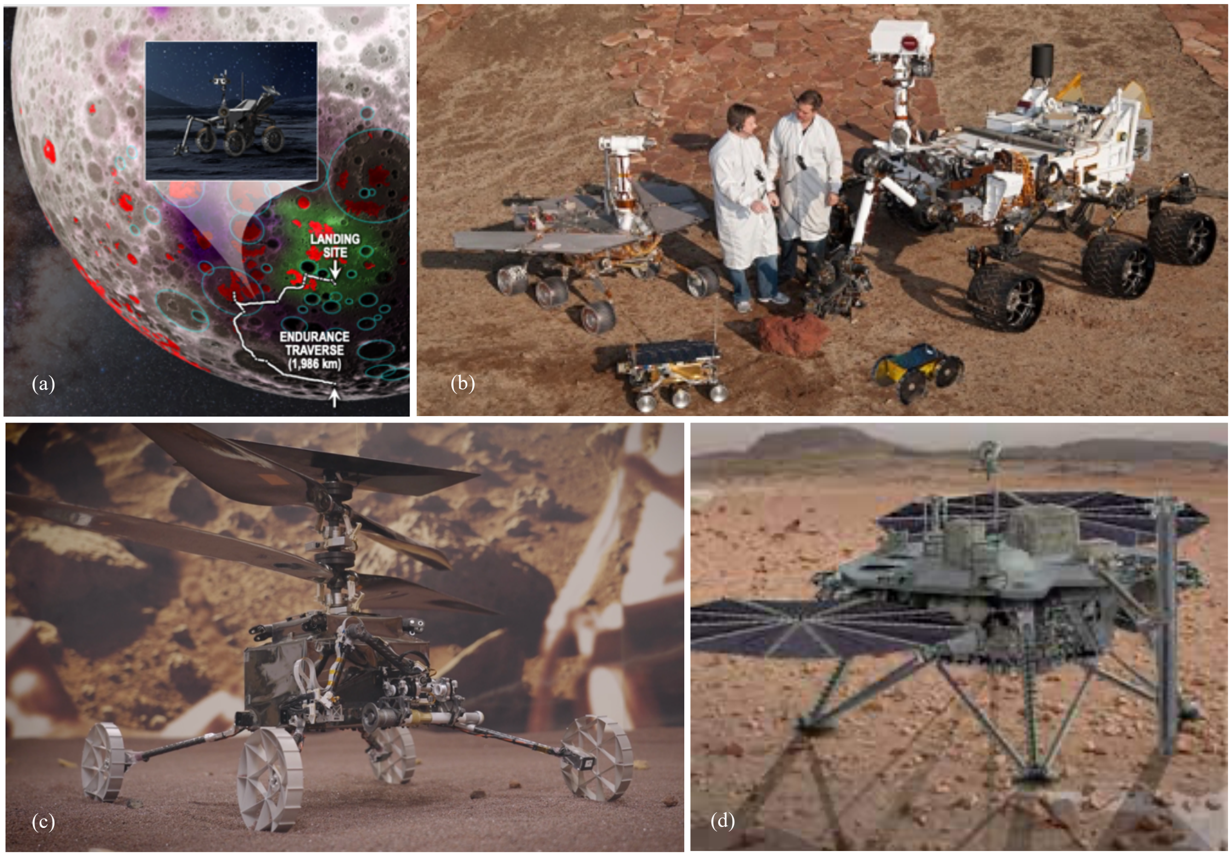

Figure 1: Planetary robotics technology themes: ***Theme 1: Go farther and sample more****. (a) Use of the capability from the Endurance-A decadal mission concept showing the different geologic contexts that the long traverse could sample. [1]* ***Theme 2: Small scale science robots.*** *(b) Scale of small robots compared to some past planetary robots is shown with the 2kg IRIS rover , designed as a CLPS payload, superimposed on an image with full scale models of the larger Sojourner, MER, and Curiosity rovers and engineers for scale comparison [2] [3]. (c) The 2.6kg Sample Recovery Helicopter development platform with wheels, a 120gm robotic arm and gripper capable of dropping and picking up 100gm payloads [3].* ***Theme 3: Access extreme terrain and deep under the surface****. (d) A use of the capability is demonstrated via an image of drilling in the Mars Life Explorer decadal mission concept [4].*

The top 10 recommendations to enable these three themes for NASA's future planetary science missions are listed below. The list factors in the expected timeline of New Frontiers, Discovery, and smaller class missions and robotics technology development necessary to achieve the highest priorities from science Analysis Groups (AGs). Theme 1, to go farther and sample more is enabled by recommendations R1–R6. Theme 2, for small-scale robots is enabled by R8 and R10. Theme 3, for extreme terrain and sub-surface access is enabled by R6–R7 and R9.

R1. Perception software/algorithms for challenging lighting conditions
R2. Perception and illumination hardware and component systems
R3. Surface navigation systems for long-range day and night driving
R4. Autonomous positioning of instruments and autonomous sample collection, handling, and verification
R5. Long-range variable-altitude balloons
R6. Drilling systems that can reach a depth of 2m or more in rock and ice
R7. Deep ice probes for accessing subsurface reservoirs on ocean worlds

R8. Small-scale (<10 kg) mobility platform for scouting and targeted science
R9. Extreme terrain mobile access system for steep and irregular terrain
R10. Components for extreme environments including cold- and heat-tolerant actuators, rechargeable batteries, and long-life wheels and mobility components

The remainder of the report provides in order:

- Details on how the study was conducted;
- A summary of the guidance from the OWL decadal survey;
- The robotics technology areas identified and science justification for them (Section 2);
- Details on top 10 robotics technology development recommendations, each of which falls in one of the technology areas identified in the item above (Section 3.1); and
- Process recommendations for technology development and infusion success (Section 3.2).

1. Introduction

1.1 Objective

The objective of this study is to provide recommendations to NASA for investments in robotics technologies that may enable future high-priority planetary science missions. Robotic systems have served a crucial role in past planetary science missions and will continue to enable future missions. However, the landscape of terrestrial robotics technologies is vast, and the rate of innovation and development tends to far outpace the frequency of mission opportunities in planetary science. In addition, terrestrial robotics technologies require investment to adapt for space environments and specific mission needs and funding is limited. Thus, this study aims to survey the state of the art in robotics technologies and the landscape of high priority science questions and missions in order to identify key areas in which targeted investments could yield significant impact for planetary science.

The approach of the study was to convene a broad and diverse panel of “subject matter experts” (SMEs) from NASA centers, industry, and academia that could best represent the diverse nature of the field and its many applications. Several planetary scientists also participated in the study to represent the diverse range of topics and priorities for NASA. Several online meetings were held in order to brief the SME panel on priorities in planetary science and brainstorm and organize candidate technologies that may have a high impact. A two-day in-person workshop was held to discuss and down-select technology priorities. These priorities were further synthesized in subsequent meetings and discussions with scientists. This report documents the findings.

1.2 Study Participants

This study brought together approximately 25 participants from 18 institutions around the country, including robotics SMEs and planetary scientists who represent a diverse set of perspectives, expertise, and career levels.

Figure 2: Study participants. Shown (left-to-right): Andrew Horschler[1], Colin Creager[2], Jaret Matthews[3], Andrew Howard[4], Sam Howell[5], Hari Nayar[5], Fernando Figueroa[6], Al Rizzi[7], Karl Stolleis[8], Ashitey Trebi-Ollennu[5], Hannah Stuart[9], Vandi Verma[5], Benjamin Hockman[5], Josh Mehling[10], Gino Perrotta[11], Louise Jandura[5], Kris Zacny[12], Joey Beckman[13], David Wettergreen[14], Helen Aslanian[15], Valerie Scott[5], Eddie Tunstel[16]. Not shown: Terry Fong[17], Laura Ray[18], Bill Smythe[5], Jim Cutts[5], Bob Balaram[5], Katie Stack[5], Chris Culbert[10], Julie Castillo-Rogez[5]

1. Astrobotic Technology, Pittsburgh, PA
2. NASA Glenn Research Center, Cleveland, OH
3. Venturi Astrolab, Hawthorne, CA
4. SpaceX, Hawthorne, CA
5. Jet Propulsion Laboratory, California Institute of Technology Pasadena, CA
6. NASA Stennis Space Center, John C. Stennis Space Center, MS
7. Boston Dynamics, Waltham, MA
8. Lockheed Martin, Littleton, CO
9. University of California, Berkeley, Berkeley, CA
10. NASA Johnson Space Center, Houston, TX
11. John Hopkins Applied Physics Lab, Laurel, MD
12. Honeybee Robotics, Altadena, CA.
13. AeroVironment Inc., Simi Valley, CA
14. Carnegie Mellon University, Pittsburgh, PA
15. Maxar Space Robotics, Pasadena, CA
16. Motiv Space Systems, Pasadena, CA
17. NASA Ames Research Center, Mountain View, CA
18. Dartmouth College, Hanover, NH

1.3 Technical Scope

The scope of this study concerns the field of “Robotics,” which is inherently multidisciplinary. For our purposes, we define a “robot” as *a physically embodied engineered system that can carry out a series of complex actions*. Therefore, the practice of robotics is the synthesis of various components and subsystems (typically structure, actuators, sensors, and software) in order to perform a task by interacting with a specific physical environment or domain. These systems often have some degree of autonomous control, especially in space applications where the opportunity for direct human operation is limited. Figure 3 shows an example of the Perseverance robot.

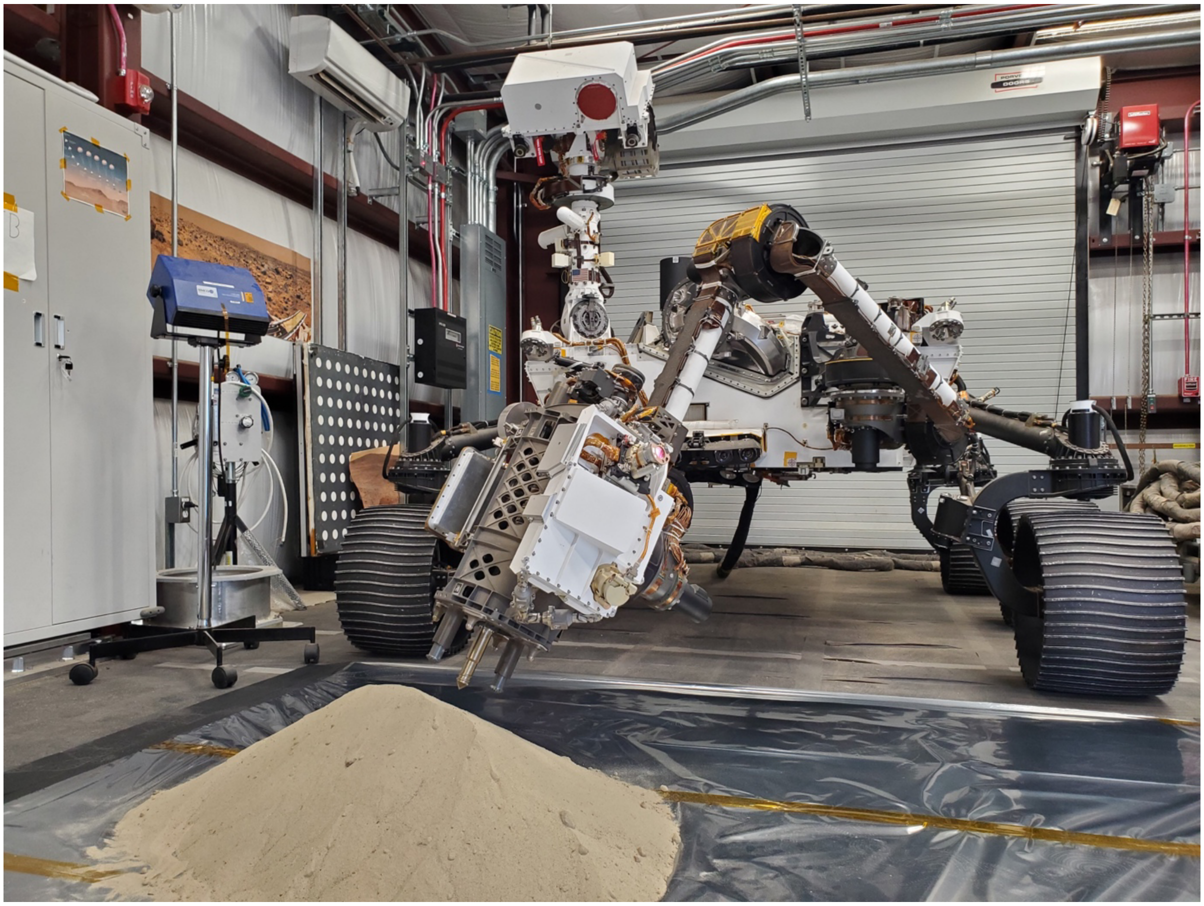

Figure 3: Picture of the full-scale Earth replica of the Perseverance robot. It has wheels for mobility, a robotic arm for positioning science instruments and tools close to the surface. It is shown here using its robotic arm to position the regolith bit for sampling. It is comparable in scale to the Curiosity rover show in Figure 1(b) [3].

To distinguish from pure software domains such as “Autonomy,” “AI,” “Integrated System Health Management (ISHM),” “Data Science,” and related system-level autonomy technologies (on which other studies have been conducted, [5], [6], [7], this study is restricted to *embodied* [8] systems that can physically act in the world; or in this case, other worlds. This study focuses on robotics for planetary science exploration. The scope of the report includes surface, sub-surface, and aerial planetary robotics, while deferring some related fields to other dedicated efforts and reports. It does not include other NASA applications of robotics, for example, In Space Assembly and Manufacturing (ISAM) [9], Guidance, Navigation and Control (GNC) [10], In-Situ Resource Utilization [11], or robotics for human exploration [12]. The scope of the missions to consider for technology needs were those not already under NASA development at Phase A and beyond. As a result, missions such as Mars Sample Return, and the Dragonfly New Frontiers planetary science mission were outside the scope.

It was also recognized that technology investment is needed in a number of related areas for the success of planetary robotic missions such as high-performance computing, power, simulation, testing, operations, autonomous resource and health management, fault handling, and autonomous science observations. These are listed as key supporting technologies.

1.4 Planetary Science Priorities

Planetary science broadly considers questions relating to planetary systems, including a large diversity of objects, processes, evolution, and systems. Thus, there are a vast number of topics of interest in the planetary science community which must be prioritized in order to steer NASA's budget, both for research and future missions. Every ten years, the National Academies of Sciences, Engineering, and Medicine (NASEM) conducts a committee-led exercise to broadly canvas the field of space- and ground-based planetary science to determine the current state of knowledge and to identify the most important scientific questions to be addressed during the next decade. The most recent survey, "Origins, Worlds, and Life (OWL)," [13] was released in April 2022. That document structured the diverse range of planetary science into 12 topics, each with a set of driving questions:

<u>Origins</u>

1. Evolution of the Protoplanetary Disk
2. Accretion in the Outer Solar System
3. Origin of Earth and Inner Solar System

<u>Worlds and Processes</u>

4. Impacts and Dynamics
5. Solid Body Interiors and Surfaces
6. Solid Body Atmospheres, Exospheres, Magnetospheres, and Climate Evolution
7. Giant Planet Structure and Evolution
8. Circumplanetary Systems

<u>Life and Habitability</u>

9. Insights from Terrestrial Life
10. Dynamic Habitability
11. Search for Life Elsewhere

<u>Cross-Cutting Topic</u>

12. Exoplanets

The decadal survey also made recommendations to NASA for mission priorities in the next decade, including specific medium-class (New Frontiers and Lunar Discovery and Exploration) and large-class (flagship) missions. The flagship missions are, in priority order:

(1) Europa Clipper
(2) Mars Sample Return (MSR)
(3) Uranus Orbiter and Probe (UOP)
(4) Enceladus Orbilander

Other flagship mission concepts that were studied include Europa Lander, Neptune Triton Odyssey, Venus Flagship, and Mercury Lander. Though these were not prioritized, they are likely to resurface in future decadal studies and should be considered in technology development priorities.

Under the Lunar Discovery and Exploration Program (LDEP), the decadal survey prioritized:

- Endurance-A, a long-range rover to collect 100 kg of samples from the South Pole Aiken (SPA) basin and return them to a location close to the South Pole for collection by astronauts [14].

Under the Mars Exploration Program (MEP) after MSR, the decadal survey prioritized:

- Mars Life Explorer (MLE), a static lander with an ice drill and robotic arm. MEP has also recently been working on a low-cost Mars program [15], which could provide more opportunities for smaller-class missions, depending on budgetary constraints.

The candidate New Frontiers mission themes are (alphabetical):

- Centaur Orbiter and Lander
- Ceres sample return
- Comet surface sample return
- Enceladus multiple flyby
- Lunar Geophysical Network
- Saturn probe
- Titan orbiter
- Venus In Situ Explorer
- Triton Ocean World Surveyor (for NF-7)

While the decadal survey's mission priorities are based around detailed concept studies, their recommendations are largely related to the science that they address. Specific engineering implementations are subject to change/reformulation, especially for those with longer time horizons, as the budgetary environment changes, new technologies become available, and science priorities drift in response to new data and mission selections. Therefore, in considering robotics technologies for this study, we treat specific mission studies as a general framework for the technologies that might be infused and could weigh more heavily on their science objectives.

In addition to specific large- and medium-class missions, the decadal survey also recommends a continued cadence of smaller PI-led missions, including the Discovery and SIMPLEx programs. These competed missions do not have specific target requirements and allow for any mission concepts that fit within the cost caps and address high-priority science. Thus, our study also considered robotics technology that could enable or facilitate wholly new mission concepts targeting decadal science priorities. Key mission themes for robotics technology include extreme terrain access, such as pits, caves, and scarps, landers with deeper drills, and small-scale, low-cost mobility platforms. Cross-cutting technologies that may impact a broad diversity of competed missions were also considered, particularly relating to mobility and manipulation.

1.5 Decadal Survey Technology Recommendations

The OWL decadal survey included a dedicated effort to assess the state of technology development at NASA and to identify key gaps in capabilities that, if brought to bear, could enable high-priority planetary science missions in this decade and beyond (Chapter 21). This technology assessment preceded the announcement of the science mission priorities and is therefore general and not specifically targeted to the outcome of the science prioritization. However, the decadal effort did approach technologies through a science-focused lens, referring to the twelve driving science questions and associated target bodies. We summarize the technology recommendations related to robotics here to serve as a reference for this study. Table 1 summarizes the robotics-related technologies from Table 21.1 of [13], and the associated findings. Further details can be found in Chapter 21 of the OWL decadal survey [13].

Table 1. Excerpt from OWL Table 21.1 [13] *related to robotics - “Technologies Identified to Be Advanced in This Decade and Beyond”*

Technology Area	**Rationale**	**Science Questions**	**Applicable Destinations**
In situ sample handling, preprocessing, and analysis	Priority missions need this technology area this decade. Sample collection without modifying/ destroying sample physical/chemical properties, robust material separation (sample handling) and high accuracy and precision detectors (sample analysis) need to mature.	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12	Venus, Moon, Mars, small bodies, ocean worlds, giant planets
Autonomy	Autonomy advancements are required at a system level to integrate and harmonize subsystems to make decisions and execute planned operations on remote, complex, and potentially unknown planetary bodies.	All	All
In situ mobility (aerial/surface)	Improved in situ mobility is required for priority missions later this decade. Aerial mobility benefits from further advances in rotor vehicles and balloon platforms, while surface mobility needs autonomy (see Autonomy) and higher mechanical endurance.	1, 3, 4, 5, 6, 8, 10, 11, 12	Venus, Moon, Mars, small bodies, ocean worlds
Subsurface access	Priority future missions targeting surface/subsurface exploration require access to pristine/unmodified materials. Technologies include drills, melt probes, tethers, submersibles, emplaced communication nodes, telemetry from the probe/drill tip, and materials capable of meeting stringent planetary protection requirements.	1, 3, 4, 5, 6, 8, 9, 10, 11, 12	Earth, Moon, Mars, small bodies, ocean worlds

Additional items *from Table 21.1 of the Decadal Survey* that overlap with robotics technology are listed below:

Technology Area	**Rationale**	**Science Questions**	**Applicable Destinations**
Cold/cryogenic sample return	Maintaining cold/cryogenic samples is the next step in sample return, and cold/cryogenic sample return missions are being considered as soon as early next decade.	1, 3, 4, 5, 6, 9, 10, 11, 12	Moon, Mars, Venus, small bodies, ocean worlds

Technology Area	Rationale	Science Questions	Applicable Destinations
Challenging environments	Priority missions and SRs need technologies for overcoming extreme temperatures, pressures, radiation, and dust accumulation this decade.	1, 3, 4, 5, 6, 8, 9, 10, 11, 12	Earth, Moon, Venus, Mars, small bodies, ocean worlds
Technology System Engineering and Integration	Many technology areas are best advanced when integrated with other technology areas, particularly for automated landing, sampling, mobility and surface operations.	All	All

In contrast to Chapter 21, this study considers the specific mission recommendations from the decadal survey and employs a diverse group of robotics practitioners, whose collective expertise may identify robotics technologies that could enable wholly new mission concepts. Therefore, this study is not constrained by the technology recommendations from Chapter 21, though it is informed by them and the emergent priorities are overlapping.

1.6 Study Procedure

The approach of the study was to convene a broad and diverse panel of SMEs from NASA centers, industry, and academia that could best represent the diverse nature of the Robotics discipline and its many applications. Several planetary scientists also participated in the study to represent the diverse range of topics and priorities for NASA. Through a series of meetings, the team reviewed and discussed the OWL decadal survey and generated, discussed, and prioritized a list of figures of merit and robotics technology items. A preliminary list of approximately 200 robotics technologies were clustered, categorized, and refined down to a list of 25 for the in-person deliberations. A two-day in-person workshop was held to further discuss and down-select technology priorities. These were distilled into nine robotics technology topic areas that cover the breadth of the discipline as applied to planetary space exploration. Specific and prioritized funding needs within each topic area were then identified through a series of report-writing assignments and discussions with additional SMEs and scientists. These priorities were further synthesized in subsequent meetings and discussions with scientists into the top 10 technology recommendations. This study strove to achieve a balance of both shorter- and longer-term investment recommendations in order to maximize and diversify the impact on planetary science. In order to assess the relative priorities of technologies, five key figures of merit were developed by the group and used in our evaluation:

Table 2. Figures of merit used in technology evaluations.

#	Figure of Merit	Description
1	**Enabling to decadal survey missions**	This criterion addresses how relevant the technology is in the success of missions identified by the decadal survey. Highly enabling technologies are crucial for mission implementation, whereas weakly enabling technologies add capability or reduce cost/risk.
2	**Groundbreaking for planetary science**	This criterion addresses the potential impact of a technology for enabling new missions or capabilities that were not in the decadal survey, but which address high-priority science in a new way. This could mean enabling new missions/capabilities for smaller class

#	Figure of Merit	Description
		missions within this decade or for larger missions in subsequent decades, but which need early investment.
3	**Diversity of impact**	This criterion addresses the breadth of applicability of a technology across a range of potential planetary science missions in this decade and beyond. While engineering adaptations are usually required to satisfy particular mission requirements, core technology capabilities may significantly reduce the cost and risk for mission adoption.
4	**Investment needed to mature**	This criterion addresses the return-on-investment (ROI) for technology investment. Some technologies may require substantial funding to mature toward mission readiness (roughly TRL 5-6), whereas others may only need a small push.
5	**Insufficiently addressed outside of PSD**	This criterion addresses the unique need for investment from NASA's Planetary Science Division. Many technologies are rapidly maturing for terrestrial applications or for other NASA interest (e.g., for human exploration), whereas others are more specific to the needs of PSD and do not have another mechanism for maturation.

It is important to note that these figures of merit are (intentionally) not quantitative metrics and were not evaluated as such. Rigorous quantification is difficult, time-consuming, uncertain, and often subjective. Rather, this study used these criteria as guiding qualities on which to base discussions and justifications of relative importance. It is also expected that most technologies are not uniformly meritorious across these criteria. While severe deficiencies may discredit a technology from contention (e.g., minimal impact or requiring significant funding), asymmetric qualities are acceptable.

Finally, while not explicitly considered in rankings and deliberations, a final assessment of the prioritized list was conducted to ensure sufficient *portfolio diversity*. In other words, we wanted to ensure that disproportionate favor did not emerge for any one type of technology, mission, target body, or science question. Ultimately, diversity emerged organically without the need for any "rebalancing" – some technologies are directly enabling for decadal missions, some more groundbreaking for future missions, and others more broadly applicable for a variety of missions.

2. Robotics Technology Areas

Through virtual and in-person discussion, this group distilled nine key robotics technology areas that are likely to have a high impact on future planetary science missions. Chapter 3 will synthesize these technology areas and further refine a condensed list of top 10 priority robotics technology recommendations.

The general technology areas are, in alphabetical order:

1. Advanced Perception
2. Aerial Access
3. Autonomy for Manipulation and Sampling
4. Components for Extreme Environments
5. Extreme Terrain Mobility
6. Long Range Mobility

7. Multi-agent Autonomy
8. Sample Handling and Verification
9. Subsurface Access

The following sections detail the findings and recommendations for each technology area, including a description of the capability, science justification for its importance, an assessment of the state-of-practice and state-of-art, identification of key technology gaps (for mission infusion), and prioritized recommendations for future investments.

2.1 Advanced Perception

Description of capability: Advancements in perception systems that enable a robot to perceive its environment are needed as new missions are proposed for harsher environments or to be operated for longer durations. This includes perception sensors, including cameras and LiDAR, algorithms, and systems used to model the topography and potentially identify features and material properties of the surface. These are essential for hardware safety and for accomplishing the desired science via robotic mobility, manipulation, and sampling. They include accommodation for large dynamic range lighting, low-light illumination, and cover a wide spectral range. Space qualification and low power, mass, and volume are also driving considerations for these applications.

Science justification: Several surface mission concepts identified in the decadal survey will be to bodies further from the sun than Mars where solar illumination diminishes rapidly. These include Ceres, Centaur bodies, Enceladus, Europa, and other Ocean Worlds. On Mars and the Moon, missions have operated primarily during the day. The Endurance-A mission to the Moon proposes to drive during the day and night to be able to cover 2000 km in 3 to 4 years. The ability to perceive in near to total darkness will also be beneficial for other inner-planet missions.

State of practice: Stereophotogrammetry and feature matching with optical cameras have been extensively used on prior missions for surface mobility, science observations, and terrain relative navigation (TRN) for precision landing. Dedicated FPGA-based fast stereovision-processing algorithms have enabled "thinking while driving" and TRN on the Mars 2020 mission. Mars missions continue to face challenges with vision-based feature tracking and navigation close to sunset and in featureless terrain. In still early analysis, these challenges are believed to have resulted in the end of the very successful Ingenuity mission. LiDAR has been used for science observations on Earth Science missions but not yet on surface mobility spacecraft.

State of the art: Improvements in processing speeds for stereovision algorithms through software and hardware advances have enabled fast off-road mobility in terrestrial demonstrations. The power, mass, and volume of the state-of-the-art systems exceed what can be accommodated on space missions. Highly sensitive low-light cameras using single photon avalanche diodes are available in commercial products. LiDAR systems are being developed for space applications [16]. Optical cameras and LiDAR are not the only means to perceive: alternative perception systems for range imaging, including structured light, time-of-flight imaging, and interferometry, have been demonstrated in terrestrial applications. Multi-sensor fused estimation has been shown for terrestrial applications. Machine-learning approaches to both structure recovery and sensor fusion are showing great promise in terrestrial applications.

Robotics technology gaps:

- Night driving will be needed for the Endurance-A mission. Approaches could include passive perception systems with artificial illumination or active perception systems that do not need natural illumination.

- Low-latency 3D perception, including use of machine learning models.
- Perception for the high contrast and dynamic lighting conditions on airless bodies. Key challenges for perception include the high dynamic range of the landscape, especially closer to shadowed or polar regions; speed of shadow changes on fast-rotating small bodies; and the bright “featureless” appearance when viewing opposite the sun direction (i.e., “opposition effect”).
- Robust matching of sensor data from frame to frame as input to state estimation and from surface data to reference maps for global localization.
- Integration of perception and state estimation from multiple sensors for planetary surface missions. Improvements in precision are possible using inputs with multiple alternative sensor modalities.
- Negative obstacle (i.e., a crater or similar) detection is of importance for mobility in terrain such as on the Moon.

Development priorities:

- Fast and robust feature matching and terrain modeling for mobility in the harsh lighting environment such as the Moon. Including scenes with sparse features.
- Space-qualified, low size, weight, and power perception system for low lighting.
- Terrain modeling for manipulation and sampling in low light conditions such as for the proposed Endurance-A sampling.

Key supporting / synergistic technologies:

- High performance space computing.

2.2 Aerial Access

Description of capability: “Aerial Access” describes vehicle platforms that operate in planetary atmospheres, including aircraft, rotorcraft, and lighter-than-air vehicles. Aerial platforms for science missions typically call for the ability to carry an instrument payload, although they may also serve supporting roles such as scouting or sample retrieval.

Science justification: While various bodies in the solar system have tenuous atmospheres, only three outside of Earth have atmospheres dense enough for practical use of aerial platforms: Venus, Mars, and Titan. Venus is especially compelling for aerial exploration, as its surface is inhospitable for long-lived landers or rovers, whereas the middle atmosphere (particularly 50–60 km) is benign in temperature and pressure. A 2018 study determined that aerial platforms—especially variable-altitude platforms—could substantially address all three major goals established by the Venus Exploration Assessment Group (VEXAG): (I) Atmospheric Formation, Evolution and Climate History, (II) Evolution of the Surface and Interior, and (III) Interior-Surface-Atmosphere Interaction [17]. The platform enables instrument access for determining the chemical composition of the gas and cloud aerosol particles (sulfur and phosphorus cycles) thought to be seeded by volcanic activity, constrain in situ the radiative balance and atmospheric dynamics of the planet, and investigate the crustal geophysics through seismic infrasound detection and remnant magnetism. The ability to perform sub-cloud imaging of the surface would further substantially improve the science return of a Venus aerial platform. Due to the interest in Venus DAVINCI (Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging), and VERITAS (Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy) were awarded in the last Discovery program. Data returned from these missions from orbit and a descent probe are expected to increase interest in in-situ exploration.

On Mars, transect-based science on exposed stratigraphy, long-range coverage for visiting multiple geological units exposed over variable elevation ranges, and atmospheric science are three areas which aerial platforms could enable. Titan is a unique ocean world with an active methane cycle and the target of aerial exploration with the upcoming Dragonfly mission that will cover a ~100 km region. Future aerial missions with long-lived balloon platforms would be a natural next step to achieve a more global characterization of Titan's hydrocarbon cycle and potential evidence for life.

Decadal Reference: The primary mission for aerial access advocated for by the OWL decadal survey is a Venus In Situ Explorer (VISE). Some science objectives for VISE require a lander and some an aerial platform such as a long-lived middle-altitude balloon. On aerial platforms specifically, the survey states "Balloon platform technology can address SRs (Strategic Research) but needs advances this decade to meet the requirements of in situ atmospheric explorations on Venus and other planetary atmospheres" with the finding of:

> ***Finding****: Balloon platform technology has not yet achieved the maturity of rotorcraft and airplanes and is enabling for rapid, precise surface analysis and in situ studies of atmospheric properties on Venus and other planetary atmospheres. The technology requires the capability of inflation, given ultralight materials and structures, without damage and for controlling altitude during science operations.*

Other in-atmosphere missions advocated for in the decadal survey include Mars Sample Return and Mars Life Explorer. While the decadal survey does not mention aerial mobility in the recommendations for these missions, the success of the Mars Ingenuity technology demonstration suggests that aerial mobility could enhance either of these missions.

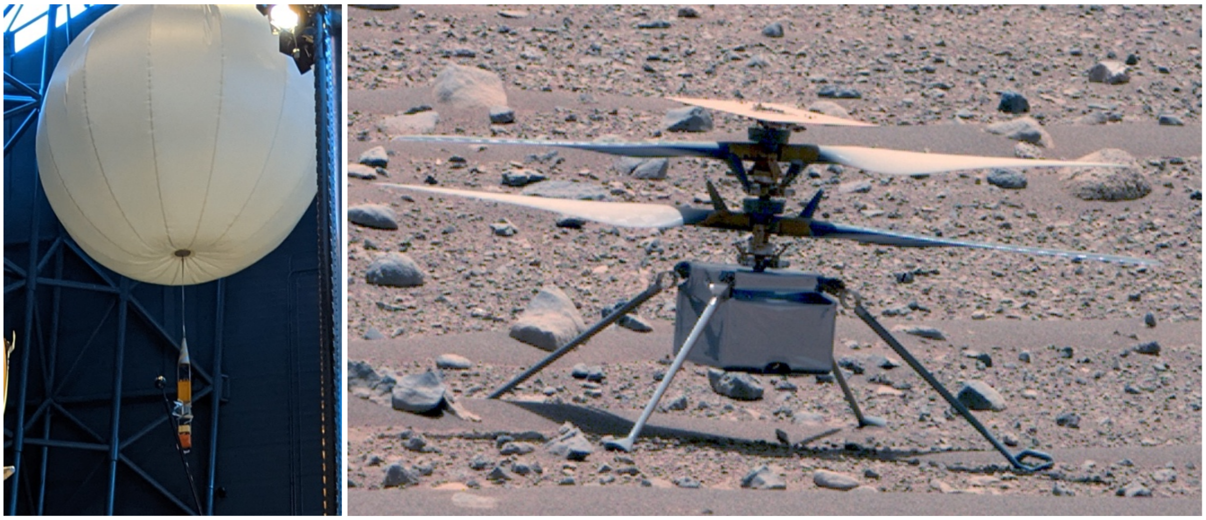

Figure 4: (a) Image of the Vega aerobot comprising of a 3.4m diameter balloon and 21.5kg probe. [18]. (b) Image of Ingenuity Mars Helicopter on Mars taken by the Perseverance rover on April 16, 2023, the 766th Martian day, or sol, of the rover's mission [19]. It has a 1.2meter rotor span with counter-rotating blades.

State of practice: In 1985, the Soviet Union inserted two balloons into the Venus atmosphere as elements of the Venus-Halley (Vega) mission. In two Earth days, each balloon traveled one third of the Venus circumference (>10,000 km) at an altitude of about 54 km, providing unique information on the circulation of the Venus atmosphere (shown in Figure 4a). In 2020, NASA launched the Ingenuity helicopter alongside the Mars Perseverance rover. Ingenuity is a 1.8 kg helicopter – with coaxial blades that spin very fast (~2500 rpm) to remain aloft in the thin Martian atmosphere – that successfully demonstrated powered flight on Mars [20] (shown in Figure 4b). The Dragonfly mission to Titan (shown in Figure 5) will consist of a 900 kg, RTG-powered dual-quadcopter, similar in configuration to modern terrestrial drones [21]. Aided by the dense atmosphere and low gravity, Dragonfly will be equipped with a substantial instrument payload and be capable of traversing roughly 10 km every Titan day (16 Earth days).

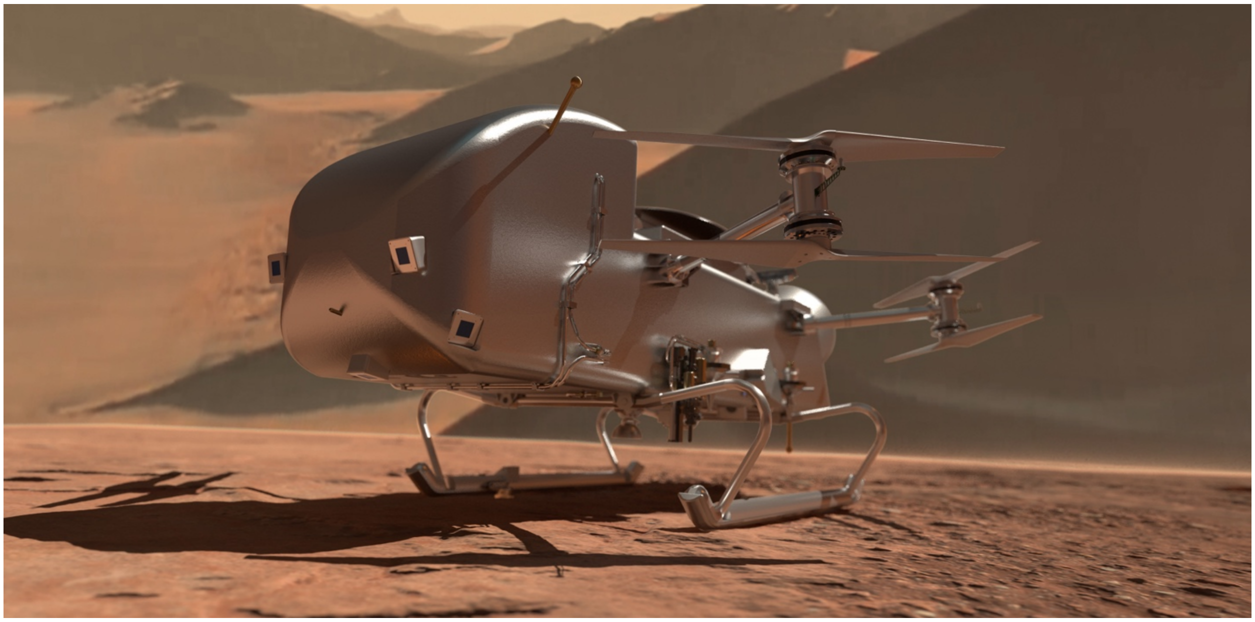

Figure 5: Illustration of the Dragonfly rotorcraft as it prepares to sample and examine the surface of a landing site on Titan [22].

State of the art: Aerial access has a long and diverse history for terrestrial applications. Particularly relevant for planetary aerial vehicles has been the recent explosion in modern drone technology, enabled by fundamental advances in various subsystems, including high-density batteries, small high-performance computers and sensors, autonomy, and materials / manufacturing. New mission concepts can substantially leverage these technologies. For Venus, several novel concepts for powered flight have been proposed [23] [24] [25]. However, the main focus has been on developing technology for the next balloon observatory, which will use modern materials to withstand the corrosive aerosols of the Venusian atmosphere for months and advanced instruments to study the atmosphere and surface in unprecedented detail. Future Mars rotorcraft aspire to perform meaningful science with a few-kg science payload. Short duration Earth atmosphere flight tests have been conducted with TRL 4 prototypes of Venus balloons.

Robotics technology gaps:

- Venus variable-altitude balloon technologies
- Sub-cloud access platforms on Venus
- Payload-capable Mars aerial vehicles
- Long-range Mars vehicles
- Mid-air deployment for both balloons and rotorcraft
- Titan balloons for global reach beyond the planned powered Dragonfly mission
- Rotorcraft or other aerial robotics applications for Mars, Titan, and Venus

Development priorities:

- Variable altitude balloons including deployment testing, analog flight testing of Venus prototypes, and onboard altitude control.
- Sub-cloud access for Venus aerial platforms. This requires flight at environmentally challenging conditions (>100°C) and is currently low-TRL, but promises substantial science rewards in nightside surface imaging in NIR.

Key supporting / synergistic technologies:

- Acid-resistant and ~100°C qualified spacecraft components for the lowest desired flight altitudes on Venus (solar panels, batteries, communication systems).
- Acid aerosol test chambers for aerial platform technology development
- Data relay capabilities for Venus orbital assets
- Autonomous navigation, planning, and resource heath management. Heavier-than-air robots cannot pause to re-evaluate or get human input, and so depend more on robust autonomy than do rovers.
- Rechargeable batteries. Driver for both rotorcraft and aerobots. Heavier-than-air vehicles need to store energy very efficiently to fly. Venus balloons must endure long periods of darkness, which currently requires a lot of battery mass.

2.3 Autonomous Manipulation and Sampling

Description of capability: Autonomous manipulation and sampling refers to planned robotic operation through periods without direct human involvement. This applies to tasks involving grasping, manipulating, positioning, or placement of objects, payloads, instruments, or samples using robotic arms and end-effectors. It also applies to autonomous control of robotic mechanisms (mobility systems, robotic arms, end-effectors, and tools) that are directly engaged in the autonomous selection, acquisition, handling, preparation, and/or caching of samples. Autonomous manipulation can involve grasping and reorienting objects or positioning instruments or tools with designated preload forces. Autonomous sampling includes performing a robotic sampling operation as well as coordination with mobility to access a target sample location.

Science justification: Autonomous manipulation and sampling could be a game changer for the viability of the Endurance-A lunar mission that would robotically collect surface samples as well as autonomously place arm-mounted instruments on science targets along a 2000-km route on the far side of the Moon. Mission concepts such as the Enceladus Orbilander with a surface phase mission that includes a lander with sampling arm; the CORAL lander that requires arm-based observations and *in situ* surface sampling from 7 to 10 AU; and the CERES concept to return a 100-gram sample acquired in pristine condition, could all benefit from autonomous manipulation and sampling.

Missions in the recent decadal survey are of limited lifetime and risk not achieving desired science within allocated mission duration and cost without autonomous robotic capability. The OWL decadal survey includes operations costs in the overall Discovery and New Frontiers missions. Autonomy for manipulation and sampling can offer time and energy savings for science investigations across mission lifetimes through reduction of time otherwise spent during frequent communications cycles for human interaction and intervention and consequently reduces mission cost. Without it, sampling will remain high-risk, particularly for limited lifetime missions.

State of practice: Mars Phoenix Lander, Mars InSight Lander, MER, MSL, and Mars 2020 have demonstrated limited autonomous manipulation and sampling, requiring significant ground-in-the-loop cycles over many sols that cannot be accommodated by sampling missions that are identified in the recent decadal survey or are likely to be considered in the future surveys. Initial sampling on all of these missions took over a month despite significant heritage from prior missions. Limited communication windows, short mission lifetime, low mass, and low power requirements dictate that future sample acquisition missions baseline true end-to-end autonomous precision science instrument placement and sample acquisition and handling to meet their threshold mission requirements. The proposed Lunar Endurance-A Rover surface mission allocated a generous sampling schedule spending several months acquiring samples on the lunar surface with heavy dependence on the ground-in-the-loop cycles to take advantage of the many communication windows between Earth and the Moon. All the sampling acquisition missions identified in the recent decadal survey or predicted to be considered in the following decadal survey have limited or single-digit communication windows over several weeks.

Prior sampling missions have relied on substantial remote human involvement. The typical process plan involves humans carefully selecting and designating target locations while ground-based operations tools and/or onboard capabilities are used to plan collision-free trajectories that are executed autonomously and facilitated by onboard fault monitoring. Multiple interactions across command cycles are typically necessary as incremental progress is made to ensure expected progress and results. The same applies to robotic sampling wherein some aspects, such as actual sampling tool operation (as in the case of drills), are automatic once engaged and disengaged and others such as target designation and sample verification typically require human interaction.

State of the art: Terrestrial robotics has advanced substantially in recent decades from automation applications, involving manipulation and pick-and-place tasks akin to certain sampling tasks, to operations employing a range of autonomous capabilities. In application domains spanning manufacturing, warehouse operations, field robotics and others, advanced capabilities continue to be demonstrated and some have been deployed in practice in progressively unstructured environments or settings. Very few applications are characterized by challenges that are pertinent to planetary surface environments, however, such as combined partially-known natural terrain, low or highly variable lighting conditions, temperature extremes, and limited computation and sensing. The following are used routinely in terrestrial robotics to perform or support autonomous manipulation: target object recognition, collision-free trajectory and motion planning, grasp planning governing how to approach and gain hold of objects, control of forces and/or torques, coordinated mobile manipulator control, dexterous multi-fingered robotic end-effectors, automatic tool or end-effector change capability, and more. Both perception and control capabilities supporting several of these aspects of manipulation autonomy have benefited in recent years from advances in data-driven machine learning approaches, which can be leveraged for planetary applications.

Robotics technology gaps:

- Tactile sensing, extending force/torque sensing beyond the wrist of robotic arms to end-effector appendages (e.g., contact-based perception of surface texture, sensing of grip/grasp strength on delicate samples, detection of grasp security against sample drops or slips, etc.), miniaturized proprioceptive sensors (sensors measuring values internal to the system (robot); e.g., motor speed, wheel load, robot arm joint angles, battery voltage), and exteroceptive sensors (environmental sensing, e.g., distance measurements, illumination intensity, sound amplitude, etc.)
- Perception and autonomous control for dexterous sampling and robust sample handling via reactivity to external forces in low-illumination conditions
- Increased manipulation robustness and via robotic "hand-eye" coordination or visual servoing
- Versatile sampling autonomy facilitated by automatic tool/instrument change or multi-purpose tools

Development priorities:

- Development of autonomous precision positioning of instruments with a manipulator in challenging terrain with no ground-in-the-loop interaction will reduce the risk for the proposed Endurance-A mission that will need to maintain an ambitious schedule.

- Development of autonomous sampling without ground-in-the-loop will enhance the proposed Endurance-A mission and enable the potential inclusion of surface sampling in future missions to Enceladus, Venus, and small bodies.
- Development of uncertainty and risk-aware autonomous manipulation, sample acquisition and handling in unknown environments. This includes potential recovery and retries.

Key supporting / synergistic technologies:

- Advanced sensing/perception (for 3D workspace mapping and target sample recognition, acquisition verification, inspection, mass determination, etc.)
- High performance computing
- Human-autonomy interaction tools and simulators
- Miniaturized sensors and instruments
- Autonomous science targeting, resource, and health management

2.4 Components for Extreme Environments

Description of capability: Advancing robotic capabilities in the extreme environments of target planets, moons and small bodies relies on component technologies. The primary advances needed are in robotic components and hardware that can survive and operate robustly in harsh space environmental conditions for long durations, while accommodating low power, mass, and volume requirements [26]. The extreme environment in space includes radiation, temperature extremes, vacuum, high pressure, dust, abrasion, and exposure to corrosive chemicals at some destinations. Advances in component technologies can also include the implementation of integrated sensing and self-regulation, for example actuators with built-in torque sensing or embedded control. Specific component technologies include, high-performance wheels, actuators, sensors, and transmissions.

Science justification: Many of the missions called out in the recent Decadal Survey require robots to operate in environmental conditions and for durations far beyond the scope of current and past planetary science missions. These include, but are not limited to, high radiation on the surface of Europa; traversing thousands of kilometers at the lunar South Pole where temperatures can reach 40°K; operating on and accessing the subsurface on Ocean World bodies; operating at near-polar regions on Mars; and on the surface of Venus. Concerns such as material fatigue due to high number of loading cycles, wear in a dusty lunar environment, resiliency at extreme cold and hot temperatures, and degradation from radiation are all prevalent issues. Developments in advanced materials, thermal management techniques, and other solutions for space environment management, will enable conception of new missions and allow for more extensive or lower cost proposed missions.

Decadal reference

> **Finding:** *Protecting spacecraft from extreme environments (for example temperature/ pressure/chemical corrosion) needs to be advanced to enable in situ priority missions. Technologies needing further advances include power generation and storage, materials, actuators, and electronics, including memory, among others. (pp. 546 of* [13]*)*

State of practice: Many robotic component systems have been developed for missions that operate during the day and hibernate during the night on the Moon and Mars. These include actuators, sensors, avionics, and energy generation and storage systems. Components are typically only viable with active or passive thermal management, or for limited durations. The Mars rover and lander missions use thermal subsystem designs that manage temperatures for the operation of mechanisms and electronics. The use of dry lubricants was baselined on the Mars Science Laboratory project to reduce the use of dedicated heaters for operation at −135°C. A redesign, however, became necessary when the dry lubricant failed in life tests, ultimately requiring the use of wet lubricant with active thermal management. This remains the current state of practice for operation of mechanisms in extreme cold environments. For extreme radiation environments, the primary mitigation continues to be shielding, such as in the case of the Europa Clipper spacecraft, with the use of a radiation vault to protect sensitive electronics. Another approach to mitigate the impact of high radiation on electronics is flying redundant components.

Current techniques to manage survival in extreme environments, do not solve the problem of long duration missions. The state of practice of dust mitigation is the use of seals for mechanisms. This has proven to be a long-enduring solution on Mars but does not address long-term usage in the harsher lunar dust environment. In the case of chemically corrosive environments, such as the clouds and surface of Venus, Soviet missions had success in methods to cope with sulfuric acid in the upper atmosphere (using Teflon-coated Vega balloons) and supercritical carbon dioxide in the lower atmosphere. The harsh thermal conditions on the surface of Venus limited operations to 2 hours. An additional strategy for survival in extreme conditions is redundancy with use of statistical reliability and assurance techniques to ensure high likelihood of survival.

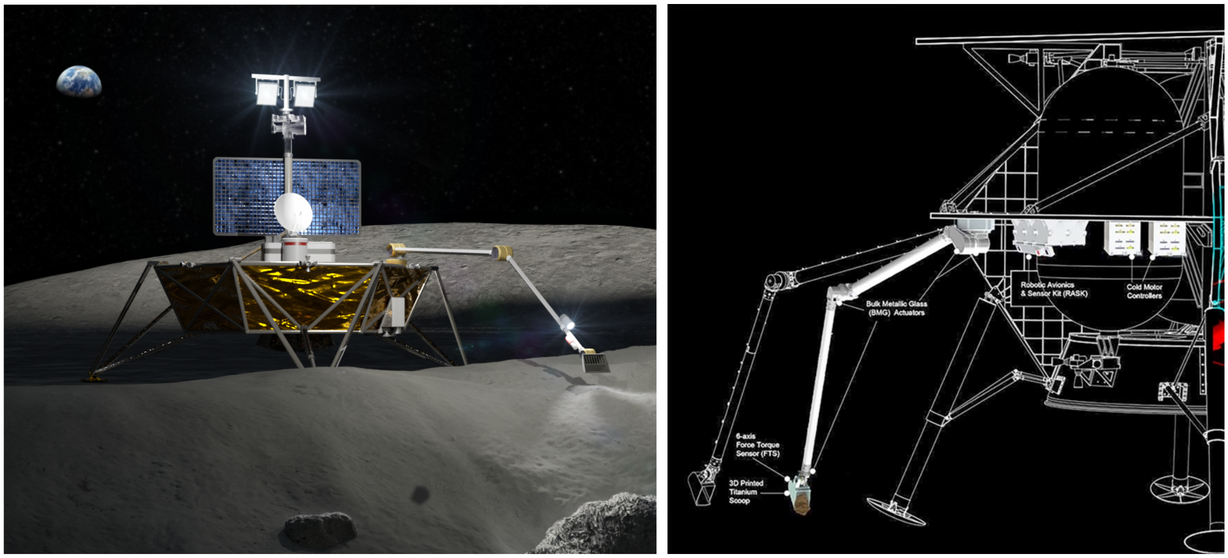

Figure 6: (a) Illustration of the 6.5 feet (2 meters) long Cold Operable Lunar Deployable Arm (COLDArm). (b) Illustration showing components on the arm designed for the lunar night when temperatures can drop below −280°F (−173°C) [27].

State of the art: The NASA COLDTech and HOTTech programs have advanced the maturity of many component technologies for space missions. Similarly, the NASA STMD GCD program has also supported the development of robotic component technologies. These include energy generation and storage systems, avionics, actuators, and materials. Some examples include: 1) COLDArm, designed using bulk metallic glass bearings in its actuators to operate at temperatures as cold as −173°C on the Moon, and 2) cold survivable distributed motor controllers, under development for several years for a potential Europa Lander mission.

Robotics technology gaps:

- Cold tolerant long-life actuators for Lunar and Ocean Worlds missions
- Hot tolerant avionics, actuators, and sensors for Venus missions

- Long life and range actuators and mobility components

Development priorities:

- Components for extreme environments including cold- and hot-tolerant actuators, rechargeable batteries, and long-life wheels and mobility components.
- Extreme environment sensors including force-torque sensors
- Components for state estimation including Inertial Measurement Units, Gyroscopes

Key supporting / synergistic topic areas and technologies:

- Advanced materials and manufacturing
- Hot/Cold tolerant avionics, energy storage
- Miniaturized, low-power avionics

2.5 Extreme Terrain Mobility

Description of capability: Extreme terrain mobility provides in-situ access to scientifically valuable locations in the solar system for which traditional rover mobility systems are poorly suited. Particular locomotion requirements are target and mission-specific, but common challenges include steep slopes, vertical cliff faces, and highly rough and irregular surface geometry. Moreover, in contrast to prior rover missions with highly pre-characterized topography/hazards, extreme terrain locations are often difficult or impossible to image from remote spacecraft, thus imposing a higher degree of terrain uncertainty and requiring a commensurate degree of locomotion robustness and adaptability.

In addition to more capable locomotion, new mobility systems must also be able to deliver a meaningful scientific payload (whether for scouting, in-situ analysis, or sample retrieval) and operate in the (often harsh) environments of these locations. For example, power, thermal management, and communication are common challenges for extreme terrain platforms. The often rough and irregular nature of extreme terrains can also pose a challenge for the placement and orientation of in-situ instruments and/or sampling devices. These “non-mobility” factors should be considered throughout the development of novel extreme terrain access platforms.

Science Justification: The scientific interest in extreme-terrain locations in the solar system is diverse. On the Moon, permanently shadowed regions (PSRs) are the primary reservoirs for icy volatiles, the most concentrated of which are often in the bottom or on the walls of steep craters. Lunar mare pits also prove a unique view of exposed subsurface stratigraphy, which could be interrogated with in-situ instruments to investigate the Moon’s volcanic history. Rocky outcrops on Mars (such as Valles Marineris) also harbor the tantalizing stratigraphic record of its geologic history. Caves have also been discovered throughout the solar system and are particularly interesting for their potential to harbor signs of life. Future missions to small bodies such as asteroids and comets call for in-situ investigations and sample return, potentially enhanced by mobility across their highly rugged surfaces in low gravity. Finally, access to deep crevasses on ocean worlds may provide access to fresh material originating from subsurface reservoirs or oceans, allowing for the potential detection of past or extant life. While not identified in the decadal survey for specific medium and large class missions, extreme terrain mobility could enable high priority science in smaller class missions this decade and pave the way for larger class missions in future decades.

Decadal reference

> ***Finding***: *Strategic research has identified scientifically valuable regions that traditional rovers and landers cannot easily access, such as caves, craters, crevasses, and other rough or fractured terrain. Technologies for accessing such challenging regions are still immature and need advancement.* (pp. 21-19)

State of Practice: The state of practice in planetary rovers are typically wheeled vehicles with passive suspension on the Moon and Mars. While these platforms can traverse a large portion of planetary surfaces, they have well-known limitations on steep, sandy, and rocky terrain — which often coincide with regions of high scientific interest. Active suspensions can enhance locomotion capabilities of wheeled vehicles (sandier terrain, steeper slopes, larger rocks) and are being developed for upcoming missions: VIPER and (possibly) Endurance-A rovers.

Figure 7: A test model of VIPER illustrates chassis body leveling via active suspension adjustments. The rover is 1.7x1.7x2.5m and weights 490kg [28].

State of the Art: While not yet incorporated into any planned missions, mobility platforms for accessing more extreme terrains have been under development for some terrestrial and planetary applications. For example, Robosimian is a four-limbed robot with several locomotion models (wheeled, bipedal walking, and quadrupedal walking) capable of dexterous manipulation. Axel is a tethered two-wheeled rover that rappels down the side of cliffs and was proposed to support the Moon Diver mission concept [29]. The Exobiology Extant Life Surveyor (EELS) is a snakelike robot concept designed to support missions to reach the ocean under the icy crust of Enceladus. Hedgehog is a novel concept for exploring small bodies through hopping and tumbling. Lemur can crawl, walk, or freeclimb rock walls. The Reachbot platform uses extendable booms to climb Martian caves. BRUIE (Buoyant Rover for Under-Ice Exploration) is a two-wheeled robot concept for underwater exploration of icy waters of ocean worlds. These concepts have generally focused on proof-of-concept level functional performance (TRL 3–4). Robot concepts for terrestrial search-and-rescue and exploring polar regions on Earth also have relevance to technology development for exploring scientifically interesting regions of the solar system. Several legged robotic machines developed at Boston Dynamics, MIT, DLR, NASA

JSC, The University of Tokyo, the Tokyo Institute of Technology, and many others [30] have demonstrated advanced mobility over rugged terrain.

Robotics Technology Gaps:

- *Alternative locomotion systems for extreme topographic roughness at the >1 m scale*, such as “bouldery” terrain likely found within caves and on the surfaces / near the vents of Enceladus and Europa, for example using limbs, tethers, and/or hopping.
- *Tether management system* is a common requirement for extreme-terrain platforms, including the controlled pay-out and (for some cases) reel-in of an onboard tether spool, coordinated with other mobility components such as wheels or legs.
- *Instrument accommodation and placement*, including both engineering and science cameras to achieve an appropriate viewshed, and placement/orientation of in-situ instruments such as spectrometers and microscopes on an irregular rocky surface.

Priorities for development:

- *Mid-TRL* (4–6) opportunities for maturing extreme terrain mobility systems towards specific mission concepts (namely, Lunar pits and Martian caves), focused on *integrated* locomotion, system engineering, and instrument accommodation / placement that are robust to the variety of challenging terrain it may encounter.
- *Low-Mid TRL* development of small daughter platforms to enhance the science return of rendezvous missions to small bodies by providing extended mobility to many locations on the surface (e.g., more capable versions of MINERVA, MASCOT).
- Focused development of multi-mission tether management capability for force-controlled pay-out and (optionally) reel-in. (Tie to STMD’s “TYMPO” project for tether power.)

Key supporting / synergistic technologies

- Components for Extreme Environments
- Advanced Perception

2.6 Long Range Access

Description of capability: Long range surface mobility is the capability to cumulatively traverse thousands of kilometers over varied planetary surfaces under the relevant environmental conditions. The immediate mission destinations are the Moon and Mars but may also include Ocean Worlds in the longer-term future. Associated with this capability is the need for greater rate of progress to increase science productivity and decrease primary mission duration. At polar regions on the Moon, increased driving speed is also needed by solar powered rovers to meet time constraints of reaching temporarily solar-illuminated "safe havens". In driving long distances, the vehicle will need to have robust mobility capabilities to overcome a variety of terrain types and topography.

Science justification: The Endurance-A mission, recommended in the recent Decadal Survey, would drive about 2000 km from the South Pole Aitken Basin, traverse through and collect samples at 12 sites with varied geological characteristics, and finish at the South Pole of the moon over a mission duration of 3 to 4 years [14]. The mission traverse distance is an order of magnitude more than currently fielded planetary science rovers. Long range mobility enables access to varied geological regions on planetary bodies that are typically separated by tens or hundreds of km. Mid-latitude regions on Mars are believed to have fractured, hummocky, layered terrain with shallow ice deposits and pole-facing scarps created by erosion. Images of Europa show varied geological units tens of km apart that include chaos terrains, lenticulae, ridges, and impact and plate tectonic features.

Decadal Reference

> ***Finding:*** *Long-traverse rover and other extended mobility missions are enabled by higher-speed, hazard-avoiding autonomous mobility over longer durations, particularly where human interactions are limited or impossible. Future remote missions with, for example, rovers and aerial vehicles, will increasingly rely on mobility autonomy to access a greater range of surface regions and features.*

State of practice: Several robotic rovers have been deployed on the Moon and Mars. NASA's Mars rover missions have demonstrated long-duration operations with limited range (e.g., 45 km total drive distance for Opportunity). In contrast to the passive suspension system on NASA's Mars rovers, VIPER, to be launched in late 2024, has greater mobility capabilities due to its actively controlled suspension system, has a top mechanical drive speed 5x faster (up to 20 cm/s) than the Mars rovers, and is anticipated to traverse 20 km over approximately 40 operational days. Prior successful deployment of lunar rovers from Russia, China, and India on the Moon and Mars have also had very limited range.

State of the art: Terrestrial research rover platforms have demonstrated driving hundreds of km under semi-autonomous control without physical interventions for maintenance. Actuators have been demonstrated to operate for more than a hundred million cycles at cryogenic temperatures.

Robotics technology gaps:

- Long range autonomous navigation with competent risk/fault detection and mitigation
- Global localization without the benefit of GPS
- Hazard avoidance comparable to human in the loop
- Multi-modal, 3D terrain sensing and modeling (spatial) with semantic interpretation
- Operation in extreme lighting conditions, both dark and light

Development priorities:

Near-term opportunities to meet the proposed Endurance-A mission needs

- Day and night unstructured terrain mobility
- Autonomous long-distance driving. Traverse planning from one region of science interest to another with options for interim human input. Approaches may address this by developing for example some combination of more capable autonomous navigation, global and local path planning, global localization, state estimation. Data and simulations from Mars missions can be utilized for demonstrating the technology with limited investment.

Key supporting / synergistic technologies:

- Components for Extreme Environments
- Advanced perception
- Extreme terrain mobility
- Active thermal management systems
- High performance computing

2.7 Multi-Agent Autonomy

Description of capability: Autonomous coordination of multiple robotic agents enables applications such as spacecraft constellations, robot swarms, scouting, networked planetary observers, and orbiting distributed apertures. Collaborative operation of disparate systems can leverage unique capabilities across agents to expand overall mission capabilities. The ability to partner a free-flying rotorcraft such as Ingenuity with the Perseverance rover, for example, has introduced the possibility of new exploration, scouting, and sample collection techniques. Ingenuity and Perseverance coordination was performed on the ground. Autonomy for multi-agent systems covers the development of algorithms for coordination, planning, and control, distributed task identification and task allocation in heterogeneous teams, and collaborative localization and observation. Software architectures and software systems engineering (integrating localization, perception, mobility, communications, and human–robot interaction) have unique requirements when applied to autonomous multi-agent systems.

Science justification: Multi-agent systems are needed for planetary exploration applications where wide baseline and distributed measurements are needed and can be beneficial for high-value science where redundant systems ensure science return. Imaging over wide baselines or with phased array antennas provide higher resolution and enable directed measurements. Alternatively, multiple low-cost explorers deployed in extreme environments can be a strategy for recovering some science where there is high likelihood of failure. Small-scale robots and manipulators are well suited to Discovery, PRISM, and CLPS missions to the Moon, Mars, and small bodies to address decadal science questions. Low-TRL development has demonstrated the promise that multi-robot systems have for cooperatively accessing extreme terrain, such as descending down crater walls and lava tubes.

State of practice: No prior planetary robotics mission has deployed a multi-rover system. However, the first such flight system implementation, the CADRE (Cooperative Autonomous Distributed Robotic Exploration) technology development, is planned for launch as early as 2025 as a technology demonstration mission. Each rover will make decisions and act, without the need for constant human intervention, to figure out how best to safely complete its assigned task involving autonomous navigation, hazard avoidance, and driving in formation. Other efforts include coordinated navigation and science actions by satellite teams (SunRISE), and distributed spacecraft autonomy. The primary capability on these projects is near-autonomous navigation but they do not include system-level autonomy nor self-sufficiency.

Figure 8: Image of the three CADRE rovers (~9kg each) designed for a CLPS lunar technology demonstration [3].

State of the art: Multi-agent autonomy is used in urban air transportation systems, coordinated navigation and science operations with rover and satellite teams, and distributed spacecraft missions. The terrestrial robotics R&D community has been developing multi-robot capabilities for terrestrial applications for several decades [31]. Recent advances include introduction of machine learning algorithms, alternative communication strategies, and handling uncertainty [32].

Robotics technology gaps:

- Algorithms and methods offering greater autonomy for task decomposition and assignment/re-assignment to relieve system designers of that burden would be enhancing
- Generalized task allocation and planning across heterogeneous systems
- Verification and validation of complex agent interactions
- Cooperative manipulation across multi-agent systems

Development priorities:

- Mothership-daughter spacecraft architectures to enhance the science return of rendezvous missions to small bodies with minimal impact to prime lander missions
- Coordinated communications relay, perception, or tethering technology for accessing extreme terrain with two or more robots

Key supporting / synergistic technologies:

- Small-scale robots and manipulators
- Advanced perception
- Deliberative planning/sequencing
- Human-autonomy interaction tools and simulators
- Cognitive architectures (including automated knowledge-based reasoning and applicable data-driven machine learning)

2.8 Sample Handling and Verification

Description of Capability: Sample handling and verification are procedures within the sampling chain of events that are performed when samples are collected and cached or fed into instruments on board spacecraft conducting in-situ science. It begins after the acquisition of samples and covers the transfer, observation, measurement, and identification, and ends with either being cached or inserted into their respective instruments. Advanced sample handling ensures that sample integrity is maintained, the sample is not contaminated or modified, and it stays in the desired state during the conveyance to the instrument. Sample verification is needed of quantity and quality by measuring the mass, volume, type, and other properties of samples repeatably and accurately in a preprocessing step before caching or feeding them to a science instrument. Depending on the planetary exploration mission and the target destination, the samples may be solid, liquid, gas, or in a combination of these states.

Decadal Reference

> ***Finding:*** *Sample acquisition has benefited from significant technology development, though work is still needed for specific cases. Sample analysis requires significant handling and pre-processing of acquired samples prior to sensor analysis. Sample handling and pre-processing technology needs urgent attention to extract target materials accurately and efficiently from acquired samples, and these implementations need to be science-requirements-driven (pp. 544 of* [13]*)*

Science Justification: In-situ sampling is performed on many planetary exploration missions either identified in the recent decadal survey or predicted to be considered in the next round. Endurance-A would collect surface samples from 12 disparate locations along a 2000-km route through the South Pole-Aitken Basin. Missions are under formulation or in development to return samples from Ceres, Centaur, and other small bodies. The proposed Mars Life Explorer mission would search for biosignatures in surface, subsurface and atmospheric samples. The proposed Europa Lander and Enceladus Orbilander mission would also perform sampling. There are proposals for additional surface sampling missions to Venus, Mars, Mercury, comets, and other small bodies.

Advancements in on-board sample handling and verification have the potential to increase science return by improving the efficiency and optimizing use of sampling resources to obtain more samples and samples of higher quality [33]. On-board verification will also influence improvements in sample selection capabilities by providing real-time information on the quality of samples acquired. On-board sample verification will also reduce data volume on bandwidth-limited communication channels by reducing the need for ground-in-the-loop verification.

State of Practice: Current sample handling and verification practices are configured for the specifics of each mission. The most rudimentary example of sample processing is to blindly process samples. This is often done for atmospheric samples. The act of acquiring a sample may be challenging enough that any sample collected is considered a success, for example on Huygens, OSIRIS-REx and Genesis. A simple verification approach is to use the sample acquisition system to convey samples to the instrument with ground-in-the-loop verification. The Mars Perseverance mission performs autonomous inspections at multiple stations during the transfer of cored samples from the drill into the sample storage. Specifically, sufficient sample volume is verified prior to sealing the sample tube. This autonomous approach minimizes sample exposure to the rover environment and its potential contaminants, thereby maximizing the science return.

State of Art: Sample handling and verification techniques designed for the specific configuration, science investigations, and instruments on the respective missions are in development. Advanced general techniques for accurately measuring mass and volume from on-board sensors have been demonstrated for specific types of samples.

Robotics technology gaps:

- Sterile or extremely clean end-to-end sampling systems
- Sample handling and verification for classes of sample types, for example, granular surface material on Mars or the Moon, water ice on Ocean Worlds bodies, and atmospheric gas sampling on Venus, Mars, and Titan. Techniques could include accurate sample mass and volume determination from visual images and intelligent sample verification techniques using miniature sensors embedded in sample processing.
- End-to-end sampling system for the proposed Endurance-A mission concept. Challenges to implementation include constraints derived from mission system engineering, the variety of sample processing instruments and sample material types (ice, icy soils, plumes, etc.), and the large range of mass and volume of samples required by science payloads/instruments.
- Simulants for ground-based testing for challenging samples (such as water ice under cryogenic and vacuum conditions); challenge to produce and maintain relevant simulants for use in verifying effectiveness of the system designs

Priorities for development:

- Development and space-qualification of multi-system sample verification components that utilize miniature and low-power imagers, strain gages, and other sensors targeting a class of sample type – for example, loose granular surface material. Development targeted towards specific missions or classes of missions based on the types of samples and science instruments, for example Endurance-A.

- Cold-operable autonomy concepts for protecting sampling systems to reduce energy usage and sample modification

Key supporting/synergistic technologies:

- Miniaturization of robotics sample acquisition sensors and instruments
- Planetary protection sterilization techniques
- Advanced perception

2.9 Sub-Surface Access

Description of capability: Subsurface access describes the ability to access materials that cannot be readily inspected on or collected from the surface. Depth requirements vary based on location and science objective, but can range from millimeters to kilometers. For science missions, access to depths of ~20 cm and below typically rely on narrow-body drills, probes or penetrators, while shallower access can use a number of methods such as scooping and vacuum/gas-based devices. Subsurface science can either use instruments emplaced below the surface or instruments above the surface (on a lander / rover / hopper / drone, etc.) analyzing material returned to the surface. The core functional capability of subsurface access technologies is the ability to robustly penetrate through the target planetary surfaces and deliver instruments downhole or return material to the surface for analysis.

Science justification: The interest in subsurface access is widespread throughout the solar system and typically has one of three primary drivers: (1) access to materials that have not been subject to surface weathering processes or which do not exist on the surface (e.g., subsurface water/oceans), (2) access to subsurface layers to understand past conditions, and (3) as a unique perspective for in situ geophysical sensors such as heat flow probes and seismometers. Lunar drilling can help us understand regolith processes, impact processes for chronology, volcanic processes, and for characterizing polar ices for ISRU. Future priorities for Martian subsurface exploration include the search for signatures of life, understanding habitability of near-surface ice (e.g., for the Mars Life Explorer and ExoMars missions), and surveying the stratigraphic climate record in the polar layered deposits. These investigations would require penetration in the 1 m to 100s of meters range [34]. While not prioritized by the decadal survey, subsurface drilling on small bodies also has potential benefits, including the characterization of space weathering and thermal excursion, the cause and mechanisms of particle ejection events and cometary sublimation, and the mechanism of formation of smooth areas and ponds. Finally, subsurface access on ocean worlds is extremely compelling for a number of reasons. Accessing the top 1-m depth (minimum several centimeters so) on Europa would enable access to pristine materials shielded from Jupiter’s harsh radiation. A similar cm to m class sampler could significantly enhance the science return of an Enceladus Lander by providing access to the plume deposition record and paleohabitability [35]. Finally, access to deep ice and subsurface reservoirs / oceans (10s of km) would revolutionize our understanding of the interiors of ocean worlds and potential life within.

Decadal References: Subsurface access addresses 10 of 12 priority science questions and is called for by several decadal mission concepts: Mars Life Explorer, Centaur orbiter and lander, Ceres sample return, Comet surface sample return, and Enceladus Orbilander. It is also specifically called out as a high-priority technology for investment in the next decade; three relevant findings are:

> ***Finding****: While 1–2 m drill technology is maturing and planned for lunar missions, 2–10 m drill technology is critical but not mature enough to robustly sample pristine materials*

from subsurface layers of the widest variety of rock and ice materials on Mars, the Moon, and other bodies (pp 555).

***Finding**: Technology development to reach beyond 10 meters and access subsurface reservoirs and oceans would revolutionize our understanding of the interiors of terrestrial and icy/ocean worlds, and enable unprecedented astrobiology investigations in the coming decades (pp 555).*

***Finding:** Efforts to develop technologies to enable landers to acquire deep samples, e.g., 10s of cm to 1 m, or other interactions that require large reactive forces in low-gravity regimes have been limited. Investment in such technologies would enable access to primordial/unmodified subsurface materials of small bodies (pp 555).*

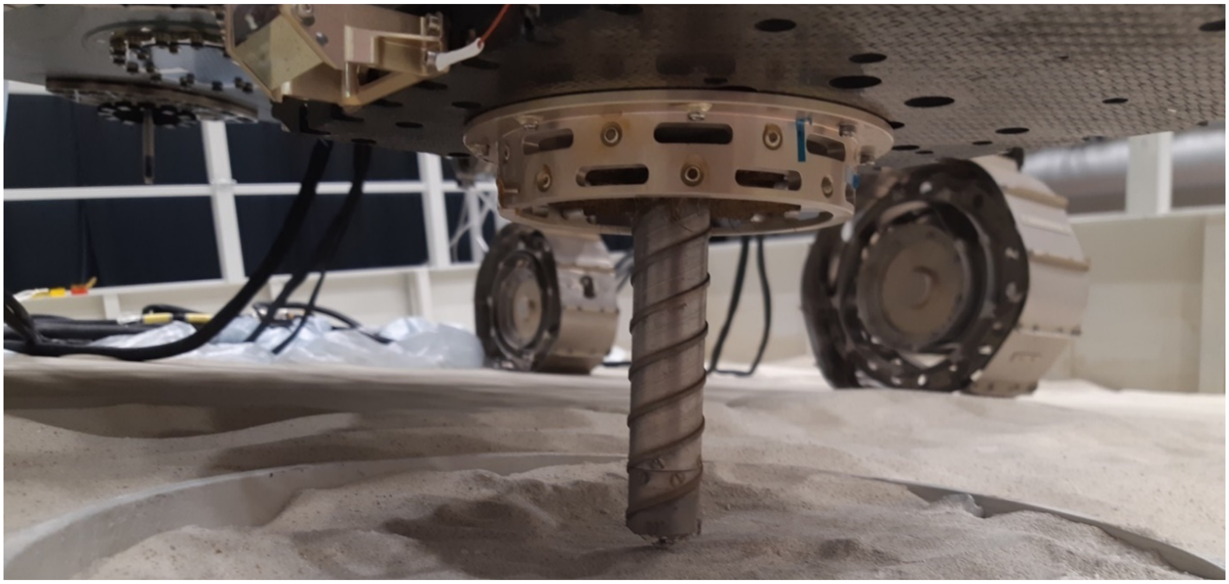

Figure 9: Image of the Ground Test Model of the European Space Agency Rosalind Franklin rover drill that would penetrate 2 meters beneath the surface to retrieve samples and deliver them to instruments [38].

State of practice: Planetary science has a long and diverse history of subsurface access. In summary, prior missions incorporating some subsurface access include (in order of increasing depth): the Rock Abrasion Tool (RAT) rock grinder (5 mm) on the Mars Exploration Rovers, the rotary soil drill (3 cm) on Russian Venus landers (Venera 13, 14, Vega 1, 2), the powder drill (5 cm) on Curiosity rover, the coring drill (~7 cm) on the Perseverance rover (shown in Figure 3), scoops (up to 20 cm) for regolith digging on Viking, Phoenix, MSL, Chang'e 5, and Surveyor landers, dynamic Touch-and-go asteroid samplers on OSIRIS-REx (gas-based) and Hayabusa 1 & 2 (projectile-based), percussive penetrators for comets (e.g., MUPUS on the Rosetta Philae lander) and Mars (e.g., HP^3 on the Insight lander), the autonomous rotary-percussive drill (27 cm–2 m) on USSR Luna 16, 20, and 24, and the handheld coring drill (3 m) on Apollo 15–17, and the 2 m Chang'e 5 lunar drill. A more complete history can be found in [36].

State of the art: Several subsurface access technologies are currently in development for upcoming missions, including a 1-meter rotary percussive drill for the lunar VIPER rover, pneumatic samplers for the Moon and Phobos, pneumatic 3-m drill with heat flow probe for the Moon (LISTER), a drill with vacuum sample collection for the Dragonfly mission, and a 2-meter drill for the Rosalind Franklin rover to Mars. Coiled tubing-based drills are being developed to address the 10-m class depth regime. Deeper wireline drills are also under development for potential future missions, including ~100 m-class drills for Mars rock and ice. Finally, nuclear-powered ice-melting probes (or "cryobots") have seen substantial development in recent years, for a potential mission through the kilometers-thick ice shells of Europa or Enceladus to reach the ocean below. Much of these development efforts have leveraged the substantial terrestrial drilling technologies, though often requiring adaptations for autonomous operation with stringent mass constraints [37]. [1]

Robotics technology gaps:

- Drilling and sampling systems through layers with different mechanical properties, e.g., consolidated rock and unconsolidated regolith
- Robust penetration of deep ice of varying composition and structure
- Sample processing to deliver desired type and quantity to instruments
- Sample transfer to the surface without modification
- Sterile or extremely clean sampling systems

Development priorities:

- Due to the long-lead nature of this technology development and its criticality for future planetary science missions, maintain dedicated programs to support the development of ocean-access technologies (e.g., SESAME, COLDTech). Key priorities include system-level concepts, ice penetrating prototypes, lab and field testing in analog locations, mechanisms for robust and autonomous ice penetration, power and thermal management, and communications through the ice shell (both wireless and tethered) [39].
- 2–10 m class drills for the Moon, Mars, and other bodies would enable access to pristine material from subsurface layers but is currently too immature for flight infusion. PESTO should provide targeted funding to support the low-mid TRL maturation of drilling systems that can reach beyond 2 m depth and return material to the surface.

Key supporting / synergistic technologies:

- Sample handling technologies for current and future planetary instruments. Sample handling and processing (including liquid) is critical to providing a sample to instruments in a manner that is suitable for proper analysis. If a sample is not presented properly (e.g., surface is not flat, particles are too large, sample volume is too low or too high), instruments will either not be able to analyze this material or the returned data will be inaccurate.
- Miniaturized down-hole instruments
- Nuclear/Radioisotope power systems (RPS) for accommodation on an ice-melting probe
- Planetary protection sterilization approaches for subsurface probes

3. Recommendations

3.1 Summary of technology investment recommendations

The nine technology areas that emerged from discussions during the workshop (Chapter 2) represent the broad areas that the group determined could have substantial impact for future planetary science missions. In discussions with scientists, further examination of the decadal priorities, and stronger assessment of potential return on investment and likelihood of maturation outside of SMD, we created a short list of the top ten investment priorities right now, including two which (as noted) are best suited for development outside of the planetary science division at NASA.

- **Advanced Perception** – Perception has applications for mobility, manipulation, and sampling. It is needed for remote operation as well as autonomous operation. Robotic missions are becoming increasingly autonomous; a core capability of autonomous operations is the ability to perceive and estimate the state of the environment robustly and rapidly under varying environmental conditions. Perception is also often an important component of health monitoring and science operations. Robotic perception systems are composed of hardware and software. Areas for improvements in hardware development include flight-qualified low-light detectors and alternative sensor modalities like LiDAR. Areas for improvement in software development include integrating signals from multiple sensors, and adaptive algorithms that improve models as more information is gained. Therefore, we make the following recommendations:

  R1 – Invest in perception software and algorithms for challenging lighting conditions. This includes fast and robust feature matching, texture detection, and terrain modeling for harsh lighting conditions on the Moon. In addition, for manipulation and sampling in low light conditions with moving shadows, develop accurate terrain modeling with uncertainty. We recommend targeting the Endurance-A mission since technology infusion in that mission would allow focused improvements for future missions where there are low levels of natural illumination at destinations further from the sun.

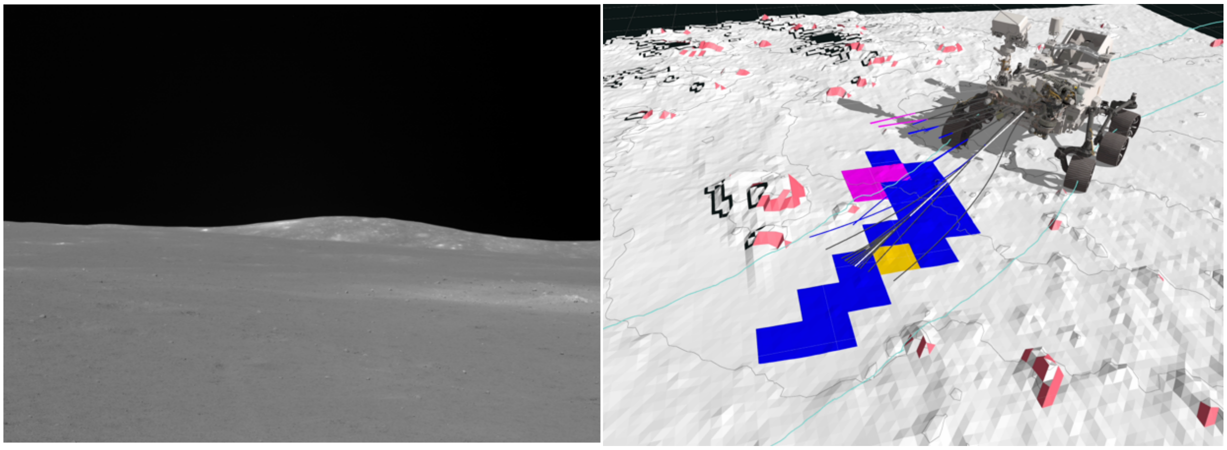

Figure 10: (a) Image taken by Yutu-2 rover [40] on the far side of the moon in the South Pole-Aitken showing the low-lighting and low texture of the terrain. (b) Image showing the terrain model derived from camera images that the Mars 2020 Perseverance rover uses to autonomously navigate. The image shows it navigating a hazard on Mars on July 15, 2023, the 854th day, or sol, of the mission [3].

  R2: In addition, we recommend **targeted perception and illumination hardware and component systems development in conjunction with industry.** Considerable advancements have been made in industry in the area of low mass, power, and cost components for perception, for example, LiDAR and cameras that could benefit planetary science missions. Targeted strategic development and qualification is needed for making them applicable for planetary missions. We recommend targeting the Endurance-A mission since it proposed to drive during the night. In addition, there is commercial interest in the Moon, which provides additional customers like the Lunar Terrain Vehicle service providers.

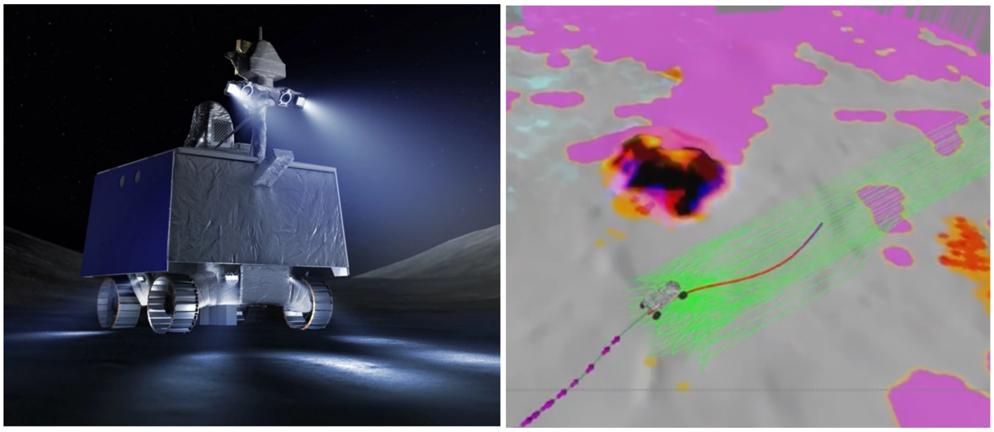

Figure 11: (a) Illustration of the VIPER rover for CLPS showing an example of illumination hardware [28]. (b) Image from X-RACER terrestrial robot showing a perception that includes LiDAR and enables autonomous driving in a variety of conditions at up to 20m/s. [8]

- **Autonomous Long-Range Mobility** – Chapter 22 of the OWL decadal survey recommends "Endurance-A should be implemented as a strategic medium-class mission as the highest priority of the Lunar Discovery and Exploration Program." Autonomous long-range mobility was identified as a required capability for the Endurance-A mission. Accordingly, this comes with a requirement for continuous driving during the day and night at high speeds (30 cm/s) compared to prior missions (~4 cm/s). Long range mobility also has applications for future missions to the Moon, Mars, and Ocean Worlds. Chapter 21 of the OWL decadal notes the finding "Long-traverse rover and other extended mobility missions are enabled by higher-speed hazard-avoiding autonomous mobility over longer durations, particularly where human interactions are limited or impossible. Future remote missions with, for example, rovers and aerial vehicles, will increasingly rely on mobility autonomy to access a greater range of surface regions and features." It also enables the capability for sun-synchronous navigation by perpetually dodging shadows on planetary bodies, such as the Moon, where survival at night is challenging. Therefore, we make the following recommendation:

  R3 – Invest in surface navigation systems for long-range day and night driving. The first priority is to develop a navigation system with integrated advances in local hazard detection and avoidance, path planning, and precise global localization that enables long-range autonomous navigation through interleaved crater-ridden, high rock density, and sandy terrain. Second priority is the capability of following a long-range drive with an autonomous precision approach that meets constraints on positioning the rover for sampling at a region of interest specified in an orbital image. After a long drive, ground-in-the-loop has been required on all Mars missions, with human operators directing the final segment of driving (typically less than 20 meters) to precisely reach a sampling target. Finally adaptive onboard state estimation, control, and planning will add robustness and enable the rover to adapt to terrain that is different from what was expected. We recommend targeting the proposed Endurance-A mission which would need to cover ~2000 km in just a few years—about 100 times more than prior missions.

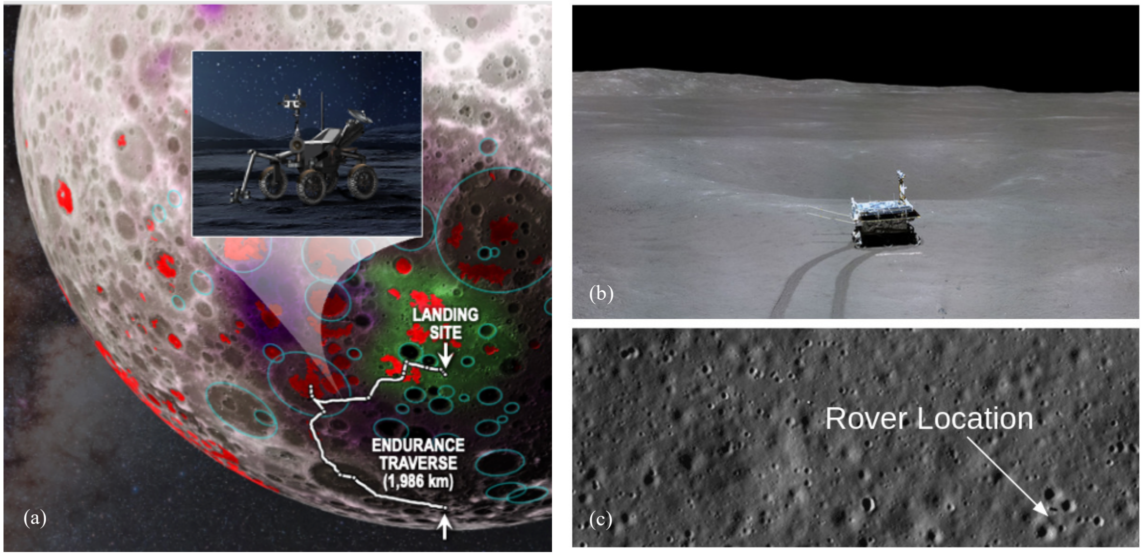

Figure 12: (a) Image showing the long traverse planned by the Endurance-A decadal mission concept. (b) Image acquired in the South Pole Aitken Basin on the Moon shows the Yutu-2 rover [40] and (c) the rover's location in an orbital view. For autonomous long-range driving global localization, the rover's location would need to be registered in an orbital map using information from the surface view.

- **Autonomous Manipulation and Sampling –** The value of science obtained by using a robotic arm to get science instruments close up to study the surface of a planetary body and by collecting samples is high. Chapter 22 of the OWLS decadal survey [13] lists six topics that appear most frequently in the chapters on science questions The top item on that list is, "The central role of sample return and in situ analyses for providing breakthrough science and ground-truth constraints." Limited lifetime missions farther from the Sun risk not achieving desired science within allocated mission duration and cost without autonomous robotic capability. The Endurance-A mission would collect ~100 kg of samples, which are delivered to a location where they can subsequently be collected by astronauts for return to Earth [13]. This technology could be a game changer for enhancing the Endurance-A mission and would reduce the risk of inclusion in future LDEP, and Discovery missions. It is only via targeted technology development that risk and cost will be reduced sufficiently to enable limited lifetime future missions as baselined in the Europa Lander concept mission and for potential inclusion in future missions to Enceladus, Venus, Mercury, Ceres, and small bodies. Therefore, we make the following recommendation:

  R4 – Invest in autonomous positioning of instruments and autonomous sample collection, handling, and verification without requiring ground-in-the-loop. The intent is to develop technology to remove all the recurring reasons for Earth-based input during planned operation. This includes designating a precise target for sampling on board. This is typically done on the ground since the target needs to meet a number of robotic arm, science instrument, and sampling system macro and micro constraints while factoring in all the sources of uncertainty in robotic systems. Ground currently also plans the sequence of moves to get the robotic arm into position for sampling and maintain hardware safety in the unstructured environment avoiding collisions with the surrounding terrain. Sampling has the potential to alter the terrain and hardware stability so any subsequent terrain interaction after sampling is done with ground-in-the-loop allowing ground to ensure safety. To develop technology for performing autonomous sample acquisition we recommend targeting the Endurance-A mission with perception that includes body mounted cameras, illumination, and LiDAR, a 5-degree-of-freedom robotic arm with arm-mounted imager, and a scoop.

Technology development should allow for refinement of sample processing and verification approaches since the study team saw the need for maturation here.

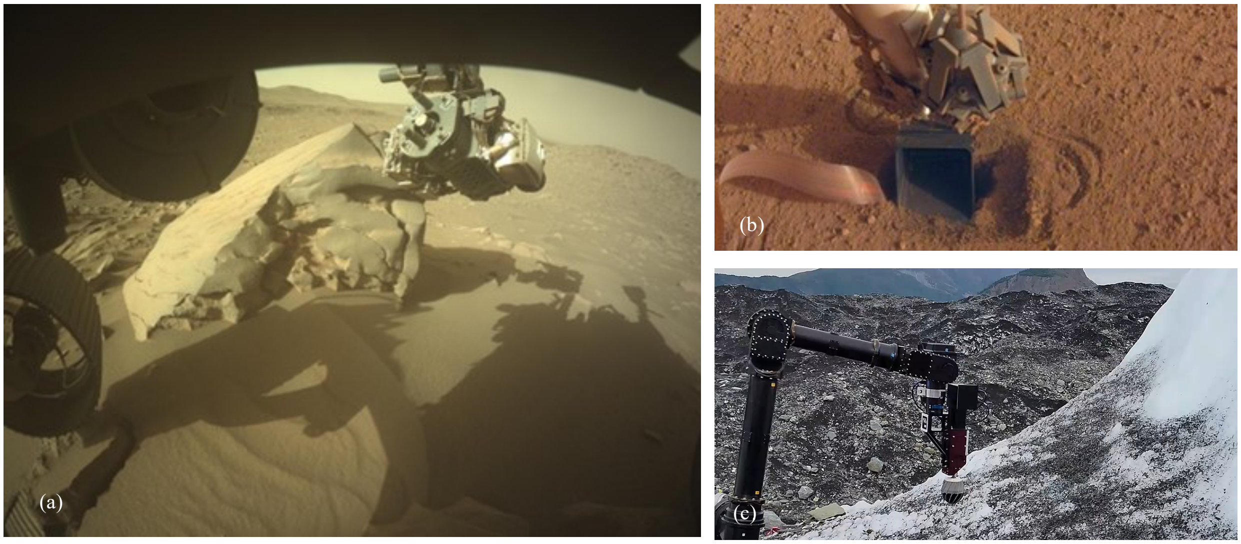

Figure 13: (a) Image showing the Perseverance rover placing the PIXL instrument on a location of science interest with its robotic arm as a pre-cursor to sampling on Feb. 24, 2024, Mars Solar day 1071 of the mission. (b) Image showing the Insight scoop on Mars. Endurance-A plans to use a scoop. (c) Image showing the Europa Lander robotic arm sampling during a field test [3].

- **Aerial Platforms** – There is a strong science pull for the future in situ exploration of Venus, including potential future New Frontiers and/or flagship missions. Furthermore, there is a consensus finding among the Venus community under VEXAG that aerial platforms are a compelling mission concepts for the next phase of Venus exploration—particularly those that remain aloft for longer periods of time (months), cover large distances, and have some degree of altitude control. However, balloon platform technology has not yet achieved the maturity required for flight infusion with an appropriate level of technical/cost risk. Therefore, we make the following recommendation:

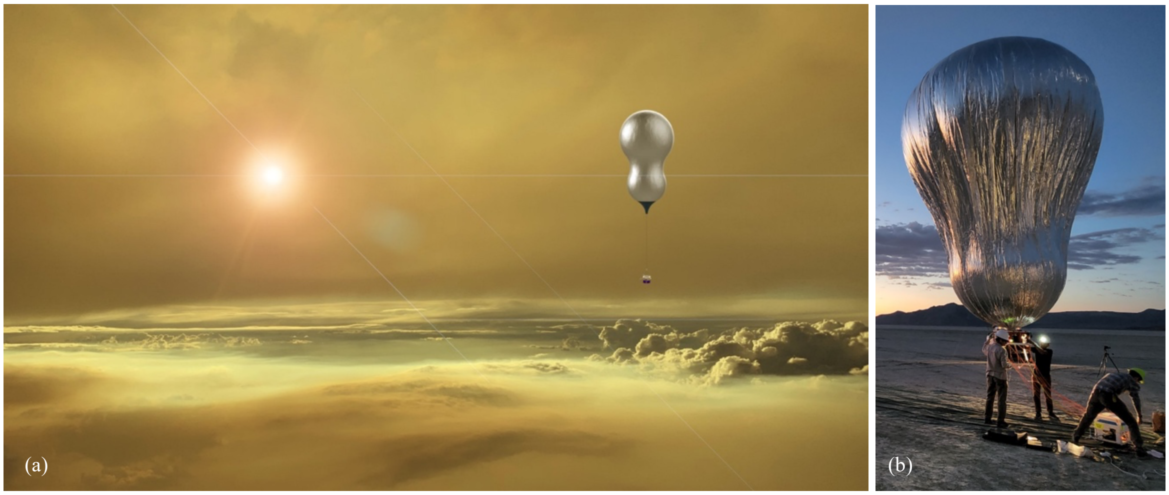

Figure 14: (a) Venus aerobot concept image [41]. (b) Test prototype of a Venus aerobot [3].

R5 – Develop long-range variable-altitude balloons, including deployment, trajectory estimation, altitude control, validated flight performance models, and technology for sub-cloud access. Aerial missions can serve science needs on Venus, Mars, and Titan;

however, we recommend that near-term funding should focus on Venus and specific science payloads.

- **Subsurface Access** – A prominent theme of high-priority future missions includes going deeper. Sub-surface access addresses 10 of the 12 decadal science questions and is applicable to nearly all rocky or icy bodies in the solar system. The Mars Life Explorer mission that will drill into Martian ice was rated as the next priority for medium class missions for MEP in the OWL decadal [13]. However, while 1–2 m class drills have been maturing for the Moon and Mars, technology for deeper access is still relatively immature and crucial for future science mission. Accordingly, we recommend the following two thrusts for prioritized investment in this area:

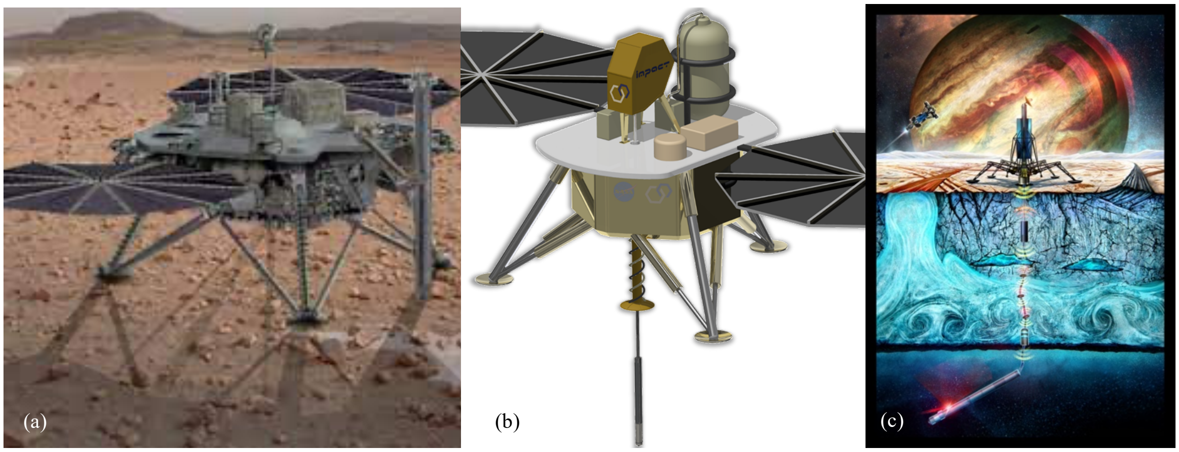

Figure 15: (a) Shows an illustration of the Mars Life Explorer decadal mission concept study drill. (b) Shows the IMPACT deep drilling system [42] (c) Shows an illustration of PRIME probe concept being deployed from a lander on the frozen surface of an ocean world [3].

R6 –Develop drilling systems that can reach a depth of 2m or more in rocky or icy surfaces. The focus should be on low mass drilling systems capable of delivering pristine samples to an instrument suite on the surface. The system needs to be robust to a wide range of potential planetary materials such as rock, ice, and concretions. The recommendation is to target permanently shadowed regions (PSRs) at the moon and mid and high latitudes on Mars.

R7 – Invest in deep ice probes for accessing subsurface reservoirs on ocean worlds. Mission application for this capability is far in the future but the anticipated long development time dictates beginning soon. Key priorities include system-level architecture design, ice penetrating prototypes, mechanisms for robust and autonomous ice penetration, power and thermal management, and communications through the ice shell. Due to the integrated nature of these technologies, efficient concept maturation would benefit from a highly coordinated effort among institutions centered around a common reference architecture and requirements.

- **Advanced Mobility Platforms** – A diverse array of locations of high scientific interest in the OWL decadal remains inaccessible to current planetary mobility systems including high slopes, caves, pits, and crevasses. Furthermore, in-situ missions can often greatly benefit from the inclusion of mobility but are reluctant to include it for lack of technical maturity and especially cost. As a result, very few mission concepts in the OWL decadal explicitly call for mobility. To reduce the risk and access high-value science, we recommend the following two technology development priorities:

Figure 16: (a) Illustration of the Moondiver Discovery concept to explore extreme terrain on the Moon. (b) Image of the RoboSimian robot in its actively articulated wheel-on-limb rover form to traverse unstructured planetary analogue terrain. It was originally developed as a mobile manipulation platform for the DARPA Robotics Challenge [3].

R8 – Invest in a small-scale (<10 kg) mobility platform for scouting and targeted science. First priority for this recommendation is to develop a mobile robot that is low-size, weight, and power (SWaP). Second priority is developing a manipulator to deploy science payloads or sample. Funding should prioritize mobility platforms with adaptable payload interfaces that are applicable to multiple mission concepts and destinations, and solutions for egress that minimize the impact on primary host mission operation. Recommend targeting a specific near-term mission concept and science payload to the Moon, Mars or small body that would benefit from extending the reach of landers by hundreds of meters.

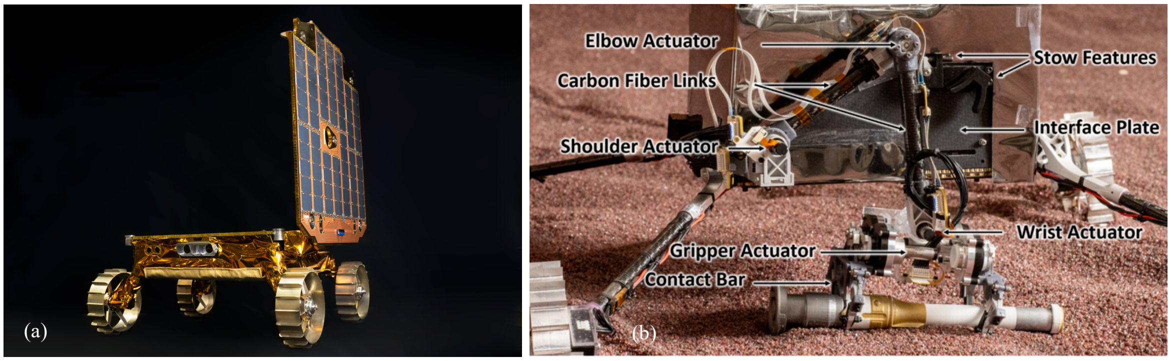

Figure 17 (a) The 7kg MoonRanger rover developed to support Lunar Surface Instrument and Technology Payloads (LSTIP) [2] (b) Labeled image of the120gm Sample Recovery Helicopter development platform with a robotic arm and gripper capable of dropping and picking up 100gm payloads [3].

R9 – Invest in developing an extreme terrain mobile access system for steep and irregular terrain. Develop hardware and a robotic system including critical subsystems, accommodation, payload deployment, and representative operations. Recommend targeting a Discovery-class mission concept for the Moon and working with the science community.

- **Components for Extreme Environments –** Advances in component technologies in several areas will enable or enhance many missions identified in OWL. Chapter 21 of the decadal survey notes the finding "Strategic research has identified scientifically valuable regions that traditional rovers and landers cannot easily access, such as caves, craters, crevasses, and other rough or fractured terrain. Technologies for accessing such challenging regions are still immature and need advancement. These include improving performance, expanding environmental ranges (for example hot, cold or radiation), and durability." Therefore, we make the following recommendation:

R10 – Components for extreme environments including cold- and hot-tolerant actuators, rechargeable batteries, and long-life wheels and mobility components. Components for industrial robotics are produced at a very large scale and industry has honed process control resulting in high performance at low cost. In these key areas for planetary robotics, we recommend targeting adaptation and characterization of industrial components for lunar applications via SBIR and STTR programs.

These eight recommendations are each important for future planetary science and cover a diverse set of needs.

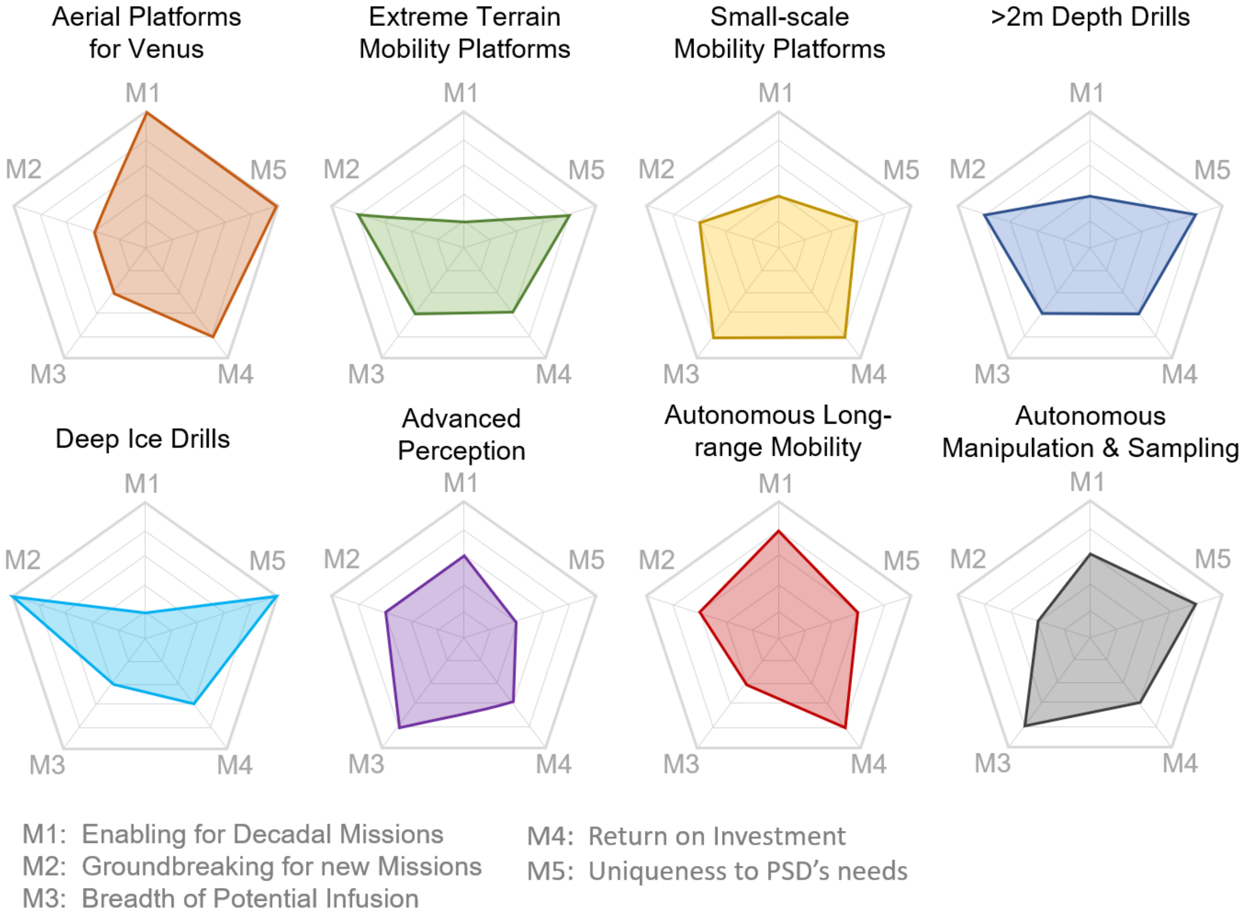

Figure 18. Evaluation of eight technology recommendations against the five figures of merit.

3.2 Process recommendations

In conducting this study, we identified several process and administrative steps that could be taken to benefit or enhance the development and infusion of robotics technologies into future planetary missions.

1. **Work with the STMD to support development of component technologies** needed for robotics systems. Some of the technologies exist at various levels of commercial maturity for terrestrial applications and environments. It is important to encourage the adaptation, maturation, and retargeting of these terrestrial technologies to planetary science. However, current commercial, terrestrial maturity does not guarantee that the technology can be adapted for space, or that there is viable commercial market for such technology. The priority list in the previous section already contains specific suggestions for priorities that STMD could support on behalf of SMD. In addition, the STMD program has already been supporting development of robotics component technologies like bulk metallic glass gears and flight technology demonstrations like COLDArm and CADRE. Component technologies that are supportive of much broader NASA interests may be more appropriately supported by STMD. PESTO could provide input to STMD on priority areas needed for planetary exploration. Similarly, the SBIR and STTR program, also administered by STMD, can support the development of NASA-identified targeted technologies by commercial organizations.
2. **Use flight technology demonstrations and secondary payload opportunities.** We see creative ways of deploying much of the recommended technology in flight demonstrations or as secondary payloads on manifested missions. In addition to raising the TRL level it reduces risk and cost to future missions by providing an opportunity to focus technology improvement on real versus perceived limitations.
3. **Facilitate interactions between technologists and planetary scientists.** Improved exposure and communication between these communities will lead to being better informed about the planetary science needs and robotics capabilities that could be applied to them and will assist in proposal development for new planetary exploration missions.
4. **Robotics technology development programs should be actively managed** to ensure that deliverables are relevant and can be infused into NASA missions.
    a. Funded efforts should clearly state milestones and deliverables in their task plans. The work should be regularly reviewed to track progress against stated objectives.
    b. Each funded effort should be associated with relevant planetary scientists and mission engineers early. Frequent interactions in the development process will maximize the utility of the technology products.
    c. Program management should review progress of each effort against milestones quarterly.
    d. Integration of technology and demonstration of capabilities into testbeds should be a required element of the development.
5. **Coordinated technology development programs for payload science instruments and robotics in areas where there is a strong correlation.** In funded missions, typically science instruments are selected based on an early concept of the robotic system. Then the science payload and robotic system typically follow parallel paths to development. By the time to integrate, it is often clear that they are a poor fit, then there

would be very little flexibility to change either and science is compromised; the robotic system could become too complicated to fit even threshold science. If instead, PESTO accomplishes one round of coordinating instrument technology development with staggered robotics technology development, there would be a lot learned that could be incorporated into missions.

References

[1] J. Keane, S. M. Tikoo and J. Elliott, "Endurance: Lunar South Pole–Aitken Basin Traverse and Sample Return Rover Mission Concept Study Report for the 2023–2032 Planetary Science and Astrobiology Decadal Survey," NASA, 2023.

[2] *Image Credit Carnegie Mellon University..*

[3] *Image Credit NASA JPL-Caltech.*

[4] A. Williams and B. Muirhead, "Mars Life Explorer Mission Concept Study Report for the 2023–2032 Planetary Science," NASA, 2021.

[5] NASA Autonomous Systems Capability Leadership Team, "Autonomous Systems Taxonomy," Moffett, 2018.

[6] F. W. Tan, "2018 Workshop on Autonomy for Future NASA Science Missions," 2018.

[7] F. Figueroa, L. Underwood, M. Walker and J. Morris, "NASA Platform for Autonomous Systems (NPAS)," in *AIAA Scitech 2019 Forum*, San Diego, CA, USA, 2019.

[8] J. Gibson, B. Vlahov, D. Fan, P. Spieler, D. Pastor, A. Agha-mohammadi and E. Theodorou, "A Multi-step Dynamics Modeling Framework For Autonomous Driving In Multiple Environments," *arXiv preprint,* vol. arXiv:2305.02241, 2023.

[9] D. Arney, J. Mulvaney, C. Williams, C. Stockdale, N. Gelin and P. le Gouellec, "In-space Servicing, Assembly, and Manufacturing (ISAM) State of Play-2023 Edition," in *Consortium for Space Mobility and ISAM Capabilities (COSMIC) Kickoff*, 2023.

[10] L. J. Wood, R. L. Anderson, S. Bhaskaran, T. A. Ely, D. V. Gerasimatos, E. D. Gustafson, T. Lam, C. J. Naudet, R. S. Park, J. E. Riedel and others, "Guidance, Navigation, and Control Technology Assessment for Future Planetary Science Missions," 2023.

[11] D. L. Linne, G. B. Sanders, S. O. Starr, D. J. Eisenman, N. H. Suzuki, M. S. Anderson, T. F. O'Malley and K. R. Araghi, "Overview of NASA technology development for in-situ resource utilization (ISRU)," in *International Astronautical Congress*, 2017.

[12] K. Hambuchen, J. Marquez and T. Fong, "A review of NASA human-robot interaction in space," *Current Robotics Reports,* vol. 2, p. 265–272, 2021.

[13] National Academies of Sciences, Medicine and others, "Origins, Worlds, and Life: Planetary Science and Astrobiology in the Next Decade," 2023.

[14] J. T. Keane, S. M. Tikoo and J. Elliott, "Endurance: lunar south pole-aitken basin traverse and sample return rover," in *Lunar Exploration Analysis Group meeting*, 2022.

[15] D. Banfield, "Mars science goals, objectives, investigations, and priorities: 2020 version".

[16] F. Amzajerdian, "An Overview of NASA Lidar Technologies for Precision Safe Landing on Planetary Bodies," in *2023 MSS Active EO Systems/EO & IRCM Conference*, 2023.

[17] J. A. Cutts, L. H. Matthies and T. W. Thompson, "Aerial Platforms for the Scientific Exploration of Venus," 2018.

[18] "Image of Vega Aerobot from NASA Space Science Data Coordinated Archive," [Online]. Available: https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=1984-128F. [Accessed 5 March 2024].

[19] "Image of Ingenuity on Mars," [Online]. Available: https://mars.nasa.gov/resources/27421/ingenuity-at-two-years-on-mars/. [Accessed 5 March 2024].

[20] J. Balaram, M. Aung and M. P. Golombek, "The ingenuity helicopter on the perseverance rover," *Space Science Reviews,* vol. 217, p. 56, 2021.

[21] R. D. Lorenz, E. P. Turtle, J. W. Barnes, M. G. Trainer, D. S. Adams, K. E. Hibbard, C. Z. Sheldon, K. Zacny, P. N. Peplowski, D. J. Lawrence and others, "Dragonfly: A rotorcraft lander concept for scientific exploration at Titan," *Johns Hopkins APL Technical Digest,* vol. 34, p. 14, 2018.

[22] "Artist's impression of Dragonfly," Image credit: Johns Hopkins APL, [Online]. Available: https://dragonfly.jhuapl.edu/What-Is-Dragonfly/img/df-screencap-1.jpg. [Accessed 5 March 2024].

[23] J. Cutts, K. Baines, L. Dorsky, W. Frazier, J. Izraelevitz, S. Krishnamoorthy, M. Pauken, M. S. Wallace, P. Byrne, S. Seager and others, "Exploring the clouds of venus: Science driven aerobot missions to our sister planet," in *2022 IEEE aerospace conference (aero)*, 2022.

[24] J. L. Hall, M. Pauken, A. Schutte, S. Krishnamoorthy, C. Aiazzi, J. Izraelevitz, T. Lachenmeier and C. Turner, "Prototype development of a variable altitude venus aerobot," in *AIAA aviation 2021 forum*, 2021.

[25] M. S. Gilmore, P. M. Beauchamp, R. Lynch, M. Amato and others, "Venus flagship mission decadal study final report," *A Planetary Mission Concept Study Report Presented to the Planetary and Astrobiology Decadal Survey,* vol. 8, 2020.

[26] T. S. Balint, E. A. Kolawa, J. A. Cutts and C. E. Peterson, "Extreme environment technologies for NASA's robotic planetary exploration," *Acta Astronautica,* vol. 63, p. 285–298, 2008.

[27] *COLDArm Illustration.* [Art]. NASA, JPL-Caltech, 2019.

[28] *VIPER Image Credit NASA.*

[29] I. A. D. Nesnas, J. B. Matthews, P. Abad-Manterola, J. W. Burdick, J. A. Edlund, J. C. Morrison, R. D. Peters, M. M. Tanner, R. N. Miyake, B. S. Solish and others, "Axel and DuAxel rovers for the sustainable exploration of extreme terrains," *Journal of Field Robotics,* vol. 29, p. 663–685, 2012.

[30] S. Kim, P. M. Wensing and others, "Design of dynamic legged robots," *Foundations and Trends® in Robotics,* vol. 5, p. 117–190, 2017.

[31] T. Balch and R. C. Arkin, "Communication in reactive multiagent robotic systems," *Autonomous robots,* vol. 1, p. 27–52, 1994.

[32] Y. Rizk, M. Awad and E. W. Tunstel, "Decision making in multiagent systems: A survey," *IEEE Transactions on Cognitive and Developmental Systems,* vol. 10, p. 514–529, 2018.

[33] M. Neveu, R. Quinn, L. M. Barge, K. L. Craft, C. R. German, S. Getty, C. Glein, M. Parra, A. S. Burton, F. Cary and others, "Future of the search for life: Workshop report," *Astrobiology,* vol. 24, p. 114–129, 2024.

[34] I. B. Smith, P. O. Hayne, S. Byrne, P. Becerra, M. Kahre, W. Calvin, C. Hvidberg, S. Milkovich, P. Buhler, M. Landis and others, "The Holy Grail: A road map for unlocking the climate record stored within Mars' polar layered deposits," *Planetary and space science,* vol. 184, p. 104841, 2020.

[35] S. M. Howell, W. C. Stone, K. Craft, C. German, A. Murray, A. Rhoden and K. Arrigo, "Ocean worlds exploration and the search for life," *arXiv preprint arXiv:2006.15803,* 2020.

[36] Y. Bar-Cohen and K. Zacny, Advances in Terrestrial and Extraterrestrial Drilling:: Ground, Ice, and Underwater, CRC Press, 2021.

[37] P. G. Talalay, Thermal ice drilling technology, Springer, 2019.

[38] "ESA Rosalind Franklin Drill. Credit Thales Alenia Space.," [Online]. Available: https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/Exploration/ExoMars/First_deep_drilling_success_for_ExoMars. [Accessed 5 March 2024].

[39] B. Dachwald, S. Ulamec, F. Postberg, F. Sohl, J.-P. de Vera, C. Waldmann, R. D. Lorenz, K. A. Zacny, H. Hellard, J. Biele and others, "Key technologies and instrumentation for subsurface exploration of ocean worlds," *Space Science Reviews,* vol. 216, p. 83, 2020.

[40] "Images from the Chang'e 4 mission," [Online]. Available: https://moon.bao.ac.cn/.

[41] *Venus Aerobot Image Credit Paul Byrne, University of Washington.*

[42] *Image Credit Honeybee Robotics.*

Acronyms

AI	Artificial Intelligence
BRUIE	Buoyant Rover for Under-Ice Exploration
CADRE	Cooperative Autonomous Distributed Robotic Exploration
CERES	Ceres Sample Return
CLPS	Commercial Lunar Payload Services
COLDTech	Concepts for Ocean worlds Life Detection Technology
CORAL	Centaur Orbiter and Lander
DSA	Distributed Spacecraft Autonomy
EELS	Exobiology Extant Life Surveyor
FPGA	Field Programmable Gate Array
GCD	Game Changing Development Program
GNC	Guidance, Navigation and Control
GPS	Global Positioning System
HOTTech	Hot Operating Temperature Technology
ISHM	Integrated System Health Management
ISAM	In Space Assembly and Manufacturing
ISRU	In-Situ Resource Utilization
LDEP	Lunar Discovery and Exploration Program
LiDAR	Laser imaging, detection, and ranging
LTV	Lunar Terrain Vehicle
M2020	Mars 2020 rover
MASCOT	Mobile Asteroid Surface Scout
MEP	Mars Exploration Program
MER	Mars Exploration Rover
MINERVA	MIcro-Nano Experimental Robot Vehicle for Asteroid
ML	Machine Learning
MLE	Mars Life Explorer
MSL	Mars Science Laboratory
MSR	Mars Sample Return
MUPUS	Multi-Purpose Sensors for Surface and Subsurface Science
NASEM	National Academies of Sciences, Engineering and Medicine
NF-7	New Frontiers Program, 7th opportunity
OWL	Origins, Worlds and Life: 2023 Planetary Science Decadal Survey
PESTO	Planetary Exploration Science and Technology Office
PRISM	Payloads and Research Investigations on the Surface of the Moon
PSD	Planetary Science Division
PSPS	Planetary Science and Program Support
PSR	Permanently Shadowed Region
SBIR	Small Business Innovation Research
SESAME	Scientific Exploration Subsurface Access Mechanism for Europa
SIMPLEx	Small Innovative Missions for Planetary Exploration
SMD	Science Mission Directorate
SME	Subject Matter Expert
STMD	Space Technology Mission Directorate
STTR	Small Business Technology Transfer
SunRISE	Sun Radio Interferometer Space Experiment
TYMPO	Tethered Power System for Lunar Mobility and Power Transmission
UOP	Uranus Orbiter and Probe

VEXAG	Venus Exploration Assessment Group
VIPER	Volatiles Investigating Polar Exploration Rover
VISE	Venus in-situ explorer

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