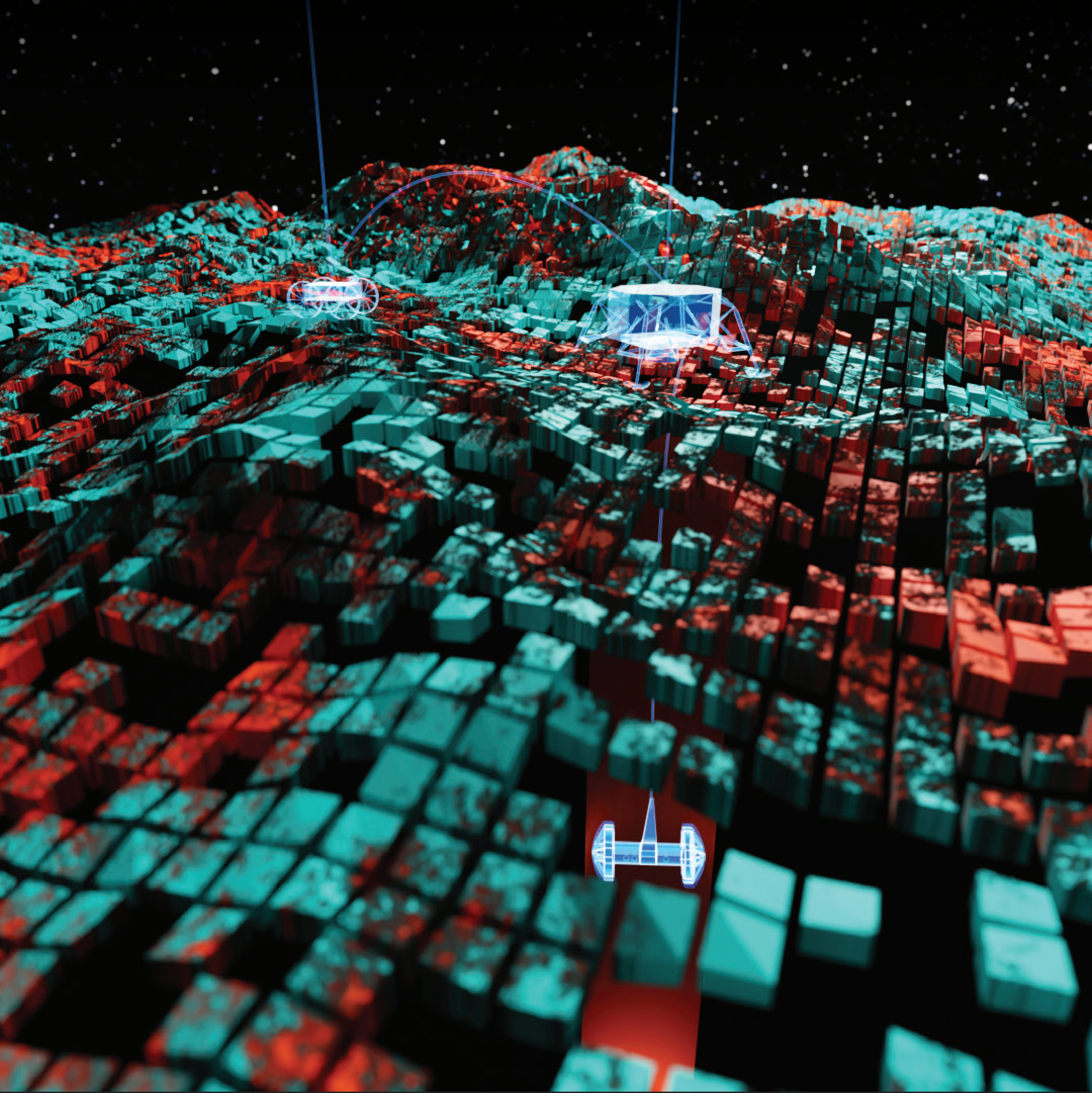

Guidance, Navigation, and Control Technology Assessment for Future Planetary Science Missions

Part III.
Surface and Subsurface Guidance, Navigation, and Control

February 28, 2023

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Guidance, Navigation, and Control Technology Assessment for Future Planetary Science Missions

Part III. Surface and Subsurface Guidance, Navigation, and Control

Engineering and Science Directorate
Jet Propulsion Laboratory
for
Planetary Science Division
Science Mission Directorate
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Authors

Jet Propulsion Laboratory, Caltech
Marco B. Quadrelli (lead)
Richard Volpe (co-lead)
Issa Nesnas
Hari Nayar
Paul Backes
Larry Matthies
Eloise Marteau
Ali Agha
Matt Gildner
Mike McHenry

Advisory Committee

Jet Propulsion Laboratory, Caltech
Patricia M. Beauchamp
James A. Cutts

Foreword

Future planetary explorations envisioned by the National Research Council's (NRC's) *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023–2032*, developed at the request of NASA's Science Mission Directorate (SMD) Planetary Science Division (PSD), seek to reach targets of broad scientific interest across the solar system. This goal can be achieved by missions with next-generation capabilities, such as innovative interplanetary trajectory solutions, highly accurate landings, the ability to be in close proximity to targets of interest, advanced pointing precision, multiple spacecraft operating in collaboration, multi-target tours, and advanced robotic surface exploration. Advancements in guidance, navigation, and control (GN&C) and mission design—ranging from software and algorithm development to new sensors—will be necessary to enable these future missions.

Spacecraft GN&C technologies have been evolving since the launch of the first rocket. *Guidance* is defined as the onboard determination of the desired path of travel from the vehicle's original location to a designated target. *Navigation* is defined as the science behind transporting ships, aircraft, or spacecraft from place to place, particularly the method of determining position, course, and distance traveled as well as the time reference. *Control* is defined as the onboard manipulation of vehicle steering controls to track guidance commands while maintaining vehicle pointing with the required precision. As missions become more complex, technological demands on GN&C increase, so continuous technological progress is necessary. Recognizing the significance of this research, the NRC of the National Academies listed many GN&C technologies as top priorities in the recently released *NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space*.

This document—*Part III: Surface and Subsurface Guidance, Navigation, and Control*—is the third in a series of four technology assessments evaluating the capabilities and technologies needed for future missions pursuing SMD PSD's scientific goals. These reports cover the status of technologies and provide findings and recommendations to NASA PSD for future needs in GN&C and mission design technologies. *Part I: Onboard and Ground Navigation and Mission Design* covers planetary mission design in general, as well as the estimation and control of vehicle flight paths when flight path and attitude dynamics may be treated as decoupled or only loosely coupled (as is the case the majority of the time in a typical planetary mission). *Part II: Onboard Guidance, Navigation, and Control*, covers attitude estimation and control in general, as well as the estimation and control of vehicle flight paths when flight path and attitude dynamics are strongly coupled (as is the case during certain critical phases, such as entry, descent, and landing, in some planetary missions). *Part III: Surface and Subsurface Guidance, Navigation, and Control*, examines GN&C for vehicles that are not in free flight but that operate on and below the surface of a natural body of the solar system. *Part IV: Aerial Guidance, Navigation, and Control*, examines GN&C for heavier-than-air and lighter-than-air vehicles in buoyant or sustained free flight in the atmospheric environment of a natural body of the solar system. Together, these documents provide the PSD with a roadmap for achieving science missions in the next decade.

Patricia M. Beauchamp
Engineering and Science Directorate
Jet Propulsion Laboratory, California Institute of Technology
February 28, 2023

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Other Reports in This Series

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- Solar Cell and Array Technology for Future Space Missions, Report No. JPL D-24454, Rev. A, December 2003.
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These and other relevant reports can be found at https://solarsystem.nasa.gov/technology-reports/technology-assessment-reports/.

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1 Executive Summary

This document provides an assessment of surface and subsurface guidance, navigation, and control (GN&C) technologies for future planetary surface missions and concludes with a set of recommendations for improving the state of the practice. The organization of the document closely follows the process used to arrive at the findings and recommendations in the previous 2013 assessment.[1] Specifically, the document is organized into four sections: 1) a review of potential future missions involving significant surface and subsurface components; 2) an outline of capabilities required for successful implementation of those missions, and a review and assessment of key technology areas addressing those capabilities; and 3) a set of findings and recommendations for future GN&C technology investments.

Even though six rovers have been placed successfully on Mars, GN&C development for planetary surface and subsurface missions is still in its infancy. Surface and subsurface GN&C must also address multiple conflicting demands. First, high levels of system robustness are required despite time delays that necessitate high levels of autonomy. Second, the operational environments are both very complex only partially known. Finally, the variability of technology needs across the expanse of prospective surface and subsurface missions is immense, yet technology development funding is extremely limited. Note that the scope of this document includes, in addition to ground systems, underground caves and lava tubes, under-ice oceans in ocean worlds, and lakes on Titan. This technology assessment, together with the findings and recommendations, are an attempt to address the above mutually conflicting demands, although not in a one-to-one fashion. The need for robust autonomy is addressed by a range of specific cross-cutting technology areas, all of which would leverage ongoing improvements in the computational power of radiation-hardened flight computing. Future surface and subsurface missions will demand much more precise interaction with the terrain soil; examples include Mars sample caching, mobility systems operating on extreme slopes or crevasses in ocean worlds, or sampling systems collecting soil in microgravity. Also, because our ability to predict the results of those surface interactions will always be limited, guiding principles for evaluating the uncertainty and risk are required (both onboard and as part of ground operations). Lastly, the diversity of GN&C needs across the full range of surface and subsurface missions makes cost-effective technology development a particular challenge. Greater reliance on system modeling and simulation will reduce costs throughout the full mission life cycle, starting with pre-mission technology investment decisions all the way through flight operations.

While not strictly technology related, some general recommendations can be made for any future surface and subsurface GN&C technology development program. ***One overarching recommendation is that flight projects should treat surface and subsurface GN&C as a distinct discipline from traditional GN&C. In that regard, flight missions need to treat the surface and subsurface phases with as much rigor as cruise and entry, descent, and landing (EDL). Similarly, surface- and subsurface-phase (particularly GN&C) requirements and flow down need to occur early in the project with dedicated surface GN&C system engineers fully integrated with the initial design team. Surface and subsurface GN&C technology development should be a sustained effort with a portfolio that includes low Technology Readiness Level (TRL) efforts as well as infusion-focused efforts. Furthermore, planetary exploration programs must be closely coordinated with each other, with related efforts focused on human exploration and, of course, with early-stage mission design efforts.***

These findings are organized into six major areas:

1. Surface and subsurface mobility systems
2. Sample acquisition and transfer systems
3. Modeling and simulation
4. Control and planning under uncertainty
5. Sensing and perception
6. Emergent technologies

The 10 findings and recommendations discussed in this report are summarized below, with the full science justifications given in Section 3 and Table 2.

1.1 Finding 1: Surface mobility systems need improvements to negotiate challenging terrains not only for the Moon and Mars but also for ocean worlds, small bodies, and Venus

Surface Rovers: Increased miniaturization and performance improvements of onboard computing architectures, navigation sensors, and communications systems, together with advances in surface navigation and localization, could open up possibilities to explore substantial planetary diversity in a single mission.

Recommendations:

- Develop and test new GN&C planning and control algorithms for fast traverses, thereby enabling a high degree of autonomy and reliability.
- Develop methodologies to achieve the required robustness and fault-tolerance of autonomy capabilities in a cost-effective manner in harsh environments.
- Address the challenges of steep slopes and operations in low gravity by developing improved environmental models and planning-and-control algorithms that are robust to significant uncertainties.
- Develop much faster autonomous navigation processing loops by much faster avionics and low size, weight, and power (SWaP) to address the unique nature of operations for mobility-based missions.

Extreme-Terrain Mobility Systems: Extreme terrains present interrelated mobility challenges that are substantially different from those of existing planetary rovers, including anchoring and de-anchoring operations, tether management, significant inertial effects (i.e., dynamic motion as opposed to static or quasi-static motion), high-lateral surface loads, and brittle terrain failure at ground contacts. Also, extreme-terrain mobility systems will be required to adapt to soil-property changes associated with solid and liquid multiphase behavior.

Recommendations:

- Develop system models of a range of systems suitable for supporting early mission concept studies and gap analyses for access to extreme terrains on Mars, the Moon, Europa, Venus, or Titan.
- Develop early-stage prototypes targeted at the highest-priority mission concepts.

Small-Body Mobility Systems: The challenges of evaluating small-body mobility systems using Earth or orbital testbeds are prohibitive and can only be addressed by simulation. Engineers need more insight into potential science objectives, while the science community needs increased awareness of mobility-system capabilities and system trade-offs.

Recommendations:

- Conduct **system studies** initiated by a workshop, bringing together engineers and scientists with the objective of reaching a consensus regarding a) the targets for which mobility provides significant science value; b) a set of science-derived mobility requirements for each target/target type (e.g., motion accuracy, instrument pointing, and surface mechanical coupling in microgravity); and c) the mobility strategies (e.g., random hopping versus controlled mobility) appropriate to each body.

OCEAN-WORLD MOBILITY SYSTEMS: Due to the exceptionally complex environment in ocean worlds, these challenging missions will require combined, highly integrated and multimodal technology solutions for surface, through-the-ice, and under-ice GN&C, which present many challenges in modeling, system integration, terramechanics and ice-mechanics, localization, mapping, and communication.

Recommendations:

- Conduct a workshop to determine the state of the art and provide directions on GN&C technology (e.g., modeling, simulation, control, and guidance) needed by cryobots, under-ice probes, and through-the-ice mobility.

1.2 Finding 2: Subsurface mobility systems need increasingly complex autonomy for all surface missions

Subsurface voids are of interest for their potential relevance to astrobiology and potential records of geology and climate, as well as with regards to the Moon and Mars, as potential habitat locations for eventual human explorers. They also pose challenges in localization, mapping, and communication. Subsurface robotic systems will require increasingly complex autonomy, leading to better communication networks, and global localization.

Recommendations:

- Conduct a workshop to assimilate lessons learned from the Defense Advanced Research Projects Agency (DARPA) Subterranean (SubT) and Robotic Autonomy in Complex Environments with Resiliency (RACER) field tests for future underground planetary robotics involving new technologies in localization, mapping, and communication.
- Develop and test system models for GN&C of tethered robotic systems with increased capability to descend, traverse, and safely return from underground destinations.

1.3 Finding 3: Sample acquisition and transfer needs more GN&C capability to navigate the widely different surfaces on planetary bodies

The wide variety of missions requires development of a range of sample acquisition and transfer technologies because few currently exist.

SAMPLING TOOLS: Including phase-change soil behavior as part of the system is also an under-developed area of investigation.

CACHING: Adopting a holistic approach with the platform and sampler target considered collectively for GN&C purposes can provide both science (e.g., sample collection) and engineering benefits.

DRILLING: More advancements are needed for deep rock and deep ice drilling.

Recommendations:

- Mature additional technology for coring and **sampling of bodies with reduced gravity** (e.g., Mars and lunar) to TRL 7.
- Develop a spectrum of low-TRL prototype sampling systems appropriate for bodies with **extreme temperatures** such as Venus (Titan missions are not in the current Decadal Survey), for bodies with low gravity (e.g., asteroids and comets), and for heterogeneous bodies (e.g., comets).
- Conduct studies of ***integrated*** **mobility and sampling systems**, merging the sampling mechanism functions with the system-level functions, e.g., small-body sampling that relies on active compliance between the spacecraft and the surface.
- Develop a flight-qualified, **general-purpose force torque sensor** to enable advanced sampling scenarios.

1.4 Finding 4: Integrated system modeling and simulation needs to be more ubiquitous for all missions

PHYSICS-BASED INTEGRATED SYSTEM MODELING AND SIMULATION METHODOLOGIES: Further improvement in high-performance computing is needed and will ultimately enable the high-fidelity modeling and simulation of systems with millions of degrees of freedom to be integrated with onboard GN&C functionality.

UNCERTAINTY QUANTIFICATION: NASA needs to expand the use of multiphysics-based QMU (Quantification of Margins and Uncertainty) technology to enable rigorous certification of models and simulations for extrapolation to poorly testable flight conditions.

VERIFICATION AND VALIDATION: In order to optimize system designs and reduce development cost/risk, more comprehensive system-level modeling is needed throughout the mission life cycle (technology investment and development, mission development and implementation, verification and validation [V&V], and training).

TERRAMECHANICS AND ICE MECHANICS: In order to understand surface missions, there is a need for more sophisticated models of soil and ice interaction for both sampling and mobility.

Recommendations:

- Conduct a workshop and systems study exploring the use of fully functional system **simulation to aid early-stage component and system design**.
- Continue to develop and disseminate physics-based simulations (similar to Ocean World Lander Autonomy Testbed [OWLAT]) to serve as a **virtual testbed** for the evaluation and maturation of prototype mobility system designs.
- Conduct a workshop to explore state-of-the-art, high-performance computing methods (serial, parallel) to handle large-scale, multiple-sampling-rate, hardware-in-the-loop, and model-order reduction techniques that can enable real-time performance assessments for planetary missions in extreme environments.
- Hold a series of workshops engaging scientists, terramechanics and ice-mechanics experts, and GN&C experts to identify the needed simulation capabilities and relevant surface-material properties to address a variety of bodies and mission types.
- Develop and validate a range of terramechanics models and/or simulations capable of supporting analysis of vehicle-soil interaction in both low- and high-gravity environments, and sampling and mobility in microgravity.

1.5 Finding 5: New control and planning techniques need to be adopted for future missions

CONTROL: In order to address the increasing complexity of spacecraft systems and interaction with the environment, new model-based control techniques that efficiently model dynamically evolving systems in order to control the system, and learning-based control techniques that infer the model parameters from sensor measurements in order to control the system, need to be leveraged.

PLANNING UNDER UNCERTAINTY: New methods for quantifying uncertainty and risk are required to address future missions involving more uncertain environments (e.g., asteroids). A large number of the envisioned future missions involve a significantly less predictable environment than previous lander and rover missions.

Recommendations:

- Conduct a systems study to identify the advantages and disadvantages of model-based and learning-based predictive control to provide significantly improved performance and conduct evaluation studies.
- Hold a workshop outlining a plan and ideas and engaging experts from diverse disciplines (e.g., control theory, mechanical engineering, systems engineering). The purpose of the workshop is to explore successful techniques for robust control and planning under different types of uncertainty.
- Conduct a multi-year, university-focused research program addressing planning under uncertainty while ensuring that a broad range of mobility systems are addressed, including aerial mobility, microgravity mobility, horizontal mobility in uncertain terrain, and vertical mobility of a tethered system.

1.6 Finding 6: High-speed autonomous navigation needs to leverage the advantages of high-performance computing

The reduced speed of autonomous navigation limits both energy efficiency and the surface area reachable in a fixed mission duration. Ongoing advances in high-performance computing (HPC) will eliminate the performance penalties associated with autonomous driving.

Recommendations:

- Undertake a systems study of the benefits of HPC on planetary rovers. Pending the results, a follow-up effort to develop a prototype of a high-speed, low-mass rover should be considered.
- At TRL 6 or 7, demonstrate high-speed navigation of a prototype planetary rover running on prototype flight avionics.

1.7 Finding 7: Range sensing needs improved detectors and metrology

There is the opportunity to leverage rapidly advancing computation capabilities towards improved range sensing. Contact sensing, especially for confined spaces, needs to be improved.

Recommendations:

- Conduct a study to estimate development/maturation trajectories of alternative range sensors, model their expected performance (including SWaP), and quantitatively evaluate the benefits to multiple applications, including mobility.
- Undertake development of reusable, high-performance, flight-qualified implementations of multiple ranging techniques and sensors.

- Develop a new generation of engineering cameras suitable for multiple applications, including deep space navigation as well as lunar and Martian surface missions.

1.8 Finding 8: Global localization needs more autonomy infusion

Small-body mobility systems, as well as Venus and Titan aerial vehicles (covered in Part IV), need the ability to determine real-time surface references for science targeting and navigation. On Mars, rovers need to use real-time localization with orbital localization data to more efficiently traverse long distances.

Recommendations:

- Develop a program to demonstrate vision-based global localization across multiple destinations.
- Develop techniques to enable efficient low-gravity, small-body exploration.

1.9 Finding 9: Ground operations tools need better human-machine interfaces

The planning and visualization tools required for surface operations for missions other than rover missions have not yet been developed. Also, tools for interfacing to much more autonomous systems still need maturation.

Recommendations:

- Conduct a study to evaluate and communicate the uncertainty and risks associated with prospective uplink sequences for an aerial platform or a rover operating in extreme terrain.
- Continue to improve 3D immersive visualization environments for surface operations.

1.10 Finding 10: Emergent technologies need to be matured and adopted

Artificial intelligence (AI), with its subareas of deep learning and machine learning, has progressed enormously in recent times, with potential advantages for the areas of planning, control, and navigation. There is also a gap between quantum technologies (which usually deal with physical processes at the atomic scale) and classical robotic systems (which usually deal with physical processes at a macroscopic scale), and combining the two can provide unmatched possibilities that can advance computation, communication, and sensing.

Recommendations:

- Evaluate possible and novel research directions with holistic networks to target how low-cost distributed sensing can be combined with machine learning to derive fundamental performance estimates.
- Because quantum technologies will inevitably be integrated with classical mechanical systems, conduct an evaluation of the impact of training GN&C engineers in quantum technologies, and start to infuse quantum technologies in the NASA Systems Engineering process.

1.11 Summary

This document proposes a vision of technology development for the next few years and is the first time that surface and subsurface GN&C has been examined in this depth and breadth. The findings and recommendations represent a spectrum of investments both in cross-cutting technologies and systems engineering and prototype development targeted at specific mission types. One overarching finding is that, because surface and subsurface GN&C is still in its infancy, the associated system architecture and systems engineering processes are still comparatively immature. For that reason, we make the following general recommendations:

- Surface and subsurface GN&C must be recognized as a distinct field rather than a subset of spacecraft GN&C.
- Sustained system-level analyses and design of surface and subsurface GN&C systems must be undertaken well before mission definition.

2 Study Overview

This document is Part III of the *Guidance, Navigation, and Control Technology Assessment for Future Planetary Science Missions* series detailing the advances in GN&C technology and mission design that are needed to achieve the goals of future planetary science missions, as outlined in the National Research Council's (NRC's) *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023–2032*.[2] The two previous documents in this series were *Part I: Navigation and Mission Design* and *Part II: Onboard Guidance, Navigation, and Control*.[3, 4] This document addresses the post-EDL phase of surface missions. For potential small-body missions, this document addresses the challenges and technologies associated with the sampling, anchoring, and other aspects involving contact (starting from the mounting point of the sampling device/arm) while leaving all other aspects to *Part II: Onboard Guidance, Navigation, and Control*. Figure 1 shows how this report fits in the report sequence.

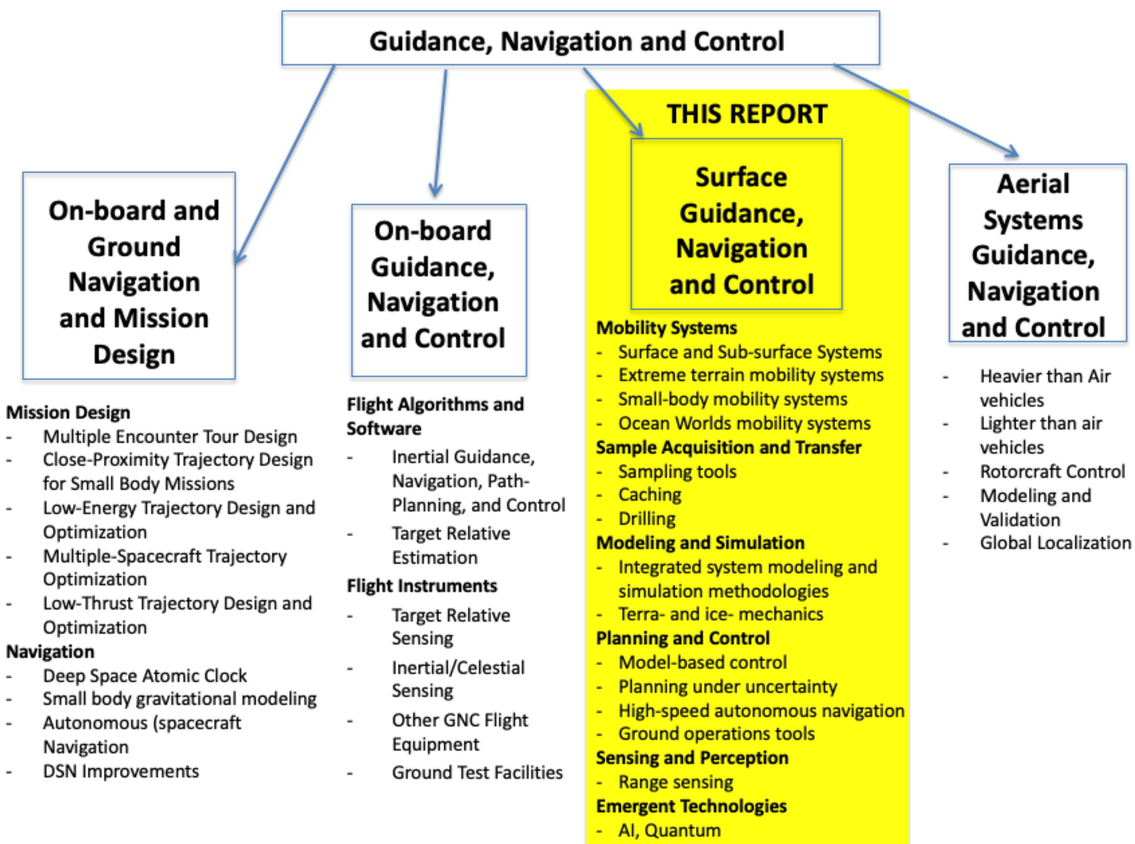

Figure 1. How this report fits into the *Guidance, Navigation, and Control Technology Assessment for Future Planetary Science Missions* series.

Planetary surface missions cover a tremendously wide range of component and system GN&C technologies, and that breadth presents a particular challenge to the study undertaken here. A greater emphasis is placed on mobility-based missions because the post-EDL GN&C challenges of purely lander-based missions are modest and are largely a subset of those associated with free-flying spacecraft (a topic covered in previous reports). Of course, the space of mobility-based GN&C challenges is itself extremely diverse, encompassing the use of wheeled rovers, aerial platforms, small-body hoppers, and others. We have tried to emphasize technical areas with applicability across a spectrum of mobility types while still identifying challenges unique to particular forms of mobility. While we have had recent successes with the Mars Exploration Rovers (MERs), Mars Science Laboratory (MSL), Mars 2020, the Mars Helicopter, and the Phoenix and InSight landers, significant improvements are needed to enable access to more challenging terrains and environments to achieve more ambitious missions. The current state of in situ planetary exploration is comparable to that of remote sensing in the 1970s. The complexity of the environment, be it poorly understood wind patterns or the behavior of heterogeneous regolith and the resulting interactions with the vehicle, present critical challenges. Findings presented in this document represent a spectrum of needs in crosscutting technologies as well as systems engineering and prototype development targeted at specific mission types. Figure 2 shows artists' concepts of several planetary robotic systems.

The thought process followed in this report is roughly as follows: Given a Science goal (from the Planetary Decadal Survey), mission objectives are determined (Section 3). These mission objectives are enabled by key Capabilities (Section 5), which are implemented by a set of Technologies (Section 6).

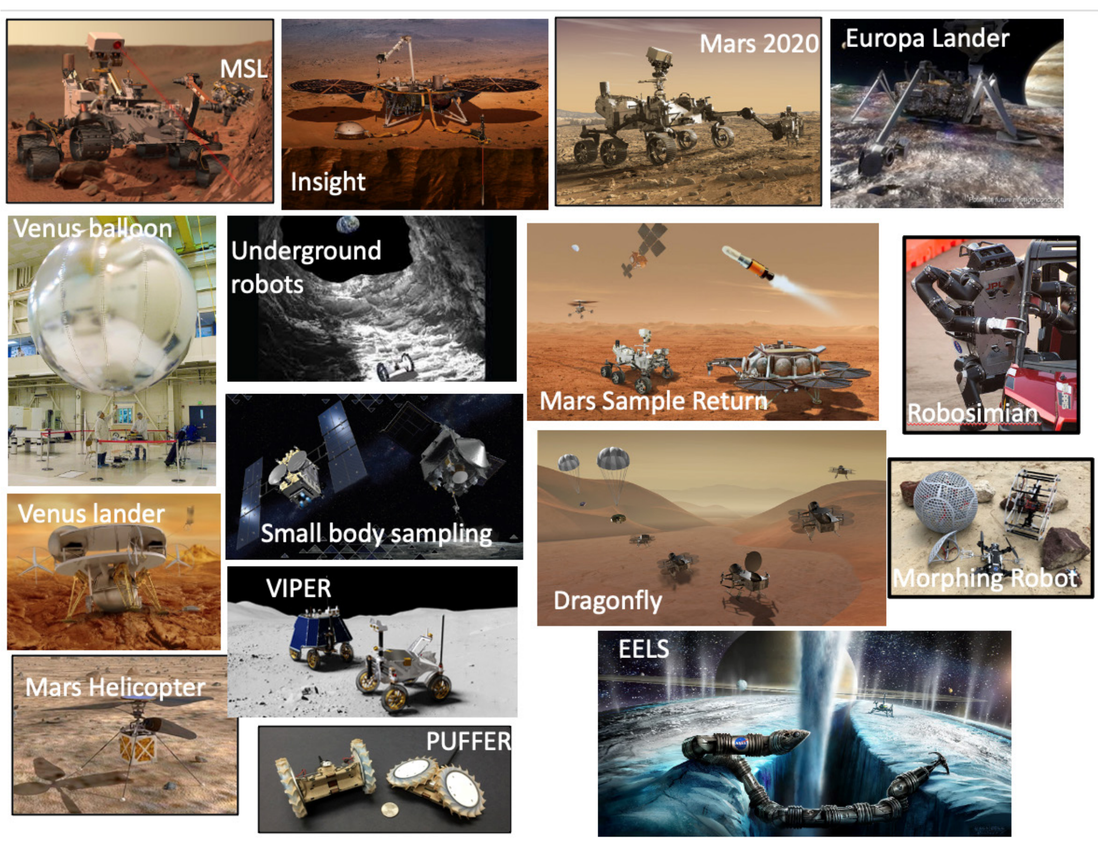

Figure 2. Artists' concepts of several planetary robotic systems.

3 Missions from 2022 Decadal Survey Requiring New In Situ Exploration Surface and Subsurface GN&C Capabilities

Recommendations for future missions have been made in the NRC's *Origins, Worlds, and Life 2023–2032* (OWL), developed at the request of NASA's Science Mission Directorate (SMD) Planetary Science Division (PSD).[2]

Currently operating planetary spacecraft in the solar system that include surface operations are the Curiosity and Perseverance Mars rovers, while surface missions in development are the New Frontiers mission, Dragonfly, and Mars Sample Return (MSR), a Flagship mission. Future Flagship missions recommended in OWL—Endurance-A and the Enceladus Orbilander—have been studied, and technology development for these should be prioritized along with New Frontiers 6 (NF-6)–recommended missions that require surface GN&C: Centaur Orbiter and Lander (CORAL), Ceres Sample Return, Comet Surface Sample Return (CSSR), Enceladus Multiple Flyby (EMF), Lunar Geophysical Network, and the Venus In Situ Explorer (VISE). In prior decadal surveys, the baseline mission for VISE was a lander; for the new decadal survey, it is a balloon mission. However, the same name was retained to establish a sense of continuity.

OWL (Chapter 21) identifies a number of technology developments involving GN&C development that it deems are high priority for "this Decadal and beyond":

- "Long traverse surface mobility is identified as an enabling technology that allows smooth traversing regardless of large rocks and steep slopes at traverse raters much greater than current technology."[2] Advances in hazard avoiding autonomous mobility will be key.
- "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."[2]
- "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."[2]
- "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."[2]

NASA should maintain cognizance of emerging new technologies, including artificial intelligence, machine learning, and quantum computing, and "encourage the science and engineering communities to explore new ways that these technologies can enable greater science while reducing development and operations costs."[2]

To reach and explore these new scientific targets of Planetary interest, advances in surface and subsurface GN&C capabilities are needed to address the following scenarios:

- Surface landers
  - Surface lander on targets with high gravity and atmosphere (type 1)
  - Surface lander with significant gravity and no atmosphere (type 2)
  - Surface lander on low-gravity, small-body targets (type 3)
- Proximity operation about low-gravity, small-body targets
- Sample return missions

Table 1 shows the taxonomy of capabilities described in this report, further discussed in Section 5. Table 2 shows the recommended PSD missions from the Decadal Survey and their corresponding GN&C-relevant functions, i.e., the capabilities listed in Table 1. Each of the mission scenarios creates its own specific challenges for GN&C. However, it is worth mentioning that there are certain fundamental drivers common to all missions: a) long roundtrip light-time, b) time-constrained in situ operations, c) unknown and dynamic environments, d) flight and mission system fault conditions, and e) mission longevity. These drivers apply to some or all of the GN&C-relevant scenarios outlined above and, together with other, more specific challenges, will drive the development of GN&C technology across a wide range of functions. The key mission scenarios and their corresponding enabling GN&C capabilities are discussed in Section 3. The supporting technologies needed to realize these required GN&C capabilities are discussed in Section 4.

Table 1. Taxonomy of capabilities described in this report.

Capability	Description
More capable rovers	Ability to rove the surface faster and for a longer distance.
Extreme-terrain exploration	Ability to negotiate steep slopes, cliffs, and very rough terrain of any slope, as well as very soft terrain of unconsolidated fine granules of rock or ice (e.g., sand and snow), liquids, and multiphasic media.
Subsurface exploration	Ability to enter and move around caves, crevices, vents, and lava tubes.
Microgravity exploration	Ability to move in the surface of small irregular bodies in the absence of an atmosphere and in the absence of a strong gravitational field.
Under-ice exploration	Ability to move through a thick layer of ice, and reach and navigate in the putative ocean.
Sampling and sample handling	Ability to interact with an end effector with the in situ material (solid, liquid), drill at depth, and collect and store the sample for possible sample return.
Efficient operations	Ability to enable increasingly more demanding forms of vehicle autonomy, with obscurations and lack of global localization, and with large latencies.
GN&C modeling and simulation	Ability to model and simulate the vehicle physics and autonomy operating together with the vehicle hardware to achieve a goal.

Table 2. Recommended PSD missions from the Decadal Survey and their corresponding GN&C-relevant functions.

Capability	MSR	Dragonfly	Enceladus Orbilander	CORAL	Ceres Sample Return	CSSR	LGN	VISE	Triton Ocean World Surveyor	Europa Lander	Planetary Defense
More capable rovers	✓						✓			✓	
Extreme-terrain exploration			✓			✓				✓	
Subsurface exploration			✓							✓	
Microgravity exploration				✓	✓	✓					✓
Under-ice exploration									✓	✓	
Sampling and sample handling	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓
Efficient operations	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓
GN&C modeling and simulation	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓

3.1 Moon

Several missions for exploring more challenging environments on the Moon have emerged in the last decade. OWL recommended **Endurance-A**, a mission to the Moon that would traverse diverse terrains and robotically collect a large (100 kg) suite of carefully selected samples from scientifically important locations access the South Pole-Aitken basin and deliver them to a human landing site for retrieval by astronauts and return to Earth. Exploring the permanently shadowed regions (PSRs) of lunar craters in search of frozen volatiles also represents a challenge for in situ exploration in terms of survival and navigation. NASA's Artemis lunar rover, the Volatiles Investigating Polar Exploration Rover (VIPER), is being developed now and will explore the relatively nearby but extreme environment of the Moon in search of ice and other potential resources, landing at the South Pole of the Moon in late 2024 on a 100-day mission. The potential NF-6 **Lunar Geophysical Network** (LGN) would examine the physical properties of the present-day Moon by deploying a global, long-lived (≥6 years) network of geophysical instruments on its surface, including seismometers and heat flow measurements requiring drilling. Other potential Discovery missions that have been proposed are Moon Diver, a concept for sending an extreme-terrain rover to explore deep caverns on the Moon.[5] On its journey, Moon Diver would examine the Moon's ancient lava layers in order to understand the nature and origins of the solar system's most extreme type of volcanic eruption.

3.2 Mars

The 2011 Decadal Survey, *Visions and Voyages*, selected the MSR campaign as its highest priority, with the Mars 2020 mission, Perseverance, being the first in a sequence of missions needed to return the sample. Perseverance landed on Mars on February 18, 2021, and is drilling core samples from about 30 promising rock and "soil" (regolith) targets and caching them on the Martian surface. A subsequent mission will retrieve the cached samples and place them in orbit for return to Earth. Perseverance incorporated new technologies, including Terrain Relative Navigation (TRN), to enable landing at Jezero Crater, a scientifically desirable site for the mission that was previously considered too hazardous for landing. (TRN is described in more detail in Part II.) It also incorporated Fast Traverse, which enables greater distances to be covered in a much shorter time (the Mars 2020 mission has advanced surface navigation, achieving autonomous navigation [thinking while driving] at rate that is a factor of five times faster and more capable of handling difficult terrain than its predecessors [100 m/hr for Perseverance compared to ~20 m/hr on Curiosity/MER rovers). OWL has recommended that after MSR, NASA should implement a **Mars Life Explorer** (MLE) mission with the goal of seeking extant life and assess modern habitability, but given budgetary changes, this is likely to be delayed into the next decade. The notional mission concept would examine Mars's lowest-latitude ice deposits that preserve a record of recent climate change and may provide a recent habitat for life. MLE would land and drill into the ice to characterize and quantify organics, trace gases, and isotopes at a fidelity suitable for biosignature detection. It would also assess ice habitability and the question of modern liquid water via analysis of elemental chemistry, salts, conductivity and ice thermophysical properties. Long-term atmospheric measurements over a Martian year would determine the current stability versus instability of the ice deposits. MLE does not require horizontal mobility but would be equipped with a 2-m vertical drill to access ice deposits beneath the lander. In addition to accessing the surface, vehicles that can access lava tubes and caves are of enduring interest and will be discussed.

3.3 Ocean Worlds

Several in situ missions to ocean worlds are among the OWL recommendations. In the Flagship class is an **Enceladus Orbilander**, a mission that would orbit Enceladus and then land on the surface. It is envisaged to orbit Enceladus for 18 months, collecting plume samples from orbit, prior to a two-year landed mission when more voluminous plume material would be acquired in both passive and active (i.e., scooping) modes. A **Europa Lander** mission, a focus for recent development in safe landing technology, was ranked below the Enceladus Orbilander among the missions for the coming decade but was among four Flagship-class missions. More ambitious Europa missions to penetrate the ice and enter the ocean were not recommended by OWL. Neither was a mission to penetrate beneath the surface of Enceladus, but technologies for carrying out both types of mission are being explored by NASA and JPL because some of these technologies could take decades to mature. Future mission concepts include under-ice and underwater vehicles exploring the putative oceans in these bodies.

3.4 Airless Bodies

Among the competitive missions in the New Frontiers class, OWL recommends a **Centaur Orbiter and Lander (CORAL)** that would rendezvous and land on a member of this asteroid class orbiting outside the Jupiter Trojans. It also recommends a **Ceres Sample Return** mission to return a sample from the largest member of the asteroid family.

4 Definitions and Taxonomy of Surface and Subsurface GN&C for In-Situ Exploration

In situ exploration GN&C is defined to be the motion planning, sensing, and control of the vehicle to achieve desired maneuvers in order to accomplish a specific goal when operating in a planetary environment. In situ exploration GN&C includes operations on the surface, subsurface, and in the atmosphere, and extends to interactions between vehicles on the surface, subsurface, and in the atmosphere. *Surface and subsurface GN&C comprise the sensing, estimation, motion planning, and control of mobile surface and subsurface assets to reach designated targets, deploy instruments and sampling tools, and acquire science measurements that accomplish science goals*. Surface and subsurface GN&C includes operations on the surface and subsurface, and extends to interactions between vehicles on the surface, subsurface, and in the atmosphere. Some of the terminology associated with surface and subsurface mobility systems can differ from that adopted for general, remote-sensing spacecraft. In this document, determination of the vehicle's position, attitude, and velocity is referred to as "localization." Determination of a desired path of travel is referred to as "path planning" or "motion planning," while the broader problem of selecting and executing a path towards a specified goal position is referred to as "navigation."

We define *autonomy* as the ability of a system to achieve goals while operating independently of external controls. A recent overview paper on space autonomy is provided in Reference 6. In this context, the following apply:

- The goal of **mobility** or locomotion is to reach and operate at sites of scientific interest on extraterrestrial surfaces. Technology needs include a) mobility on, into, and above an extraterrestrial surface using locomotion like flying, walking, climbing, rappelling, tunneling, swimming, and sailing; b) melting through the kilometers-thick ocean worlds' ice shells of Europa, Enceladus, or Pluto; and c) Manipulations to make intentional changes in the environment or objects using locomotion like placing, assembling, digging, trenching, drilling, sampling, grappling, anchoring, and berthing. In terms of science, locomotion represents the ability to explore an environment, such as rovers, aerobots, and submarines do. Melting through ocean worlds' ice shells enables access to habitable oceans underneath. Digging, trenching, and coring enable access to materials without atmospheric contamination or radiation.

- The goal of **sample acquisition and transfer** is to create access to, acquire, and transfer extraterrestrial materials of scientific interest into containment or instrument systems. Sampling tools make intentional changes to the environment for access and capture of rocks, soil, liquid, and complex phase-change materials. Transfer technologies move the sampled materials via a wide array of driving mechanisms, including gravity and gravity agnostic (e.g., pneumatic). Caching technologies store samples over short (days) and long (years) duration while maintaining integrity over extreme temperature, pressure, and radiation. Autonomous sampling technologies enable adaptation to uncertain and dynamic tool-terrain interactions. Models and simulation of terra-mechanics, ice-mechanics, and phase-change mechanics for extraterrestrial materials enable the development of new sampling architectures and tools, and can be leveraged in situ by sampling autonomy.
- The goal of **sensing and perception** is to provide situational awareness for space robotic agents, explorers, and assistants. The technology needs are new sensors, including sensing techniques; algorithms for 3D perception, state estimation, and data fusion; onboard data processing and generic software framework; and object, event, or activity recognition. Sensors provide the bulk of the direct science: Increases in instruments, both remote sensing and in situ, enable more precise measurements (e.g., spatial and spectral resolution, while reducing volume, mass, and power); and new types of instruments are emerging. There is imaging spectroscopy to determine composition; LIDAR (light detection and ranging) for 3D mapping; interferometric radar for change detection and structure; and sample processing for life detection and astrobiology to enable novel measurements for new types of science.
- The goal of **high-level autonomy** for systems and subsystems is to provide robust and safe autonomous navigation, rendezvous, and docking capabilities and to enable extended-duration operations without human intervention to improve overall performance of human and robotic missions. To enable closed-loop science for more efficient, novel science (e.g., tracking a dynamic plume at a comet), GN&C algorithms are needed: docking and capture mechanisms and interfaces; planning, scheduling, and common autonomy; software frameworks; multi-agent coordination; reconfigurable and adjustable autonomy; automated data analysis for decision-making; fault detection; isolation and recovery/integrated vehicle health management (IVHM), ; and execution. For science, enhanced GN&C means higher-precision navigation for better science measurements. Scheduling, execution, and IVHM enable more productive science time for vehicles. Automated science analysis and scheduling enable closing the loop without ground in the loop, enabling more science cycles per mission (i.e., higher productivity and unique, opportunistic science).
- The goal of **human-robot interaction** is to enable humans to accurately and rapidly understand the state of the robot in collaboration and act effectively and efficiently toward the goal state. This involves technologies for multimodal interaction, remote and supervised control, proximate interaction, distributed collaboration and coordination, and common human-system interfaces. Virtual reality and augmented reality allow more

natural interfaces to analyze vast acquired data streams. Virtual reality and augmented reality also allow for natural means of vehicle controlling, such as by reach, touch, and gesture.

- The goal of **system engineering** is to provide a framework for understanding and coordinating the complex interactions of robotic assets and achieving the desired system requirements. This requires modularity, commonality, and interfaces, V&V of complex adaptive systems, robotic vehicle modeling and simulation, software architectures and frameworks, and safety and trust. To enable science missions, high stakes in billions of dollars require a reliable mission. As systems become increasingly complex, being able to characterize robotic behavior (especially for multi-vehicle swarms) becomes increasingly challenging.

The list of missions outlined in Section 2 demonstrates the multitude of challenges presented by future surface missions. Challenges common to virtually all of the surface missions include the following:

- Limited bandwidth and high-latency communications preclude real-time tele-operation (except to the near side of the Moon), thus requiring a high degree of autonomy and reliability.
- Harsh environments lead to rapid degradation of components/systems and significant aging during longer missions. Achieving the required robustness and fault tolerance in a cost-effective manner is a challenge of growing importance. More important is the case of missions of shorter duration, which need to operate at a faster pace only possible with autonomy (and without many ground communication cycles between small actions).
- The limited capability of available radiation-tolerant, flight-qualified processors constrains onboard processing, even while avionic and software systems continue to grow in complexity. Currently, the performance gap between standard commercial processors, where the trend is toward greater parallelism, and flight processors remains large. Obtaining the levels of robustness and reliability required for space applications in the face of increasing cost constraints remains an open problem.
- Perhaps the single greatest determining feature of surface missions is the need to operate in a complex and only partially understood environment. We should point out that natural environments on planets are not always analogous to Earth. For example, comet surfaces, cryolakes, thermal extremes in shadows, etc., can require novel system designs and autonomy algorithms tailored for these environments. Many of the future missions detailed above involve levels of interaction with the environment (terrain and soil, atmosphere, and lakes) far beyond that demonstrated in previous missions. There is a need for improved environmental models, as well as for planning and control algorithms that are robust to significant uncertainties to better address the challenges of steep slopes, operations in low gravity, or for aerial vehicles operating in changing and poorly understood winds.

The tables discussed next are a snapshot of the state of the art and will prepare the reader for the following sections, where the capabilities and technologies are discussed in more detail.

Table 3 shows the benefits these capabilities will enable as a function of target destination. Table 4 presents a taxonomy of the technologies discussed in this report, further discussed in Section 6. Table 5 summarizes the mapping between those technologies and the surface GN&C capabilities discussed in the previous section. Finally, Table 6 outlines key advances in surface

GN&C capabilities. These capabilities and associated technologies will be further discussed in Sections 5 and 6.

Table 3. Benefits that the capabilities will enable as a function of target destination.

	Moon	Mars	Enceladus	Ocean Worlds	Small Bodies
Exploration of ice	x	x	x	x	x
Mining and in situ resource utilization processing	x	x			
Propellant transfer	x	x			
Constructing landing pads	x	x			
Autonomous operations of vehicles	x	x	x	x	x
Extreme-terrain locomotion	x	x	x	x	x
Subsurface mobility and sample acquisition	x	x	x	x	
Sample systems and sample preservation	x	x	x	x	x
GN&C modeling and simulation	x	x	x	x	x

Table 4. Taxonomy of technologies described in this report.

Area	Technology	Description
Mobility Systems	Surface mobility systems	Conventional mobility types, such as planetary rovers.
	Extreme-terrain mobility systems	Unconventional mobility types targeted at vertical access in strong gravitational fields, as well as mobility on liquid and multiphase media.
	Subsurface mobility systems	Systems for access and exploration of underground caves, voids, lava tubes, etc.
	Small-body mobility systems	Unconventional mobility types targeted at locomotion in weak gravitational fields.
	Ocean worlds mobility systems	Through-the-ice, under-ice, and underwater robotic systems.
Sample Acquisition and Transfer	Sample tools	All forms of devices and techniques used to collect a sample from a planetary body.
	Caching	All forms of devices and techniques used to place and store a sample from a planetary body.
	Drilling	All forms of devices and techniques used to drill the surface of a planetary body.
GN&C Modeling and Simulation	Physics-based modeling and simulation	Mathematical modeling and software simulation technologies of dynamical systems interacting with the environment.
	Terra- and ice-mechanics	The understanding of the physics of the vehicle-soil and ice interaction.
	Uncertainty quantification	Quantitative characterization and reduction of uncertainties in both computational and real-world applications.
	Verification and validation (V&V)	The application of modeling and software simulation technologies to functionally integrated processes that model one or more elements at various points of the design life cycle.

Area	Technology	Description
Planning and Control	Model-based control	Approaches to control a vehicle component or subsystem based on an understood state model of the system.
	Learning-based control	Approaches to control a vehicle component or subsystem based on an inference of the model parameters from sensor measurements
	Planning under uncertainty	Trajectory planning that reflects quantitative estimates of sensing and control uncertainty.
	High-speed autonomous navigation	Way-point guidance and hazard-avoidance methodologies to navigate the vehicle.
	Ground operations tools	All the visualization and planning tools used in mission operations.
Sensing and Perception	Range sensing	Sensing and computation that produce estimates of range to remote and distant features.
	Global localization	The determination of the position and attitude of the vehicle with respect to a specified reference frame.
Emergent Technologies	AI	Machine learning, deep learning, data analytics.
	Quantum technologies	Applications to deliver useful devices and processes that are based on quantum principles.

Table 5. Technologies that impact surface GN&C capabilities.

Technology		Fast and Energy-Efficient Rovers	Extreme-Terrain Mobility	Small-Body Mobility	Sub-surface Mobility	Under-ice Mobility	Sampling and Sample Handling	Efficient Operations
Mobility Systems	Surface	✓	✓	✓				✓
	Subsurface				✓			✓
	Extreme		✓					✓
	Ocean Worlds					✓		✓
Sample Acquisition and Transfer	Sampling Tools		✓	✓	✓	✓	✓	
	Caching						✓	
	Drilling						✓	
Modeling and Simulation	Integrated system modeling and simulation	✓	✓	✓	✓	✓	✓	✓
	Terra- and Ice-Mechanics	✓	✓	✓	✓	✓	✓	✓
	Terra-mechanics	✓	✓	✓	✓	✓	✓	
Planning and Control	Planning under uncertainty	✓	✓	✓	✓	✓	✓	
	High-speed autonomous navigation	✓	✓					

Technology		Fast and Energy-Efficient Rovers	Extreme-Terrain Mobility	Small-Body Mobility	Sub-surface Mobility	Under-ice Mobility	Sampling and Sample Handling	Efficient Operations
	Ground operations tools				✓			✓
	Control	✓	✓	✓	✓	✓	✓	✓
Sensing and Perception	Range sensing	✓	✓	✓	✓			
	Global localization	✓	✓	✓	✓	✓	✓	✓
Emergent Tech	AI	✓	✓	✓	✓	✓	✓	✓
	Quantum	✓						✓

Table 6. Key advances in surface GN&C capabilities.

Capabilities	Current Status*	Desired Status	Benefits to Missions
Fast and Energy-Efficient Rovers	• Limited traverse rates, performance penalty associated with autonomous hazard detection and avoidance, leading to rationing of autonomous capabilities	• Always-on hazard detection and visual odometry at higher vehicle speeds • Improved energy efficiency by eliminating time and power spent while rover stops to perform hazard detection and visual odometry	• Increased traverse distances, energy efficiency, mission safety, and greater sample diversity
Extreme-Terrain Mobility	• Low- and mid-TRL prototypes of tethered systems (e.g., JPL's Axel, EELS)	• High-TRL robotic prototypes capable of exploring gullies, cliffs, and caves • Autonomous traverses and science operations in extreme terrains (control, traversability analysis, motion planning, and localization)	• Access to and sample return from high-value science targets inaccessible by conventional rover-based sample acquisition robotic arm systems
Small-Body Mobility	• JAXA MINERVA (Hayabusa II) • Low-TRL prototypes (e.g., NIAC hedgehog)	• Instrumented mobility platforms (e.g., hover spacecraft with tethered penetrators; hoppers; wheeled, legged, or hybrid platforms) • Autonomous traverses to designated targets and in situ measurements	• Access to high-value science targets • Enable heterogeneous sample collection
Sampling and Sample Handling	• Mars 2020 Sample Acquisition/Sample Processing and Handling System • OSIRIS-REx • Hayabusa2 • Honeybee, ATK designs	• Efficient cache retrieval and handoff, solid/liquid sample acquisition, handling, and distribution • Autonomous sampling of limited-knowledge extraterrestrial terrains • Subsurface sampling via deep drilling	• Enable heterogeneous sample collection • Access to high-value sampling targets with reduced engagement with ground operations
Efficient Operations	• Mars 2020 state of art	• Greater operational efficiency (in terms of time and workforce) • Improved situational awareness of science and operations team • Greater understanding of viable operations procedures and tempo for targets with very limited communications	• Reduced mission cost and improved science

Capabilities	Current Status*	Desired Status	Benefits to Missions
GN&C Modeling and Simulation	• Modeling and simulation of small mission segments • Limited spatial and temporal scales	• Modeling and simulation of entire mission phases, across multiple spatial and temporal scales of operation • GN&C functions integrated with physical system behavior and environmental models	• Iterate among predictions of system performance in realistic environment before design is initiated, so that the best instrument selection can be made

* See the acronyms list at the end of this report for acronym definitions.

5 Surface and Subsurface Systems Needing GN&C

This section describes the key capabilities that will enable or enhance the missions described in the previous sections.

5.1 Surface Mobility

Relevant future missions: Endurance-A, Mars Sample Return (MSR), Enceladus Orbilander, Centaur Orbiter and Lander (CORAL), Ceres Sample Return, Comet Surface Sample Return (CSSR), Lunar Geophysical Network (LGN), Venus In Situ Explorer (VISE), Mars Life Explorer (MLE), Europa Lander

Faster autonomous traverse speeds would enable samples to be collected over a wider area and/or allow more time for sample selection and site characterization.

Although the Mars 2020 mission advanced surface navigation, achieving autonomous navigation (i.e., "thinking while driving") at a rate that is a factor of five faster and more capable of handling difficult terrain than its predecessors (100 m/hr for Perseverance compared to ~20 m/hr on Curiosity/MER), the rover's mechanical speed remains at a relatively slow pace of 4.2 cm/s. Studies of a solar-powered sample fetch rover for MSR obtained mobility improvements with fewer actuators for a four-wheeled architecture with all-wheel drive/steer and large, compliant mesh wheels that stow in a smaller volume for interplanetary cruise. This concept benefitted from significant miniaturization of DC brushless motor controllers and other avionics components. This architecture may be a model for reducing the cost of science rovers for future missions.

More recently, the Sample Return Helicopter plans to collect samples and bring them back to the rover. For a mission utilizing the Mars Ascent Vehicle (MAV), faster autonomous driving would enable shorter mission duration (an important factor, given concerns about the potential degradation of the MAV rocket fuel). Another benefit is improved mission safety by enabling always-on hazard avoidance and slip detection. Further improvements are needed in autonomous navigation speeds to enable future Mars and lunar rovers that are faster, can drive farther, and can operate more safely than current rovers.

Perseverance is the baseline for delivering samples to the Sample Retrieval Lander; the two helicopters are a backup. The plan for acquiring the backup samples and depositing them at a safe landing cache is described in Reference 7. The cache was recently completed in Jezero crater. Perseverance plans to climb out of the crater during the rest of its mission. If it fails at some point, then the Sample Retrieval Lander will go to the cache. All 10 samples in the sample cache were completed on January 29, 2023.[8] The rover is carrying 10 nearly equivalent samples, but it will continue to collect new samples until all 38 tubes are filled.

Surface mobility provides access to science targets not reachable from a static lander. On Mars, rovers to date have been limited to fairly benign terrain, driving three to four hours per day and a few tens of kilometers in the life of a mission. The past two decades has revealed that Mars is more diverse than originally thought, and there is a need to access a much greater range of that diversity to understand its habitability, geology, and climate history.[9] This requires access to widely separated sites; to a wide range of latitudes, including mid-latitude and polar sites; and to a wide range of terrains, including steep slopes.[10-15] Aerial mobility provides an alternative approach to traversing potentially hazardous terrains and was a key motivation for Dragonfly at Titan as well as the Mars Science Helicopter (see Part IV).

The Moon is also diverse, with widely separated science targets. The Planetary Decadal Survey recommended the Endurance rover mission, which has a need for a nearly two-orders-of-magnitude longer traverse at an-order-of-magnitude faster pace compared to its Martian counterpart.[16] The distance for this concept is around ~2,000 km over an approximate four-year mission duration. The concept also requires significant night driving in the low-light South Pole–Aitken basin for a 100-kg lunar sample return.[17-19]

The Endurance lunar rover Planetary Mission Concept Study for the 2023–2032 Planetary Science and Astrobiology Decadal Survey shows that very long-range surface mobility on the Moon is possible, with driving speeds up to 30 cm/s (~5 times more than possible on Mars to date), given increased power, longer lunar days, and readily achievable advances in onboard autonomy to reduce the frequency of unplanned stops and to maintain absolute position knowledge of the rover.[16] Increased miniaturization and performance improvements of onboard computing architectures, navigation sensors, and communications systems, combined with advances in surface navigation and localization, could open up possibilities to explore substantial planetary diversity in a single mission, as seen by the Endurance-A mission concept study.

NASA science and human exploration objectives for the Moon and Mars present synergistic needs for surface mobility over much longer ranges and at colder temperatures than ever before.[20] For example, Endurance aims to traverse about 2,000 km over four Earth years with a four-wheeled rover at high latitudes on the lunar far side, including short drives during lunar night. This is 40 times farther than the longest total traverse for a planetary rover (Opportunity drove 45 km on Mars over 14 years). This requires driving at speeds up to 30 cm/s (~6 times more than the peak speed of Mars rovers to date) for a kilometer between stops and driving at temperatures as low as −180°C. Because current wet-lubricated actuators don't operate below −55°C, this would involve substantial actuator preheating. Other lunar rover mission concepts have similar needs, though not necessarily over as much range, such as for the VIPER mission.[21] Mars science objectives have been identified at equatorial, middle, and north polar latitudes that also require combinations of long traverse and cold-temperature operation far exceeding previous missions. Extremely long-range traverse is harder to achieve on Mars than on the Moon due to lower solar energy availability, higher gravity, and much longer communication latency with Earth; nevertheless, new technology could enable traverse ranges that would be revolutionary for Mars. Design studies to date on long-range lunar rovers have largely used heritage components; however, innovations now in progress have the potential to enhance the lunar scenarios and to enable these Mars scenarios. Processors analogous to the smartphone computer in the Mars Helicopter, Ingenuity, may achieve three orders of magnitude more computing throughput than the RAD750 and one to two orders of magnitude more than the Vision Compute Element (VCE) coprocessor used in the Perseverance rover, with far lower SWaP. Other avionics advances in progress include major size and power reductions for motor controllers, inertial measurement units (IMUs), and radios. Finally, much faster autonomous-navigation processing loops are required to keep up with the above actuator speed; this would be enabled by much faster avionics with low SWaP. The lack of an onboard absolute-position-estimation capability currently requires rovers to get position updates through ground-in-the-loop (GITL) cycles every few hundred meters of travel. “Mobility faults” also require frequent GITL cycles for diagnosis and recovery. Both of these limitations can be greatly alleviated with better onboard autonomy. A key point is that for slow-moving rovers, non-propulsion energy use (e.g., avionics, thermal management, heaters) often exceeds drive-motor energy use. Driving energy is a function of distance travelled, not velocity, whereas non-driving energy is a function of time. Therefore, if avionics can “keep up” with faster actuators without increased avionics energy usage, there is a benefit to overall energy budget.

Note that scientific discoveries at other planetary bodies besides the Moon and Mars also would benefit from access to multiple surface locations.

5.2 Subsurface Mobility

Relevant future missions: Same as for Section 5.1.

There is a growing interest from scientists in gaining access to the subsurface environments of rocky planets such as caves and pits that have, for the most part, been identified putatively using orbital imaging cameras and could offer protection from harsh surface conditions. They could also house valuable resources such as ice or, in the case of Mars, evidence of prior life. Recent advances in alternative robotic platforms and autonomous navigation, however, now make exploring these caves a viable option for near-future robotic deployment on Mars.[22] If successful, missions such as these could shed light on Mars’s geologic past as well as its potential for supporting life. Subsurface voids are of interest for their potential relevance to astrobiology, potential records of geology and climate, and in the case of the Moon and Mars, as potential habitat locations for eventual human explorers.[23] Many pits that appear to be openings into lava tubes exist on the Moon and Mars, and vents that link to a subsurface ocean exist on Enceladus. Other terrestrial planets, dwarf planets, asteroids, and icy moons have landscapes with potential to contain caves or crevasses. Exploring pits on the Moon and Mars can be approached several ways. Currently, the most mature concept involves rappelling rovers similar to the two-wheeled Axel or the four-wheeled DuAxel vehicles that have been developed for descending steep slopes on Mars. Indeed, a proposal—Moon Diver—was submitted to the 2019 Discovery Program mission solicitation to explore a lunar pit with this approach, using precision landing near the pit and a two-wheeled vehicle that would egress from the lander and rappel into the pit on a tether. Figure 3 illustrates the proposed Moon Diver concept. A similar approach is conceivable for Mars, though limited to caves at elevations low enough that landers can decelerate adequately in the thin Martian atmosphere. Synergies between steep-terrain access and pit access may provide multiple uses to further the development of rappelling vehicles. Other vehicles have been prototyped for planetary cave exploration, including limbed wall-crawlers that use microspines or other forms of attachment, small rough-terrain ground

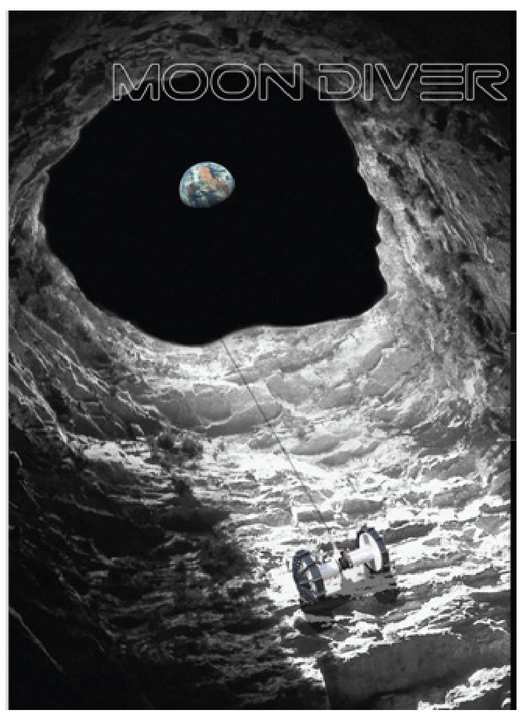

Figure 3. Moon Diver illustration.

vehicles that might explore horizontal reaches of caves, and rotorcraft (discussed in Part IV) for bodies with atmospheres.[23] There may be synergies among some of these concepts and vehicles for surface mobility on small bodies or icy moons.

Robots are likely to be the first explorers of planetary caves.[23] To effectively explore these targets, future robotic systems will require the functionality to 1) properly sense their environment, 2) support and deliver scientific payloads to sites of interest, 3) plan actions and movements, and 4) negotiate a complex landscape to execute these actions. All of these functionalities will be challenged by the unique features of planetary caves, including aphotic conditions, indirect line-of-sight communication requirements, subsurface power considerations, and rough, uneven, 3D terrain that precludes satellite pre-mapping.

Constrained by limited payloads, cave robotic designs will represent a barter between every gram of mobility and navigational sensing technologies and scientific instrumentation.[24] Limited payload capacity driven by navigational and mobility systems better suited to the challenging environment will preclude the more comprehensive science laboratories common to previous Mars surface rover missions. While payloads will be determined by mission objectives, highly accurate 3D maps of caves represent the geospatial backbone for any planetary caves mission—as navigation and mobility will be reliant on how well the rover can “sense” its surroundings. For example, an astrobiology-focused mission may feature a combined mobility, navigation, and life-detection payload that leverages dual-purpose mapping. Even in well-studied terrestrial settings, most caves have not been mapped at sufficient resolution for robotic exploration. Thus, advancing onboard survey instrumentation to obtain high-resolution, 3D cave geometries to both establish safe traverse routes and avoid hazards will be required.

A variety of robotic approaches have been proposed to overcome key obstacles related to entering and navigating caves, including a) entry from the surface down into the lava cave system through a skylight – these entrances often include a large vertical drop (> 50 m), b) traversing an irregular floor surface and/or over large blocky obstacles, c) operations in darkness, and d) autonomous operation and localization (out of line-of-sight to surface communications). In addition to traditional wheeled rovers, robotic vehicles using biomimicry offer alternative locomotion in challenging subsurface terrain. Prototypes include fleets of coordinating robotic ants, butterflies, dragonflies, and spiders optimized for relay communications away from a control center. Robotics technologies that link perception, navigation, mapping and decision-making have made great advances. This means that previously impractical approaches for exploring cave environments are near-future possibilities.

Other relevant work: With advances in mobility systems enabling cave exploration in the past two decades, cave-exploration (and, in general, subsurface-void-exploration) technologies have matured enough to enable future space robotic missions. These advances have been expedited by synergistic collaborations between the rising commercial space sector, traditional mining companies, and other government agencies. Most prominently, the U.S. Department of Defense has made significant investments in autonomy technology demonstration for exploration of caves through its current DARPA SubT Challenge, in which NASA-led teams have been active participants and challenge winners.[25] Thus, autonomy capabilities developed and tested for resource characterization and acquisition in terrestrial settings have a second utility in the search for signs of past and/or extant life. While several of the aforementioned platforms are capable of negotiating cave interiors, most still require human-assistance or direct navigation. Overall, successful exploration in a 3D landscape will require the tight integration and codesign of mobility systems, traversability-assessment instruments, and innovative automation/AI algorithms. Using onboard autonomy and perception capabilities, robots will need to traverse terrain that is partially characterized at best and completely unknown at worst, as well as respond to off-nominal and unexpected events during operations.[26, 27] Additional challenges to robotic exploration will include the availability of a communications link between mission control and the robot and powering systems while underground. Wireless communication is impaired by the lack of line-of-sight both in communication with the surface and within the cave, which can result in signal fading, multipath effects, and diminished signal strength at the boundaries. Various solutions have been proposed to address some of these challenges, including bundling power delivery within a tether connected to a surface lander or rover, data muling where the mobile robotic systems repeatedly come near the cave entrance to establish line-of-sight communication, and a set of repeaters deployed along a line-of-sight to construct a wireless mesh network. A repeater network could be established from the cave to the surface and may be either static or locally mobile. These solutions may be used singularly or in combination based on data bandwidth requirements, maximum tolerable latency, mission duration, endurance and power requirements, mass and size limitations, and environmental considerations.

5.3 Extreme-Terrain Mobility

Relevant future missions: Same as for Section 5.1.

In this report, extreme-terrain mobility refers to surface mobility over challenging topographies and different regolith types on bodies with substantial gravity fields, such as Mars, the Moon, Venus, and Titan. Examples of such topographies include crater walls and floors, cliffs, lava tubes, sand dunes, gullies, canyons, cold traps, and fissures. While other extreme environmental conditions are also present at these sites (e.g., high temperatures on Venus, low temperatures on Titan), the technologies to address these extreme environmental conditions are not addressed here but in an earlier assessment in this series.[28] Extreme-terrain mobility here covers capabilities that enable access to sites, movement in and out of those terrains, and safe traverses to designated targets; loitering at targets for in situ measurements from aerial vehicles; sample collection (covered elsewhere in this document); and return in the case of sample collection from an extreme geologic feature. Extreme-terrain mobility encompasses a heterogeneous array of potential platforms that may include wheeled, legged, snake, hopping, tracked, tethered, and hybrid platforms. Surface GN&C for such diverse platforms depends in part on the nature and constraints for the mobility approach. The key areas of technology advances for extreme-terrain access include traverse to designated targets in extreme terrains, retro-traverse for captured samples, traversability analysis and motion planning, possible anchoring and de-anchoring, docking and undocking, control of tethered platforms, and high-fidelity terrain modeling and simulation of extreme-terrain mobility.[29]

5.3.1 Tethered Robotics

Considerable progress has been made in the last decade toward improved mobility across steep and challenging terrains for Mars, the Moon, and ocean worlds. Tethered vehicles for accessing steep slopes by rappelling down from the top have been demonstrated.[30] Figure 4 depicts the Axel rover descending a 20-m cliff face with slopes ranging from 65° in angle to near vertical at a quarry in Canyon Country, Santa Clarita, California. Such concepts are relevant to Mars, the Moon, and steep slopes on icy moons, as well as to pits on the Moon and Mars (see Section 5.2). While progress has been made with extreme-terrain mobility for terrestrial applications, and the MERs

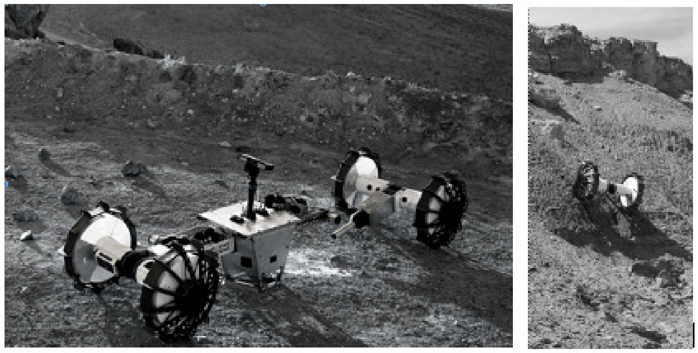

Figure 4. The Axel rover descending a 20-m cliff face with slopes ranging from 65° in angle to near vertical at a quarry in Canyon Country, Santa Clarita, California.

have explored the sides of craters, to date no planetary mission has attempted to access geologic features such as cliffs. State-of-the-art surface-exploration platforms are designed to operate on relatively flat terrain (less than 20° for the MERs and less than 30° for the MSL rover). The OWL recommended the continued development of mobility technology, like the Axel rover, to enable greater access to sites of scientific interest that are still inaccessible to state-of-the-art rovers. Additionally, technologies such as precision and pin-point landing (discussed extensively in Part II) would also complement extreme-terrain mobility, shortening the distance to reach extreme terrains while providing safe landing in the vicinity of the desired terrain. Control, traversability analysis, and path planning for an extreme-terrain mobility platform take on a new meaning where motion may be more constrained. In particular, for tethered systems, control may require more sophisticated dynamical models, and in some cases knowledge of regolith properties may be critical. Progress has been made in tether rover navigation, both in simulation and through field trials.[29] Control of tethered systems is one of the most important needs for extreme-terrain access. One limitation to controlling a vehicle in extreme terrain by means of a tether is the feasible length of the tether for long excursions.[30] While initial designs of the Axel robot targeted a kilometer-long tether with a 2-mm diameter, the tether ended up being 4 mm in diameter to maintain a tenfold margin on tether strength and redundancy in the number of conductors, as well as provide the necessary tether abrasion resistance layer. Combined with volume and mass limitations, this resulted in a tether spool capacity of just 250–300 m. Clearly, careful design of the tether and winching drum are required for kilometer-scale descent into craters.

5.3.2 Hybrid Surface-Aerial Robots

Recently, two hybrid Mars rotorcraft have been baselined for the MSR missions to provide sample-fetch capability as a backup to sample delivery by Perseverance.[31] The concept of operations is similar to the coaxial Mars Helicopter, Ingenuity, flown as part of the Mars 2020 mission, with the fetch rotorcraft stowed on a lander or rover through EDL at Mars, followed by deployment to the surface and operation as a standalone spacecraft. The payload capability of the rotorcraft is 280 grams when outfitted with a manipulator arm and wheeled mobility system (Figure 5); this payload could take the form of samples being collected for retrieval, a camera for terrain mapping, high-resolution cameras for imaging science targets inaccessible to rovers, or Micro Electro-Mechanical System (MEMS) sensors such as gravimeters or soil humidity sensors. The helicopter includes a wheeled mobility system mounted to the landing gear, which has been prototyped and tested in representative conditions on Earth.

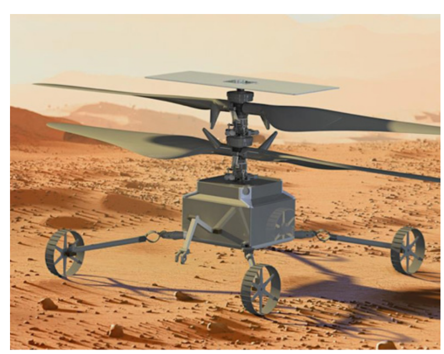

Figure 5. Notional Mars Sample Fetch Helicopter concept.[31]

Future research: New hybrid aerial-ground mobility system concepts for extreme terrains have also emerged. Among the many possibilities, Rollocopter, a hybrid aerial and terrestrial platform (Figure 6), uses a quadrotor system to fly or roll along on two passive wheels.[32] The proposed platform would be able to achieve multimodal locomotion, collision resiliency, and high-level controllability due to 3D actuation.

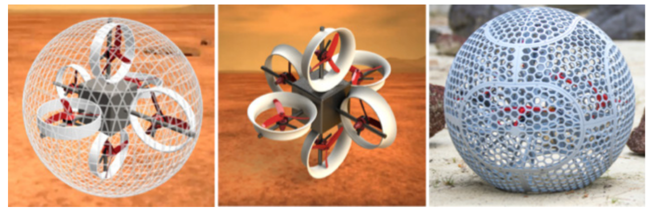

Figure 6. Left: Rollocopter concept art, including propellers, electronics (gray box), and the impact-resilient cage. Middle: Hexacopter configuration of the propellers. Right: A Rollocopter prototype.

5.4 Small-Body Mobility

Relevant future missions: Centaur Orbiter and Lander (CORAL), Ceres Sample Return, Comet Surface Sample Return (CSSR)

Small-body mobility concerns spatial surface coverage on planetary bodies with substantially reduced gravitational fields for the purpose of science and human exploration. This includes mobility on irregular-shaped objects such as near-Earth objects, asteroids, comets, and planetary moons (e.g., Phobos, Deimos, Enceladus, and Phoebe).

The relevance of exploring small bodies in the context of future human exploration programs was highlighted in the exploration roadmap published by the Small Bodies Assessment Group.[33] Specific technology needs include novel mobility systems as well as associated control techniques and novel localization techniques.[24]

For science missions, an in situ, spatially extended exploration of small bodies would mainly fulfill the objectives in the "Building New Worlds" theme.[34] In addition, a variety of observations have recently shed new light on the astrobiological relevance of small bodies as a source of organics to Earth and/or as potentially habitable objects.[35]

Surface mobility platforms for small bodies differ from their planetary counterparts because the microgravity environment largely influences their design. Microgravity can be leveraged as an asset for mobility, as in the case for hopping platforms, or overcome as a challenge, as in the case for anchoring systems. Anchoring and de-anchoring are two of the key areas of technology investments for small-body mobility and extreme-terrain access. This area was thoroughly described in a previous report.[4]

Microgravity mobility could include hoppers as well as wheeled, legged, hybrid, and other novel types of mobility platforms, such as electrostatic-based mobility. Hoppers can use different actuation for mobility, such as propulsive thrusters, spring-loaded mechanisms, and internal actuation that generates reaction forces or changes the center of gravity.

Microgravity environments pose many challenges not only for mobility and manipulation at the surface of small bodies but also for control, localization, and navigation. The Discovery Mission proposal Comet Hopper planned to land on Comet Wirtanen, where the vehicle would "hop" to different locations on the comet.[36] What may seem like simple operations, such as drilling or coring on bodies with substantial gravity fields, can be quite difficult for a robot in microgravity environments, unless some form of fixture or anchoring is used to impart the necessary forces. The use of tethers or other aids could enhance control and improve maneuvering precision but also add mass and complexity. Recent observations from both space missions and ground-based telescopes have revealed a more diverse landscape than previously thought. Small-body surfaces can range from areas covered with a thick layer of fine regolith to ones that have rocky and protruded regions.

At this point, it is not clear what the most effective form of mobility for small bodies is. It might be the hopper, or it might be a legged or wheeled vehicle that remains in contact with the surface. This usually is the subject of a trade study that includes issues like the size of the body, the surface material composition, the ease of sampling, and the types of science being studied as part of the assessment. Other types of surface mobility systems that have seen development toward planetary science applications include mechanical hoppers for small bodies and limbed systems for extreme terrain.[37, 38] A more recent and comprehensive review is provided in Reference 39.

5.4.1 Contact Mobility

Controlled mobility in low gravity poses very different problems from those faced by robots operating in high-gravity environments. The first challenge is specification of mobility requirements in terms of motion accuracy, instrument pointing, and surface mechanical coupling (particularly problematic in microgravity). Few results are available in the literature. A recent study for an in situ mission to the Martian moon Phobos shows that motion accuracy on the order of 20–30% over a surface of 1–5 km^2 would be sufficient for a number of scientific objectives, such as evaluation of regolith maturity, characterization of mechanical properties, gravity mapping, and study of surface dynamics and electrostatic environment. The platform, in this case, would carry an x-ray spectrometer, a radiation monitor, a thermocouple, and a microscope.[35]

The second challenge is the design of motion-planning algorithms for loose, dusty, and rocky terrains in low, nonuniform gravity environments. For example, some regions might be covered with loose dust, and the mobility platform could sink and become stuck. Assuming that such regions can be detected, it is paramount to be able to plan trajectories around or over them. The limited attitude control of the craft would also complicate the task of instrument pointing, which might lead to the need for gimbaled instrument platforms. Additionally, on a rotating small body, the motion of a robotic platform can be significantly influenced by the Coriolis and centripetal accelerations, which could make potential regions of interest (e.g., those around an unstable equilibrium for motion dynamics) hard to reach. Very few studies are available that explicitly address the problem of controlled mobility (as opposed to random hopping) in low-gravity environments.[40] The JPL-developed MUSES-CN Nanorover was designed for precise mobility in micro gravity levels; the achievable motion accuracy, however, was not reported. A recent study focused on an internally actuated platform and demonstrated 10–15% motion accuracy in a benign environment with a gravity level in the mm/s^2 range.[41]

A third challenge is associated with the localization task, which is essential to plan paths and track a trajectory. For most proposed platforms relying on an orbiting mother ship, surface perception and planning operations are independent of the mother ship, which is used as a communication "bent pipe," and that makes such platforms fully fledged spacecraft in their own right. Through inertial sensors, the platform could reconstruct its trajectory and hence determine its current position; however, this approach would lead to large position errors due to sensor drift. This motivates the use of vision sensors, which can provide absolute position measurements but could suffer from dirty optics and challenging illumination. However, considering a small hopping platform as an example, the compact shape would severely constrain the baseline for stereo vision and hence preclude precise depth estimation. A significant percentage of images would be captured from a low vantage point, and the continuously rotating field of view would make the estimation process particularly challenging and computationally intensive. An alternative approach would be adoption of synergistic mission operations, wherein the mother ship bears the primary responsibility for determining the position and orientation of the mobility platform, and the platform is only responsible for local perception. Past examples are the Mars Pathfinder and Sojourner, which operated jointly. A preliminary study for this approach is provided in "Internally-Actuated Rovers for All-Access Surface Mobility: Theory and Experimentation."[41] Additional work is needed to quantify the impact of synergistic mission operations within the context of a mission. While mobility-based missions to small bodies are further out in time than many of the missions covered in this document, the scientific value, magnitude of the technical challenges, and potential relevance to Human Exploration and Operations Mission Directorate (HEOMD) plans call for some early-phase technology investments.

5.4.2 Noncontact Mobility

The environment near the surface of asteroids, comets, and the Moon is electrically charged due to the Sun's photoelectric bombardment and lofting dust, which follows the Sun's illumination as the body spins. Charged dust is ever present in the form of a dusty plasma, even at high altitudes, following the solar illumination. If a body with high surface resistivity is exposed to the solar wind and solar radiation, Sun-exposed areas and shadowed areas become differentially charged. The Electrostatic Glider (E-Glider, Figure 7) is an enabling capability for operation at airless bodies, a solution applicable to many types of in-situ missions that leverages the natural environment.[42-44] This platform directly addresses the "All Access Mobility" Challenge, one of NASA's Space Technology Grand Challenges. Exploration of comets, asteroids, moons, and planetary bodies is limited by mobility on those bodies. The lack of an atmosphere, the low gravity levels, and the unknown surface-soil properties pose a difficult challenge for all forms of known locomotion at airless bodies. The E-Glider levitates by extending thin, charged appendages, which are also articulated to direct the levitation force in the most convenient direction for propulsion and maneuvering. The charging is maintained through continuous charge emission. It lands, wherever it is most convenient, by retracting the appendages, firing a cold-gas thruster, or deploying an anchor. Preliminary calculations indicate that a 1-kg mass can be electrostatically levitated in a

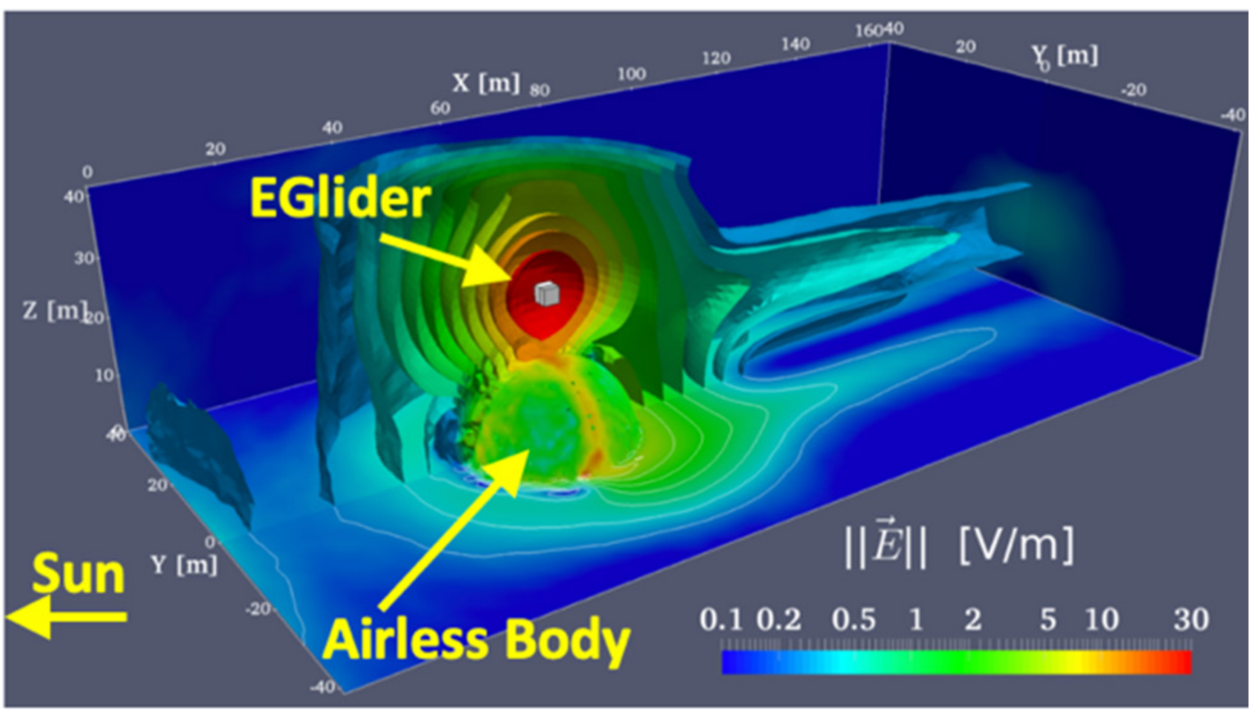

Figure 7. Stable hovering of electrostatic glider around a charged small body.[42]

microgravity field with a 2 m–diameter electrostatically inflated ribbon structure at 19 kV, hence the need for a "balloon-like" system. The wings could be made of very thin Au-coated Mylar film, which are electrostatically inflated, and would provide the lift due to electrostatic repulsion with the naturally charged asteroid surface. Because the E-Glider would follow the Sun's illumination, the solar panels on the vehicle would constantly charge a battery. Further articulation at the root of the lateral strands or inflated membrane wings would generate a component of lift depending on the articulation angle, hence a selective maneuvering capability that, to all effects, would lead to electrostatic (rather than aerodynamic) flight.

5.5 Ocean Worlds Mobility

Relevant future missions: Enceladus Orbilander, Europa Lander

Investigating the prebiotic chemistry and potential habitability of ocean worlds is a high priority for the science community. Understanding the geology and determining the origins for ocean world bodies like Europa and Enceladus are science goals defined in the Planetary Decadal Surveys. Long-range mobility at an appropriately selected site on the surface and with the requisite science instruments will address these goals. This includes the possibility of crevasse-deployed instruments, deep drills, and in the long term, potential mobility within a subsurface ocean. Mission concepts and in situ mobility system concepts for accessing crevasses on Enceladus are in development. Figure 8 depicts a vision for future robotic exploration of ocean worlds and a recent review is given in Reference 45. The challenges for mobility are rugged terrain, unknown and potentially soft regolith, extremely low temperatures, and on Europa, possible corrosive materials and exposure to radiation. Among the ocean worlds within our solar system (including Earth, Europa, Ganymede, Callisto, Titan, Enceladus, Mimas, Tethys, Iapetus, Rhea, Triton, Ceres, and Pluto), Europa and Enceladus are two moons currently garnering significant interest from the scientific community and are the focus of this section. The surface topographic, mechanical, radiation, and thermal environments of these moons pose a significant challenge to robotic exploration. Surface temperatures range from approximately 76 K to 130 K on Europa and 65 K to 140 K on Enceladus. The ionizing radiation environment (high intensities of particles in the hundreds to thousands of MeV) of Europa in particular also creates challenges for the longevity of robotic surface missions and the fidelity of near-surface measurement. Perhaps the greatest challenges to multisite surface operations are the topographic and mechanical properties of ocean worlds' surfaces. The majority of ocean worlds are covered by icy crusts, kilometers in depth. These crusts are composed largely of pure water ice but also contain salts and potentially organics, deposited on the surface by endogenous processes.

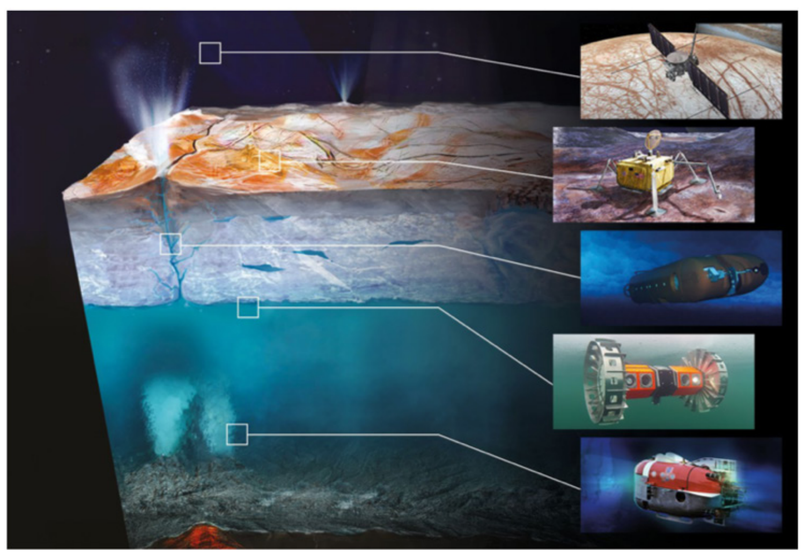

Figure 8. A vision for future robotic exploration of ocean worlds.

Images taken by Cassini and Galileo show distinct surface morphologies in the form of double ridges, bands, chaos, and lenticulae, each of which pose challenges to the concept of surface mobility. Plume vents detected on Enceladus by Cassini and more recently on Europa by Hubble, show that significant deposition of subsurface material exists, likely yielding a somewhat localized, fine-grained cryogenic ice regolith, whose properties require unique design solutions for mobile robotic platforms. The successful design of these platforms for ocean worlds requires a-priori knowledge of the surface topography and mechanical properties. From a mobility perspective, topography yields an understanding of the surface roughness as well as the range of obstacle sizes and gradients the vehicle will likely encounter. To date, surface imagery from Galileo and Cassini have yielded pixel sizes only on the order of ~6 m and ~20 m, respectively, which while globally informative, do not provide insight into the surface characteristics at the vehicle scale. As such, any proposed vehicle design must be robust to a range of surface conditions.

5.5.1 Approaching and Entering the Vent

In addition to wheeled mobility described previously, ice mobility has other features that are characteristic of ocean worlds. Crevices and vents that are hypothesized to make up the surface topography of ocean worlds pose challenges for many mobility architectures. Snake robots are known for high adaptability to different terrain types. Exobiology Extant Life Surveyor (EELS), shown in Figure 9, is a potential snake-robot solution addressing the environmental parameters relevant to mobility that have been modeled for Enceladus.[46] The EELS architecture is designed to be adaptable to traverse ocean world–inspired terrain, fluidized media, enclosed labyrinthian environments and liquids. It is a snake-like, self-propelled endoscope comprising serially replicated segments with encapsulated locomotion and bending. Multiple segments sequentially reverse rotations to reduce torsion in the endoscope, or replicate rotations to perform holonomic movements for steering. The concept includes a first-of-its-kind Archimedes screw propulsion configuration that acts as wheels, tracks, gripping mechanisms, and propelling units underwater, working as propellers. In an open fracture system, EELS extends across the gap near the initiation point of a fracture out of the streamline and pushes the two end screw mechanisms on each side into the walls, driving into the plume, then descending. In the vent, the threads bite into the side walls, reacting to the plume jet forces and creating forward movement when rotated. The robot stays outside of the vent, pushing on the outer walls, allowing the vent streamline to pass through the middle. The rotation of the screws is reacted by counter-rotating secondary units, which provide anchoring and thrust. In the case of wide caverns or a slip of the leading screw unit, the additional Archimedes screw units provide grip until the leading units find their next secure position. Figure 10 shows the sequence of autonomous guidance, navigation, and operations for robotic ocean world missions. Navigation is required for missions that penetrate the surface and even more so when they shall explore the ocean beneath the ice shell.[47] Navigation on an icy moon is challenging, given that no natural external references exist other than the local gravity vector and the magnetic field vector at the surface. Generally, one has to distinguish between the navigation of an ice-penetrating probe and the navigation of an underwater vehicle. A probe that is connected to the surface via a tether could measure the propagated way and thus, when combined with a tilt-measuring accelerometer, derive the

Figure 9. EELS robot.

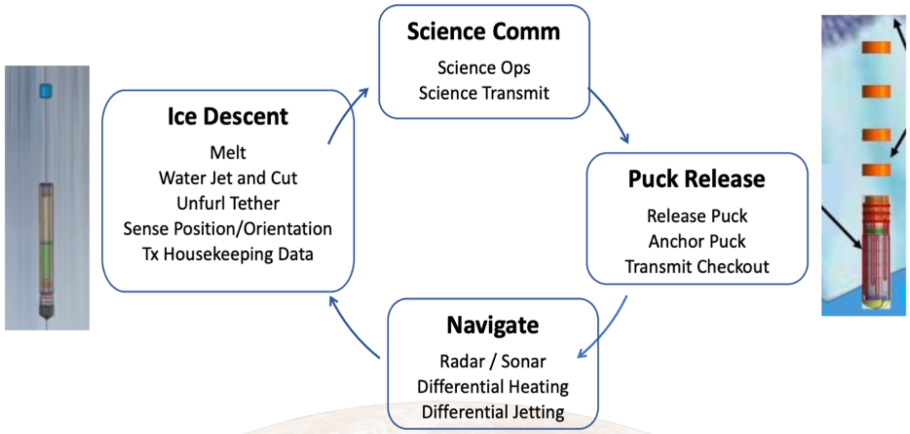

Figure 10. Autonomous guidance, navigation, and operations for robotic ocean world missions.

depth from the surface. When reaching the liquid ocean, pressure sensors could give depth information.

5.5.2 Cryobots—Melting Probes

The Scientific Exploration Subsystem Access Mechanism For Europa (SESAME) program was initiated by NASA with a Research Opportunities in Space and Earth Sciences (ROSES) call in 2018.[45] Much of that work focused on optimizing the use of energy in penetrating ice. A maneuverable subsurface probe designed for penetrating solar system ices has been demonstrated in Antarctic deployments by researchers at the German FH Aachen University of Applied Sciences.[48] It achieves maneuverability in ice by differential heating of the melting head. It uses a field of ultrasound emitters or pingers for navigation. It also includes work on sonar detection for avoiding solid objects and the use of surface reference beacons to locate the object.[47] Beginning its journey on a frigid surface, exposed to vacuum and radiation, the cryobot must operate for several years, meeting and overcoming hazards en route until it reaches its aqueous target many kilometers below. The cryobot exploits both ice cutting and water jetting for descent. The cutter can enhance progress during the initiation phase, when the cryobot will be sublimating rather than melting ice, or to penetrate through dust layers. Water jetting improves descent time and has been demonstrated to move cuttings past the probe. A range of models are being developed to provide high-fidelity, accurate prediction of the cryobot descent rate for a given set of ice-shell characteristics.[49, 50] Models range from extensions to classical thermodynamic ones to grid-based models that consider the cryobot, fluid-thermal environment.

5.5.3 Under-Ice probes

BRUIE (Figure 11), or the Buoyant Rover for Under-Ice Exploration, is being developed at JPL for underwater exploration in ice-covered regions on Earth and in the icy waters of ocean worlds elsewhere in our solar system.[51] The long-term goal is to be able to deploy BRUIE for autonomous operations in an alien ocean, where it would search for signs of life at the boundary between the ice shell and ocean. GN&C challenges include stable buoyancy, mobility, interaction with the ice and liquid medium, tethered link dynamics, guidance, and control in highly uncertain topography.

Exploration of planetary oceans requires landing on the surface, penetrating the thick ice shell with an ice-penetrating probe, and probably diving with an underwater vehicle through dozens of kilometers of water to the ocean floor, to have the chance to find life, if it exists. Technologically, such missions are extremely challenging. The required key technologies include power generation,

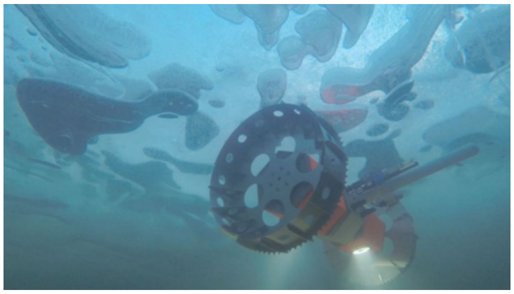

Figure 11. A prototype undersea rover called BRUIE being tested in Alaska in 2015. (Courtesy NASA/JPL-Caltech)

communications, pressure resistance, radiation hardness, corrosion protection, navigation, miniaturization, autonomy, and sterilization and cleaning. Simpler mission concepts involve impactors and penetrators or—in the case of Enceladus—plume-fly-through missions.

5.5.4 Submersibles

The speculative concept of a hydrobot for exploring the ocean beneath the Europa ice cap originated in the 1990s, the same time when cryobot concepts for exploring Europa were being considered.[52] The challenges of not only reaching the ocean but also navigating it once it has been reached remain formidable, and only limited efforts are being made to address them at this time. For example, the Titan Submarine concept does not confront the challenge of penetrating a thick ice cap before entering a liquid medium, and a concept for one was proposed to investigate a full spectrum of oceanographic phenomena: chemical composition of the liquid, surface and subsurface currents, mixing and layering in the "water" column, tides, wind and waves, bathymetry, and bottom features and composition.[45] Measurements of all these aspects of Titan's hydrocarbon ocean environment can only be made through focused in situ exploration with a well-instrumented spacecraft. After deployment at the surface of the hydrocarbon seas of the northern polar region, it would use conventional propulsors to yaw around, using a Sun sensor to determine the initial azimuth to Earth (Earth is always within 6° of the Sun as seen from Saturn) and begin communication using a terrestrial radio beacon as a more precise reference. After initial trials to determine dynamic characteristics in situ and verify guidance/performance models, the vehicle would begin its scientific traverse. Navigation underway between communication fixes would be inertial, supplemented by acoustic doppler measurements. Power would be used alternately for submerged propulsion at up to ~1 m/s and for surfaced communication to Earth. During northern summer (one Titan year is equivalent to 29.5 Earth years), Earth is continuously visible from Titan's arctic, although from some locations (Kraken sprawls from about 60° to 80°N latitude), Earth would be below the horizon for a few days at a time. The vehicle would observe—and perhaps ultimately exploit—tidal currents in the sea, which follow a cycle, once per Titan day, or 16 Earth days. Cryobots can act as deployers for swarms of submersible vehicles. This is the approach of the Sensing with Independent Micro-swimmers (SWIM) concept, shown in Figure 12. SWIM trades a single, sophisticated, *meter*-scale robot for tens to hundreds of simpler, *centimeter*-scale micro-swimmers that have sufficient systems (sensing/mobility/ communications/power) to remotely survey ocean properties in a monolithic design to survive extreme environments and to fulfill planetary protection requirements. This concept has high redundancy and could improve mission viability in unknown conditions, have an ultra-low volume, and could be easily packaged within a larger mothercraft cryobot.[53] SWIM builds on the three science objectives of JPL's PRIME (Probe Using Radioisotopes for Icy Moon Exploration) concept: 1) search for and characterize life, 2) characterize chemical environments and processes by interrogating the ice shell and ocean, and 3) characterize physical environments and processes within Europa's ice shell and ocean.

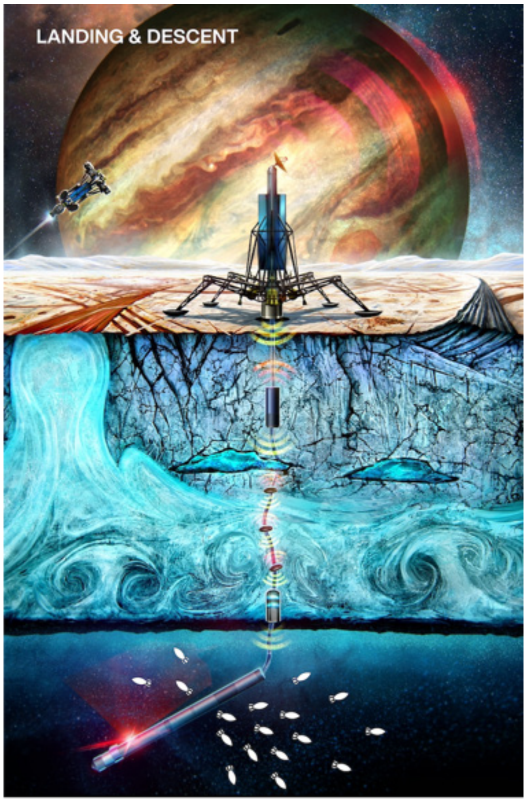

Figure 12. SWIM concept.

5.6 Sample Acquisition and Handling

Relevant future missions: Endurance-A, Mars Sample Return (MSR), Enceladus Orbilander, Centaur Orbiter and Lander (CORAL), Ceres Sample Return, Comet Surface Sample Return (CSSR), Lunar Geophysical Network (LGN), Venus In Situ Explorer (VISE), Mars Life Explorer (MLE), Europa Lander

The process of retrieving, collecting, and packaging a sample for the purpose of sample return must be distinguished from the kind of manipulation used in in situ missions. There is a clear distinction between sample acquisition, which relies on an end-effector to collect the sample, and sample caching, which involves the transfer and handling of the sample so that it is safely placed for subsequent analysis (either in situ or for transfer back to the Earth). Furthermore, there are significant differences between sampling on bodies with significant gravity and sampling on small bodies with little gravity. On bodies with significant gravity, the lander can be used as a reference station (such as a rover) from which the sampling arm can operate. On bodies with negligible gravity, the lander needs to be anchored to avoid dynamic backreactions. Among small bodies, there are differences between sampling comets (geophysically active due to ice sublimation and outgassing) and sampling asteroids (generally geophysically quiescent). For instance, sampling of small bodies takes place in an environment where a) material cohesion and surface adhesion effects dominate particle interactions at small scales through Van der Waals forces, b) electrostatic forces are generally negligible except near terminator crossings where they can lead to significant dust transport, and c) microgravity and solar radiation dominate system behavior prior to end-effector soil engagement/anchor penetration. Recent reviews are provided in References 54 and 55. For sampling at the surface of bodies with significant gravity fields (the Moon, Mars, and Venus), the weight of the sampling device and the landing platform can be used as an advantage in sample acquisition.

One challenge in small body sampling is the uncertainty in surface material properties and the interactions between the surface and sample tools. Materials on small bodies are also challenging due to the volatile nature of the target material under vacuum and exposed to heat generated by a spacecraft. Another challenge is caused by the interaction between the manipulation system and the spacecraft stabilization control. Two solutions (entailing both hardware and algorithm innovations) have been proposed to enable safer, longer duration, and more active surface activities at small bodies: a) a long stand-off boom,[56] which retires risk by not requiring the main spacecraft to be on an impact trajectory to the surface at any point in the mission and allows traditional fault response techniques to be used even while in contact with the surface; and b) a short stand-off boom, which enables landing and/or the application of larger forces at the surface of small bodies for longer periods of time without incurring additional risk beyond what is currently envisioned for touch-and-go (TAG) scenarios.

The Curiosity and Perseverance Rovers have used end-effector, mounted force sensing during drill-based sample collection and handling. Addressing more complex tool-terrain interactions through increased force sensing and active compliance has been proposed and is another example of close integration between GN&C functions and sample-collection dynamics.[57] This solution allows the sampler (typically a robotic arm) to tightly control the tool-terrain interactions to optimize sample capture and modulate forces on the parent spacecraft. This approach can be deployed from short standoff booms/articulated arms or small body sampling from a long stan-off booms. Sampling from long standoff booms not only poses lower risk to the spacecraft but also allows for longer sampling durations and depths than possible with existing articulated arms and booms in close proximity to the surface, and for sampling multiple times at multiple locations for a fixed spacecraft position.

The approach used by the InSight lander on Mars is an example of integrating the sampling event with the GN&C functions, where imaging was used during operations to guide the motion of a tool. This is discussed in Reference 58, which highlights the methodology used in controlling the arm's motion and executing complex trenching operations while efficiently handling faults and anomalous events. The InSight lander included the Heat Flow and Physical Properties Package (HP^3) to measure the surface heat flow of the planet. The package uses temperature sensors that are brought to the target depth of 3–5 m by a small penetrator, nicknamed "the mole."

It is important here to acknowledge that the mole failed despite months of effort to get it to work. The Decadal Survey makes a major point about the importance of being able to get down 10 m (see Chapter 21).[2] Reference 59 describes the results; this paper attributes the failure to the existence of a thick duricrust beneath the surface and contends that an improved mechanical design and more massive devices could be successful.

Acquisition of samples from steep slopes is required for some scientific applications, such as for potential lunar or Mars missions and mobility concepts for access to these sites have been proposed, but new sample acquisition and transfer technologies are needed for these concepts.[30] An in situ sampling mission to Venus requires technologies that can acquire samples and transfer them in the extreme temperature, pressure, and atmospheric environment of the Venus surface.[60] In Reference 60, JPL and Honeybee Robotics have designed, built, and successfully tested a fast end-to-end sample acquisition and transfer system for the Venusian surface. This full-scale prototype system uses a rotary-percussive drill designed to penetrate to a 5-cm depth in saddleback basalt in 15 minutes under Venus surface conditions of 470°C and 92-bar pressure and supercritical CO_2 atmosphere. The entire drilling and sample transfer process completes in 30 minutes, thereby allowing it to support almost any kind of future short-duration Venus lander mission. Various concepts for sample acquisition and transfer have been proposed for small-body sample return, but many of the promising concepts need to be developed to higher technology readiness and validated in order to understand their relative benefits. An in situ sampling mission to Titan requires development of new sample acquisition and transfer technology and different approaches for sampling the exotic surface features of frozen organics and liquid methane/ethane.[61] Dragonfly is actively working the design of these for solid surfaces.[62] Initial experiments using a harpoon system deployed from a prototype airship platform demonstrated the feasibility of surface sampling from an aerial platform, but far more research and development is required. A Europa Lander mission will require new technologies for sampling and transferring surface and subsurface ice; this was investigated by the Europa Lander pre-project team.[63] The interaction between the spacecraft and manipulator control, the mechanical structure, and the terrain poses key technological challenges, but solutions do exist.

An example of integration of the GN&C functions for mobility with sample collection is discussed in "Anchoring Foot Mechanisms for Sampling and Mobility in Microgravity."[64] In this paper, an innovative solution for sampling and mobility in near-zero-gravity environments has been proposed, based on an omnidirectional anchoring mechanism that can withstand over 100 N of force in all loading directions on natural rock surfaces.[64] This holding force is sufficient for a legged rover to climb vertical and inverted rock surfaces, or to support the necessary weight on the bit of an extraterrestrial drill.

5.6.1 Small-Body Sampling

Most of the current prototypes for small body mobility cannot achieve precise targeted sampling. For example, NASA, the Russian Space Agency (RKA), the European Space Agency (ESA), and the Japan Aerospace Exploration Agency (JAXA) have all recognized the advantages of hopping on small bodies. However, ESA's hopper prototype Mobile Asteroid Surface Scout (MASCOT) that hops by spinning two eccentric masses, some of NASA's hopper prototypes that rely on sticking mechanisms, RKA's landers for the failed exploration of Phobos that hop by sticking the surface, and JAXA's MIcro Nano Experimental Robot Vehicle for Asteroid (MINERVA) rover that hops by rotating a single flywheel mounted on a turntable but did not succeed during its deployment, do not allow for precise traverses to designated targets.[65] There are various architectures possible for a small-body sampling mission. Sticky-pad samplers utilize an adhesive that sticks to surface regolith; a sticky pad is pressed against the small-body surface to collect the sample, and then the pad is returned to Earth in a sampling mission.[56] Similar to a sticky pad is NASA;s Origins, Spectral Interpretation, Resource Identification, Security-Regolith Explorer (OSIRIS-REx) sampler that released a high-pressure gas onto the surface upon contact and then captured material forced up into the sampling tool.[56] The OSIRIS-REx spacecraft performed a successful TAG sequence in October 2020 at the asteroid Bennu, and the samples are planned to arrive back to Earth by September 2023.[66, 67] Honeybee robotics has suggested using high-pressure gas to force regolith into a tube and then into a sample canister.[68] Utilizing a rover-mounted harpoon to collect samples from Mars cliffs and a balloon-mounted harpoon to sample the surface of Titan has also been proposed while Goddard Space Flight Center has proposed using a harpoon sampler for comet sampling.[63, 69] The Hayabusa mission did fire a projectile into the surface to dislodge surface material, which was captured.[24] Small-body sampling using an untethered penetrator was proposed by Lorenz and analyzed for various applications.[70, 71]

For finer, powdery terrain, a sticky-tape device would be best suited. After a reconnaissance to identify optimum sampling locations, the spacecraft would use a hover-descent-touch-ascent sequence to allow the touch-and-go-impregnable-pad (TGIP), located on the end of a robotic arm, to collect a sample of loose material from the surface. The TGIP has been designed as a simple, passive collector that can collect ~100 g per sample with particles ranging from dust to centimeter-size clasts. Once the collection sequence is complete, each TGIP would be examined by an onboard camera to ensure successful sample collection and then stowed in a sample-return canister.

Another option is the pellet gun, a sampling device used in the MUSES-C (Hayabusa) asteroid mission. Figure 13 shows the Hayabusa sampling system.[67] In the Japanese, small-body Hayabusa mission to asteroid Itokawa and the successor Hayabusa2 mission to asteroid Ryugu, TAG events were performed, in which a small bullet from a pellet gun was fired into the asteroid's surface and the ejected fragments were collected with a sampler horn.[72-75] After completing global mapping, the first Hayabusa descent for TAG sampling was conducted. Before touching the surface, however, one of three target markers was dropped to track its passage by autonomous navigation.

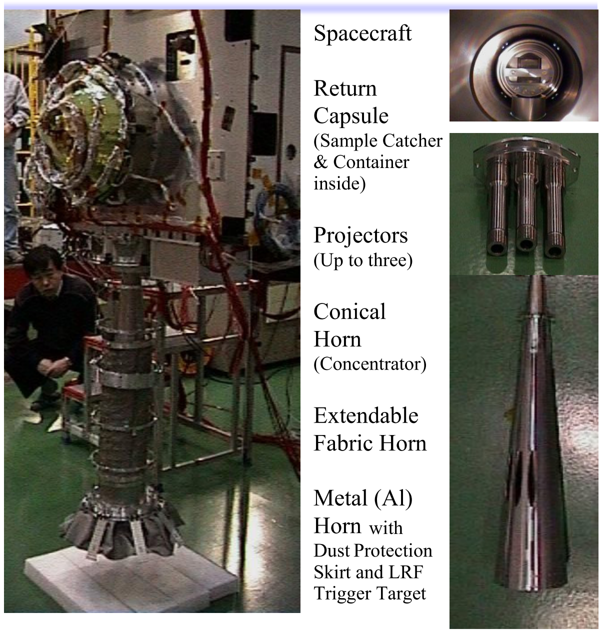

Figure 13. Hayabusa sampling system. Reprinted from "Sampling Systems for Hayabusa and Follow-on Missions: Scientific Rationale, Operational Considerations, and Technological Challenges."[56]

Also, a hopping rover called MINERVA was deployed but never made it to the surface. Because the actual surface conditions of the Itokawa asteroid were unknown, Hayabusa employed a sampling mechanism that was designed to work for a diverse heterogeneity of target surfaces, from hard metal-silicate surfaces to fluffy regolith. In the ground tests, within 0.3 s after the tip of the sampler horn touched on the asteroid surface, a projectile of 5-g mass was shot at 300 m/s by a small projector onto the asteroid surface.[67] Although the sampling mechanism did not work exactly as intended for Hayabusa, thousands of Itokawa particles were still collected from the container and successfully returned to Earth in June 2010. The Hayabusa2 spacecraft arrived at Ryugu in June 2018. It deployed a series of landers and collected multiple samples from the asteroid. It performed TAG sampling twice, once in February 2019 and again in July 2019, using the pellet gun–approach described above. The second sampling event was scientifically notable because earlier in the mission, the spacecraft had deployed a gun that fired a compact kinetic impactor to remove the asteroid surface regolith locally and create an artificial crater, which exposed pristine subsurface material.[76] This deployed gun required an integrated GN&C and mission-design approach, and allowed the second sampling event to effectively retrieve a sample from beneath Ryugu's surface. In December 2020, Hayabusa2 delivered its asteroid samples to Earth.

An important conclusion of the evaluation discussed in Reference 77 is that the sampler is not just one of the spacecraft subsystems but the spacecraft itself. Based on lessons learned from the Hayabusa mission, the point is made that we can target the maximum science output with ample sample mass for the mission design goal; however, we must also define the minimum requirement that still justifies the mission in the worst-case scenario. Besides having a sampling strategy and flight system, which must be robust and flexible for unexpected surprises while retaining high TRL with space-proven subsystems, the pinpoint landing accuracy and autonomous maneuvering capability dictate the selection of the sampling sites more than just the scientific arguments. The sampling device must also be suitable for any surface conditions unless the sampling ellipse is less than the size of the sampling device. Reference 77 also points out the key developments of the Hayabusa mission and two of its follow-on missions, stressing the fact that they are in the direction of increased autonomy, with surface science instruments requiring both a micro-rover and a lander engaged in collecting samples via three different methodologies: impact sampling, projectile shape and angular momentum, and a sticky pad.

The development of high-fidelity simulations of the regolith and its interaction with the platforms, such as granular media microgravity simulations, would also play an important role in enhancing our understanding of small body mobility.

5.6.2 Caching

Sample caching for planetary missions involves storing samples in a container that is left on the surface of the planetary body (e.g., Mars 2020) for retrieval and use by a subsequent mission. The subsequent mission might not retrieve the container for a decade or more. An example of such a mission is the current Mars 2020 rover releasing containers on the surface of Mars for retrieval by a later MSR mission.

The MSR campaign involves sample acquisition and caching (SAC), which has produced cached samples in canisters that could be returned to Earth as part of a later MSR mission.[78] The potential multimission campaign includes the caching mission using Perseverance to collect and cache the samples. The SAC capability includes acquisition of rock and regolith material, encapsulating them and storing them in cache canisters. The samples are about 1–1.1 cm in diameter by 6–8 cm long and are encapsulated individually and hermetically sealed.

The GN&C challenges include autonomously detecting the container on the ground, collecting it via manipulation, and returning it to the MAV (Mars Ascent Vehicle) for return to Earth. The Mars 2020 Perseverance rover gathers samples from Martian rocks and soil using its drill.[79] The rover then stores the sample cores in tubes on the Martian surface, positioning them to be collected by the helicopters. The belly of the rover houses all the equipment and supplies needed to collect samples; it contains a rotating drill carousel, which is a wheel that contains different kinds of drill bits, and the 43 sample tubes waiting to be filled. While the rover's big arm reaches out and drills rock, the rover belly is home to a small robotic arm that works as a "lab assistant" to the big arm. The small arm picks up and moves new sample tubes to the drill and transfers filled sample tubes into a space where they are sealed and stored. After a sample is collected, the sample tube is transferred back to the rover's belly. There, it is handed off to the small interior arm and moved to inspection and sealing stations. Once the tube is hermetically sealed, nothing can enter or leave it. The tubes are stored in the rover belly until the Mars 2020 team decides on the time and place to drop the samples off on the surface. Some of the samples have been deposited on the surface of Mars, at spots that the team designated "sample cache depots." The depot locations have been well-documented by both local landmarks and precise coordinates from orbital measurements. The cache of Mars samples remains at the depot, available for pickup and potential return to Earth. Figure 14 shows a photo of the first container tube released under the Mars 2020 rover.

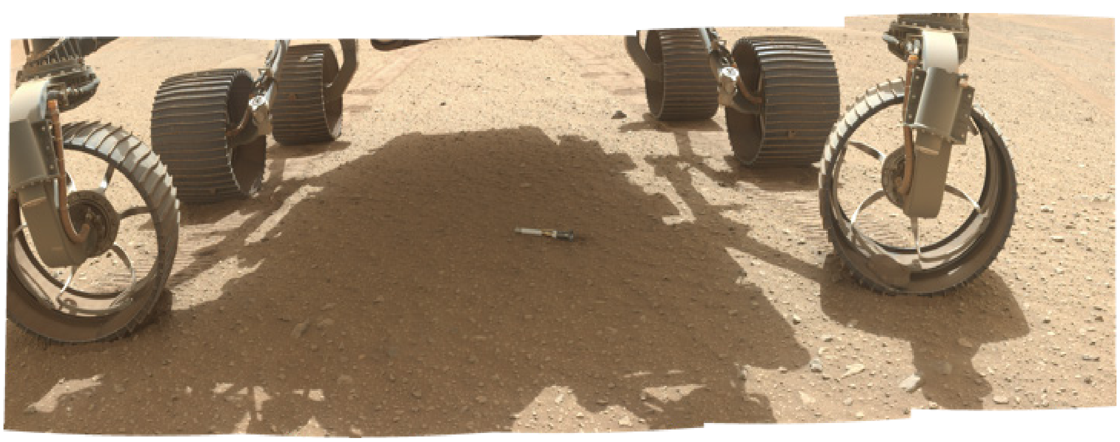

Figure 14. Photo of the first container tube released under the Mars 2020 rover.

5.6.3 Proposed Systems for Sample Acquisition

Several sampling systems have been developed for planetary sample acquisition. Some of these systems require more autonomy than others. While much can be learned from the challenges of drilling, collecting, and processing powder samples, acquisition and caching of core samples comes with many unique challenges. Sample acquisition relies on multiple elements of the GN&C functionality to succeed: a) perception to detect the area to be sampled, b) force or impedance-based control to stably interact the end effector with the environment, and c) precision motion control to retrieve and place the sample back on the lander.

Systems for Colleting Surface Material

The Dual-Rasp sampling system (Figure 15) has been developed for landed missions to low-gravity planetary bodies and is particularly well suited for the unique environment of Saturn's moon Enceladus.[80] The Dual-Rasp sampling system has two counter-rotating rasp cutters that remove material from the surface and direct it into a guide. The cuttings follow the guide into a sample collection cup. When the sampling collection completes, the tool reconfigures by rotating the guide to create a closed circuit for pneumatic sample transfer from the collection cup to science instruments on the lander. A valve opens a gas tank, and the gas flows from that tank into the sample collection cup and down rigid tubing to the science instruments chamber on the lander. A two-degree-of-freedom arm with base actuators is used to deploy the sampler and control its sampling location.

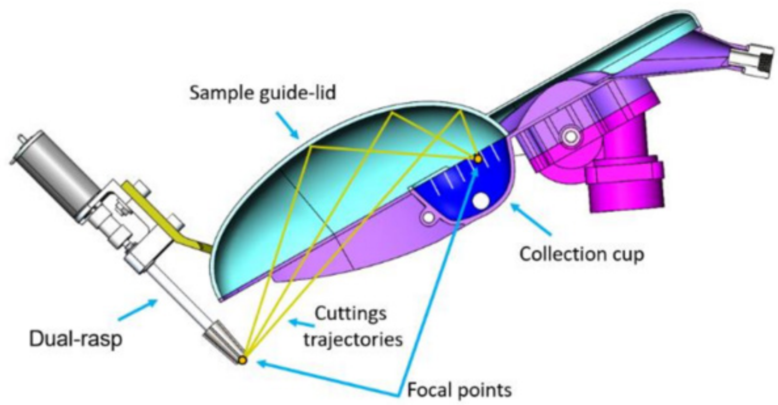

Figure 15. Sample collection in the Dual-Rasp.

Systems for Deep Rock Drilling

Mars science interests include deep (100 m–10 km) drilling capabilities. In the OWL, after MSR, the next-priority medium-class mission for the Mars Exploration Program would be MLE, whose focus would be to seek extant life and assess modern habitability, and will therefore require more precise drilling and coring capabilities due to the oxidizing nature of Mars' surface, as well as higher UV radiation levels at the surface of Mars. The search for existing life will likely focus on subsurface locations at depths sufficient to allow liquid water. A lunar sample return mission could use the SAC approach proposed for MSR if there are similar requirements for rock core and regolith samples. If only surface regolith is required for a sample return mission, then a lunar sample return mission might use a scoop-with-sieve approach.[81] If acquisition and distribution of only regolith is needed, then a scooping approach similar to the Mars Phoenix mission might be used.[82, 83] The need for autonomy is particularly important for all missions, especially for time-critical missions like VISE, which have such a short duration that, in all likelihood, they have to be completely autonomous. For longer missions, autonomous drilling is equally important to enable a continuous drilling process and not to be slowed down by GITL commanding.

GN&C challenges of deep drilling, which is based on the hammering motion of a tool such as the 2-m drill and sample-transfer system from the Honeybee Robotics TRIDENT (The Regolith and Ice Drill for Exploration of New Terrains) system, include removal of drill cuttings, observability of interactions at the drill head, system robustness, and variability of substrate the drill must penetrate.[84] Most terrestrial deep drills use liquid-based drilling "muds" to remove rocky cuttings, an approach that is not an option on rocky planetary bodies. Deep drills are used in a variety of missions, from Mars sampling to small-body sampling. For example, the Russian Phobos-Grunt mission had a hammering mechanism–based sampler.[84]

Deep drilling through rock and regolith has been demonstrated using the Drilling Automation for Mars Exploration (DAME) system, and a multi-segment, 2-m-deep drill was developed for the ESA ExoMars mission.[85, 86] The Auto-Gopher, a wire-line rotary-hammer ultrasonic drill, whose main feature is its wireline operation, has also been developed over the years by Honeybee, JPL, and the University of Southern California.[87] The drill is suspended on a tether, and the motors and mechanisms are built into a tube that ends with a coring bit. The tether provides the mechanical connection to a rover/lander on a surface as well as power and data communication. Upon penetrating to a target depth, the drill is retracted from the borehole, the core is deposited into a sample-transfer system, and the drill is lowered back into the hole. This wireline system allows core acquisition from depths limited only by the length of a deployment tether. Wireline operation sidesteps one of the major drawbacks of traditional continuous drill string systems by obviating the need for multiple drill sections, which add significantly to the mass and complexity of the system.

Other options exist besides hammering drills. Corers are also valuable for certain applications. Honeybee Robotics developed the MiniCorer for possible use on a sample return mission.[88] The MiniCorer and Coring Abrading Tool (CAT) are both rotary drag coring tools and push the sample out of the front of the sampling tool using a push rod. The Mars 2020 drilling and caching is discussed in Section 5.6.2.

A technology that addresses cutting transport, system robustness, and substrate variability is the Compressed CO_2 Hard Rock Drill technology for Mars.[89] The technology is a down-the-hole rotary percussive drill that could operate on compressed Mars atmospheric CO_2 gas with a wireline drilling approach. This technology addresses the need for more aggressive sampling and drilling techniques, for both scientific purposes and to obtain in situ resources for future NASA missions and human crew support. Using a spool of lightweight, high-pressure capillary, a down-the-hole drill assembly would be moved in and out of the hole that could be a kilometer or more in depth. The CO_2 drill is designed so that Mars atmospheric CO_2 could be collected, compressed, and supplied down the hole and routed through microducts, valves, and reservoirs for the purpose of controlling miniature mechanical actuation in the assembly. By using compressed CO_2, the drill system avoids the need for heavy electrical cabling and actuator systems or a liquid media for carrying away particulates as is typically used in terrestrial drilling systems. Instead, the liquid CO_2 that powers the drill expands to a gas and could be channeled around the drill housing to carry cuttings that could be collected in a bailing bucket.

Systems for Deep Drilling through Ice

Deep drilling through ice has also been proposed for Mars ice caps and icy moons. Examples are the Cryobot, Subsurface Ice Probe (SIPR), and IceMole.[90-92] The Sampler, Drill and Distribution System (SD2) is part of the Rosetta mission and is designed to collect 1–40 mm^3 of sample from a comet at a maximum depth of 230 mm.[93] Ocean world science interests include deep (100 m–10 km) drilling capabilities, where the search for existing life will likely focus on subsurface locations, at depths sufficient to allow liquid water.

Deep ice drilling requires self-contained thermal probes, powered electrically either via a cable to the lander or via an onboard radioisotope power system. Thermal ice drills can take many forms and have been used extensively in terrestrial ice, readily achieving depths of several hundreds of meters. Broadly speaking, thermal ice drills can be categorized into 1) open-borehole systems, which use a surface cable winch and allow for sample delivery to the surface (via pumped meltwater or core shuttling) and 2) closed-borehole systems in which the meltwater refreezes behind the probe and all tether and instruments are housed onboard. Planetary mission concepts for deep ice access are varied and include the Mars polar drill (e.g., Chronos mission study) and the ocean-access "Cryobots" for Europa and Enceladus (e.g., PRIME and others). Much of the work on both terrestrial thermal ice drills and concepts for planetary exploration are summarized in Reference 94.

6 Surface and Subsurface GN&C functions

This section describes the key technologies that will realize the capabilities that enable or enhance the missions described in the previous sections.

6.1 Sensing and Perception

Range sensing and global localization will be key to a wide range of future surface missions.

6.1.1 Range Sensing

For surface rovers in relatively benign environments, stereo vision sensors have proven highly effective and efficient. However, many unique hazards, from complex interior geometry to dust and darkness, will challenge sensor arrays in Martian caves and will likely require the development of new sensors. For example, terrestrial cave rotorcraft drones use micro-depth sensors to map and navigate around obstacles, while LIDAR has been used for navigation of multi-limbed climbing robots. Currently, there is no LIDAR system available for a 100-kg rover and certainly not for a 5-kg drone. Importantly, if this technology represents the most viable approach for navigating and mapping caves, this technology will need to be matured and miniaturized.

The MER and MSL rovers, as well as Mars 2020, rely on fixed baseline binocular stereo imaging for both hazard detection and relative localization measurements.[95] Such systems have the advantage of being low power and free of moving parts. They do, however, rely on sufficient illumination and adequate terrain texture. In some environments, such as permanently shadowed lunar craters, lunar nights, or lava tubes, reliance on ambient lighting is not possible, and some form of active sensing such as LIDAR, structured lighting, or simple headlights will be required. To date, the only active illumination system flown on a surface mission is the laser striper utilized by the Sojourner rover of the Pathfinder mission.[96] Flash LIDAR is a maturing technology that could find a role in future surface missions.[97]

Measuring terrain elevation from aerial platforms requires larger baselines that cannot be realized on a single vehicle and therefore require methods that fuse measurements taken from different viewpoints and different times. The production of high-resolution terrain maps of the Martian surface from High Resolution Imaging Science Experiment (HiRISE) imagery utilizes such techniques.[98-100]

6.1.2 Global Localization

For Earth, we clearly understand that global localization is implemented with GPS and carried out without reference to surface features or terrain. In the absence of GPS, the best means of localization for a rover or lander is likely to be Terrain Relative Navigation.[101] However, an alternative is the use of various types of radiolocation, such as that described in Reference 102. Much of the work to date has involved manual localization of planetary rovers or TRN applied to precision landing.[103] For localization of planetary rovers, there may be near-term operational advantages to automating the existing manual processing. In the longer term, future faster planetary rovers will benefit from onboard global localization capabilities that would enable robust global optimization of long traverses by considering the traversability of terrain beyond the range of onboard sensors.[104, 105]

Other relevant localization technologies that require further maturation include Simultaneous Localization and Mapping (SLAM), a technique that simultaneously estimates spacecraft motion and the 3D location of environmental features.[103] By themselves, such approaches produce only local motion estimates, but when combined with other global position measurements (such as TRN-based methods), they can provide greater robustness and accuracy.

Not only does the limited onboard computational power limit rover traverse rates and energy efficiency, but it also constrains the fidelity and sophistication of the hazard-detection and autonomous-navigation algorithms that can be fielded. Figure 16 illustrates the ENav simulation environment. The green-yellow terrain shows how the Gradient Convolution heuristic, developed in this work, has assessed the cost of traversing the terrain (yellow regions are higher cost) and steers the rover toward safer regions.[106] The limited computational power of previous flight processors restricts processing to the lowest possible resolution (for both stereo ranging and for traversability maps), and the hazard analysis relies on a wide range of simplifying assumptions. For example, a limited set of discrete actions are evaluated, and that evaluation does not fuse the cumulative effects of the surface geometry at each wheel, nor is there any ability to detect high-slip areas before the rover enters. In addition, the autonomous-navigation functions rely on simple heuristics to try to minimize path length and limit wear on the steering actuators. The impacts of these algorithmic and computational limitations are that a) the rovers are limited to more benign terrain than the mechanical/electrical system is capable of navigating, b) rover operations in modestly challenging terrain are limited to labor-intensive manual driving, and c) onboard vehicle safety checks are often limited. Leveraging the dramatic increases in computational performance of more powerful flight avionics by developing more sophisticated hazard-detection and autonomous-navigation algorithms offers a wide range of benefits: reliable access to more ground areas and reduced ground operations costs, improved mission safety, additional increases in effective traverse rates and efficiency, and reduced actuator wear. In summary, faster and smarter rovers will enable increased traverse rates and distances, reduced mission duration, lower operations costs, and improved mission safety.

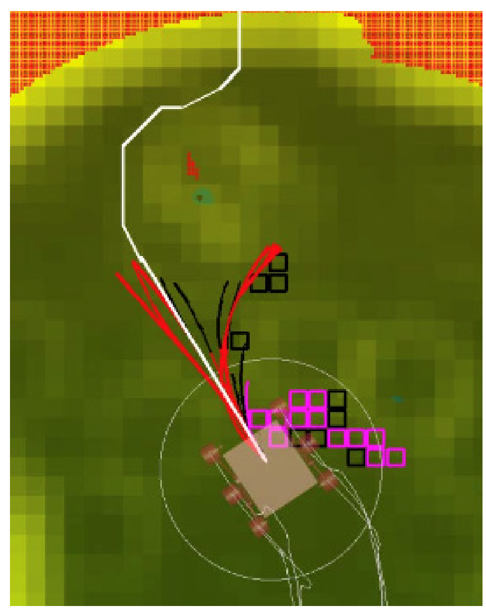

Figure 16. A view of the ENav simulation environment. The green-yellow terrain shows how the Gradient Convolution heuristic, developed in this work, has assessed the cost of traversing the terrain (yellow regions are higher cost) and steers the rover toward safer regions.

Ice and under-ice probes pose a localization and navigation challenge. One additional navigation aid within an ice-penetration probe or an underwater vehicle could be an IMU, which measures the orientation of the probe/vehicle. If the attitude and the velocity over time are known, the trajectory of the probe/vehicle can be determined (or, more precisely, estimated). The disadvantage of IMUs is their drift on relatively short timescales, so regular updates from external references are required. One potential artificial external reference concept that allows relative navigation between two (or more) elements of an under-ice system could be the deployment of an acoustic (or electromagnetic) transponder network that allows the estimation of positions via trilateration. Any communications system could be upgraded with such a transponder system (receiving and returning acoustic or electromagnetic pulses with time stamps), thereby allowing range information between the ice-penetrating probe and the surface station and between the base station at the ocean-entry point and the underwater vehicle. Due to attenuation, the range of signals in ice and water is limited. In both media, attenuation and wave propagation speed are strongly affected by the currently unknown salinity and particle content and impurities such as cracks and bubbles are additional factors in ice. Therefore, unless the acoustic system is self-calibrating, navigation must be based on estimated values and is consequently less accurate. If there were more than one fixed transponder, even some kind of ultra-short baseline navigation would be possible. Releasing a transponder to the bottom of the ocean could be considered. This would give a second reference point, but the exact lateral position would be uncertain. A setup with transponders at known locations (like in terrestrial oceans) would probably go far beyond the scope of a first mission to explore the oceans of Europa or Enceladus. The variable magnetic field can only be used as an additional relative external reference with respect to a lander/base station, if the latter also carries a magnetometer.

6.2 Planning and Navigation

Planning under uncertainty is a key area, as deterministic mobility planning requires an accurate understanding of the future motion of the vehicle given a particular control input. High-speed autonomous navigation is enabling for future surface missions and facilitated by advances in high-performance computing. Multi-agent robotic systems hold promise to enable new classes of missions in space, as well as aerial, terrestrial, and marine applications, and deliver higher resilience and adaptability at lower cost compared to existing monolithic systems.

6.2.1 Planning Under Uncertainty

For a rover operating on solid, level ground, it is often sufficient to view this as a deterministic problem with an environmental model that can be assumed to be correct. But for vehicles operating on steep slopes or climbing over loose terrain, and for aerial vehicles subject to wind, there is a high degree of uncertainty associated with even the best predictions of vehicle motion given a particular control input. That uncertainty derives from multiple sources, including errors in measurements, limitations in the understanding of the environment (e.g., wheel-terrain interactions), and uncertainty in the dynamics of the environment (e.g., changing winds and turbulence). Another attribute of these more challenging environments is that the results of prediction errors can be amplified in a nonlinear fashion, in a manner determined by vehicle and environment dynamics. For a planetary rover on benign terrain, the uncertainty associated with a single short drive command may be reasonably well-characterized using linear models, but for a climbing robot evaluating the strength of a particular handhold or a balloon looking to skirt the boundary of a jet stream, the result of a small mobility prediction error can be a large deviation from the nominally expected motion.

There are many aspects of mobility planning with uncertainty, many of which have been explored at fairly low levels of maturity. Examples include the use of a priori traversability data such as might be obtained from aerial or orbital sensing, offline probabilistic planning methods capable of producing paths with a bounded probability of failure, methods for view planning that take into account potential benefits of paths that provide improved visibility of the area towards the goal, and methods specific to wind-assisted navigation planning for lighter-than-air vehicles.[107-110]

6.2.2 High-Speed Autonomous Navigation

There are a range of dramatically more powerful flight computing technologies on the horizon that will have a dramatic positive impact on future surface GN&C capabilities. Avionics developments include radiation-hardened-by-design (RHBD) field programmable gate arrays (FPGAs), RHBD multicore processors, and even potentially the use of modern commercial, off-the-shelf (COTS) processors for some environments. FPGAs offer low-power, high-performance computing via low-level parallelism. Until the 2013 GN&C report, RHBD FPGAs were limited to smaller fuse-based devices, but Xilinx's introduction of the Virtex-5QV in 2010 offered dramatically more capable and reconfigurable devices.[111] The larger number of FPGA resources facilitates more computationally intensive processing, particularly for data parallel-processing, as is common in image processing. The RHDB Maestro processor represents an alternative solution based on general-purpose computing.[112] Until the 2013 GN&C report, the Maestro was a 49-core RHBD processor developed by Boeing under DARPA and Defense Threat Reduction Agency funding and is based on the commercial Tilera processor. Lastly, the commercial world, and low-power mobile computing in particular, is pushing toward hybrid single-chip solutions that incorporate general-purpose processing with digital signal processors or FPGAs (e.g., Xilinx's Zynq and Actel's Fusion lines). For some environments, the application of external fault tolerance mechanisms may enable the use of COTS components for planetary surface missions.[113] Each of these alternative means of deploying higher-performance computation comes with its own set of trade-offs, and the appropriate technology will vary for each mission. Adoption of any of these parallel-computing technologies will require corresponding changes to existing algorithms, programming methodologies, and V&V processes.

These next-generation flight avionics will enable improvements of existing surface GN&C capabilities as well as entirely new capabilities. For rover-based missions, one near-term impact will be the reduction or even elimination of the performance penalties currently incurred by the use of onboard rover autonomy. The immediate result will be significant increases in traverse distances, energy efficiency, and mission safety. The Mars Technology Program funded FPGA implementations of existing machine vision and autonomous-navigation algorithms, and several have already been demonstrated on a research rover.[114] The availability of much faster driving will facilitate additional improvements, enabling new system design trade-offs. For example, with greater computing, smaller vehicles may be able to traverse terrains at rates that are currently only possible with larger vehicles. Similarly, the longer daily traverses enabled by faster driving will also require associated changes in a variety of mission elements, including downlink bandwidth, long-term navigation planning, and potentially site selection. Careful revisiting of past trades studies is necessary to take into account these new capabilities and constraints. To date, funding has limited current rover efforts to accelerate existing algorithms via reimplementation on FPGA-based avionics. In the longer term, high-performance computing will enable novel and more sophisticated solutions to capabilities such as geometric hazard detection. In addition, high-performance computing will enable entirely new onboard capabilities that are not viable using current flight avionics. Examples include nongeometric hazard detection (e.g., remote identification of areas of high slip), explicit consideration of uncertainty and risk in autonomous navigation, and semiautomated activity planning and scheduling.

For missions involving other forms of mobility, future GN&C technology development efforts should encompass higher-performance flight avionics to improve capabilities. Extreme mobility systems are likely to make use of onboard terramechanical models of the nearby terrain to produce motion plans that balance efficiency against quantitative measures of risk. High-rate force control and control of very high-degree-of-freedom systems are other areas enabled by high-performance flight computing. A survey of recent path-planning algorithms for mobile robotics is presented in Reference 115.

Interest has grown in missions involving longer traverses in different illumination conditions. For example, Endurance-A proposes driving several kilometers a day in order to reach its target traverse of 2,000 km in 4 years. The lack of natural light available during such missions limits what can be used as visual landmarks and the range at which landmarks can be observed. ShadowNav is an onboard localization methodology that involves a perception system to detect landmarks for lunar navigation covering longer distances around permanently shadowed regions of the Moon.[116]

6.2.3 Multi-Agent Surface Robotics

Example applications of multi-agent robotics include coordinated patrols of uninhabited aerial vehicles, satellite formations for astronomy and Earth observation, and multi-robot planetary exploration. Many algorithms have been proposed to control the collective behavior of such systems, ranging from low-level position control to high-level motion planning and task allocation algorithms.[117]

The Cooperative Autonomous Distributed Robotic Explorers (CADRE) lunar technology demonstration is a flight technology demonstration manifested as a payload on the Intuitive Machines 3, or CP-11 (Commercial Lunar Payload Services [CLPS] Payloads and Research Investigations on the Surface of the Moon [PRISM]) mission, targeting launch April 15, 2024, on a Falcon 9 rocket. CADRE is funded by NASA's Space Technology Mission Directorate under the Game Changing Development Program, and its lunar destination is the Reiner Gamma area, known for its mysterious lunar swirls, where dark and light regolith mix. In CADRE, three rovers will work together to explore the surface nearby during a single lunar day (about 10 Earth days). The objective of CADRE (Figure 17) is to demonstrate the first autonomous exploration and distributed measurement by a team of rovers on another planetary body. CADRE is a new generation of robotic technology that utilizes multi-agent autonomy, allowing robots to work cooperatively to ensure success in exploring and performing distributed science measurements on lunar and other planetary surfaces. CADRE capabilities include cooperative autonomous exploration by navigating, communicating, computing, perceiving, and decision-making without human interaction; ground-based V&V tools that predict performance in an operational environment; and small-scale flight hardware capable of traversing the daytime lunar environment. In terms of science applicability, the CADRE network has the capability to accommodate a

Figure 17. CADRE rovers.

payload and perform distributed measurement. The surface-distributed measurement is a multi-static, ground-penetrating radar. Much of this work is based on Reference 118.

6.3 Model-Based and Learning-Based Control

In general and for the purposes of the systems considered in this report, *control* is defined as the onboard manipulation of vehicle steering controls to track guidance commands while maintaining vehicle pointing with the required precision. Control could be divided into two categories: model-based control and learning-based control. In *model-based control*, a preexisting model of the system being controlled is relied upon algorithmically to close a feedback loop. In *learning-based control*, the parameters of the model are inferred using machine-learning techniques. The approach in most surface and subsurface GN&C applications is the use of sensor data for state estimation and subsequent control, with little use of dynamic data derived from a physical model of the system/process being controlled. Improved trajectory-tracking performance is achievable with the incorporation of model-predictive elements that augment current sensor-based reactive control. Model-predictive approaches for GN&C, which rely on modeling the dynamic system using physics-based methods and leveraging these models in sensing, estimation, and control, can provide an anticipative component in control that can compensate for uncertainties originating from unmodeled vehicle dynamics and enable greater precision under feedback and feed-forward control. All types of surface vehicles, including aerial, ground, and subsurface vehicles, could greatly benefit from model-based and learning-based approaches for control. In Reference 119, using a unified notation, comparison tables, and discussions, researchers can compare various GN&C approaches and contribute to the next-generation GN&C systems for space robots, focusing on methodologies relevant to on-orbit servicing and operations, sampling, and space debris mitigation.

6.4 Efficient Operations

The surface-operations phase is different from other mission phases in several ways, including the sustained demands on communications bandwidth, the complex and changing environment, and perhaps most importantly, the nature and pace of the interaction with ground operators.

6.4.1 Challenges of Surface Operations

Communications bandwidth is a critical resource that must be shared between engineering and science needs. Given the complexity of evaluating the value of particular data products, the prioritization of downlink bandwidth will continue to rely on the judgment of ground operators; however, various bandwidth optimizations are possible. One strategy is to rely on more onboard processing to reduce or eliminate the need for communication. On the science side, this could involve preliminary onboard image analysis used either to key opportunistic data acquisition or simply to better prioritize downlink of existing data products.[120] On the engineering side, this could involve the deployment of specific capabilities that eliminate the need for ground interaction, such as autonomous instrument placement.[121]

Ultimately, the goal of virtually all downlinked data is to develop and maintain situational awareness of the science and operations teams. Of course, the specific needs of the science team differ from those of the engineering team, and thus ground tools targeted toward each have been largely developed independently, though some tools such as 3D immersive visualization are readily applicable to both user communities (Figure 18).[122, 123]

Just as the complex and dynamic environment challenges the science and engineering team's ability to maintain good situational awareness, the complexity and changing capabilities of the rover

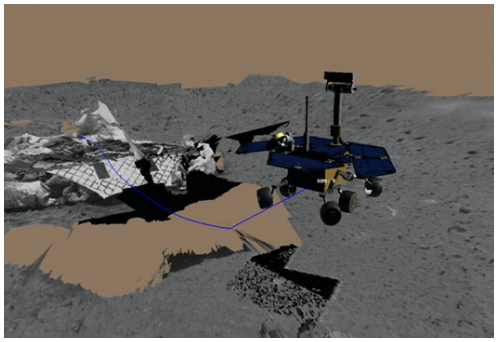

Figure 18. Rover Sequencing and Visualization Program (RSVP) being used during MER operations to rehearse Spirit's initial drive off the landing platform. Reprinted from Reference 122.

challenges the engineering team's ability to safely and efficiently direct the rover to selected goals. Each day, the rover drivers program the day's activities based on their current understanding of the environment and expectations of the performance of the rover's hardware and the onboard software. Existing ground tools help verify the safety and correctness of command sequences prior to uplink, but those tools could be improved in several areas. The first area is fidelity, particularly in challenging terrain such as on slopes or in loose soil; existing simulations rely on a variety of simplifying assumptions. But given the limited knowledge of the terrain available on the ground, our ability to predict the result of a particular drive sequence will always be limited. Another means of improving mission safety would be to quantitatively characterize the uncertainty associated with uplinked drive sequences and to intuitively convey that to the operators as part of the daily planning process. Lastly, computer-aided optimization of command sequences could improve drive efficiency, improve resource utilization, and reduce risk.

There are also benefits to integrating surface operations at higher fidelity earlier in systems design. Given the many challenges of surface operations, it is not surprising that surface operations have entailed a degree of learning as you go. There are, however, potential risks and lost opportunities associated with the mid-mission evolution of operations tools and processes. Namely, the performance and reliability of the overall mission (and potentially mission costs) could be improved if some of those lessons learned were obtained earlier in the mission life cycle. For example, a modest development-phase investment could save many hours of labor from each day's operations, but identifying this opportunity is difficult before real operations have begun. Alternatively, science instruments could be simplified and reduced in mass by adding a new operational constraint. These system optimizations are currently difficult to identify without some human-in-the-loop experience.

One potential means of addressing this challenge is via sustained modeling and simulation efforts that enable substantial operational experimentation before, as well as during, mission development. Such experimentation using low- or moderate-fidelity simulation and prototype operations tools could enable low-cost design changes (including instrument selection) and generate early feedback from science investigators and operators. Such a tool could also be used for pre-mission evaluation of new technologies for possible injection into future flight missions or simply to improve the technology via simulated experiments in an operational environment.[124] This kind of early operational capability would be particularly valuable to future non-rover missions (e.g., aerial or small body) that will have shorter but more intensive operation periods and will not have the advantage of existing experience and operations tools. In addition, the mature operations tools and models could be leveraged for enhanced pre-landing training.

Onboard autonomy technologies such as planning and scheduling, identification of scientific targets, and content-based data summarization, will lead to exciting new space science missions. However, the challenge of operating missions with such onboard autonomous capabilities has not been studied to a level of detail sufficient for consideration in mission concepts. These autonomy capabilities will require changes to current operations processes, practices, and tools. In Reference 125, a case study was developed to identify the technology gaps and workflows needed to operate an autonomous spacecraft involving models of the ground personnel and the onboard algorithms.

6.4.2 Ground Operations Tools

The ground operations tools represent a critical component in optimizing science return and in attaining overall mission success, as they are the interface between the science and engineering teams on Earth to the precious spacecraft residing hundreds of thousands miles away. Quantifying the value of any particular element is difficult, but substantial dividends can be achieved, particularly for developments that can be shared across multiple missions. Three examples discussed below include support for simulated operations in early phases of technology development and mission design, natural and compelling visualization tools, and decision-support tools that leverage advanced computing to better estimate and communicate uncertainty and risk.

Simulation-based rehearsal of operations offers benefits across the entire mission life cycle. At the earliest technology development stage, it facilitates direct communications between the technology developers, scientists, and mission designers. That communication helps educate planetary scientists about the technology so that they can help direct its development to maximum utility and eventually its adoption for future missions.[124] At the mission-development phase, it serves as an essential component of end-to-end system testing and can serve to work out the kinks in planning processes prior to landing. It also serves as a training tool prior to and during the operations phase.

Existing ground operations tools such as Rover Sequencing and Visualization Program (RSVP) are valuable for providing operators and scientists with situational awareness of the terrain in the vicinity of planetary rovers.[122] However, additional capabilities are needed to improve these virtual-reality environments, such as deeper integration of engineering data into the graphical displays. For example, the visualization of estimated terrain classification and conditions should be superimposed over the 3D graphic of the terrain. Similarly, the display of vehicle engineering data (battery charge, vehicle motion, wheel torque, etc.) should be intuitively superimposed over the appropriate part of the vehicle 3D graphic model.

RSVP is also used to visualize the predicted results of prospective uplink commands. The incorporation of higher-fidelity dynamic models of the vehicle, the environment, and their interaction would allow more accurate evaluations of prospective plans. Of particular importance are tools for quantifying risk and uncertainty, and communicating those to the operations team.[126]

6.5 System Modeling and Simulation

Modeling and simulation capabilities are ubiquitous across all GN&C technologies and are mature and effective enough for spacecraft mission design. They are also used effectively in other fields, such as aircraft design, car design, oil and gas, and other large-scale industrial processes.

6.5.1 Modeling to Retire Risk

Advanced modeling and simulation capabilities that integrate the system behavior with the GN&C functions in the proper environment would be able to identify and retire risk early before the hardware is built.

Once the hardware is built, modeling and simulation is also necessary to correlate both open-loop and closed-loop modeled system behavior with experimental data so that useful inferences can be made on the true response of the system. By properly integrating component system behavior in simulation into a working model of the entire system in operation, system-level assessments of performance and system-to-system comparisons can be iteratively carried out to predict cost, mass, and power, and identify critical interfaces before the design is begun.

New design and integration paradigms have been developed in other sectors and could be leveraged by surface GN&C technologists and future planetary exploration missions. An established paradigm for modeling, design, and integration of complex vehicles is under development in the military world—the Adaptive Vehicle Make (AVM) vision proposed and sustained by DARPA. In this vision, the AVM portfolio of programs seeks to revolutionize the design-and-build process for complex defense systems by compressing the development timelines at least fivefold while increasing the nation's pool of innovation by several factors of 10.[127] Some major elements of this vision of cyber-electro-mechanical systems include shorter development times, enabling better designs through model-based verification, and open-source developments. Future technology development of surface GN&C for planetary science could benefit much from leveraging the AVM paradigm.

6.5.2 Uncertainty Quantification

While other agencies (Department of Defense, Department of Energy) are making significant advancements in Quantification of Margins and Uncertainty (QMU) methodologies, it is important to recognize here that planetary surface missions have unique environmental and autonomy requirements, which have to be defined separately.[128] NASA should be pursuing multiphysics based QMU technology to enable rigorous certification of models and simulations for extrapolation to poorly testable flight conditions. QMU seeks to quantify margins and risk from both simulation and test uncertainties, and can supplement traditional margin rules when experience is sparse. Furthermore, there is a need to establish "simulation credibility" via application of rigorous process, and the QMU process is aligned to do just that.

6.5.3 V&V

Modeling can be used for V&V of GN&C performance across all systems. System-level testing in a mission-relevant environment is costly. The multiple spatial and temporal scales encountered in the analysis and design of the behavior of complex systems in uncertain environments requires new analytical techniques for efficient modeling and simulation. V&V of the component technologies is a critical step that needs to be done before delivery of a flight unit. A model-based engineering approach applies advanced modeling techniques in combination with observed data to the engineering process. The objective is to enable exploration of the process decision space as fully and effectively as possible, and support design and operating decisions with accurate information.

6.5.4 Physics-Based Integrated Modeling and Simulation

Integrated modeling of spacecraft on planetary bodies, both on the surface and subsurface, encompasses addressing multiple dynamics, domains, and multiple scales of time and space. There are often interactions between these domains that require an integrated approach to modeling and simulation. For example, the motion of a rover on the terrain, its location on the planetary body, the location of the planetary body with respect to the Sun, the surface albedo, the geometry of the surrounding terrain, local atmospheric conditions, and many other parameters affect the thermal dynamics of the vehicle. Some of these parameters also determine the power dynamics of the rover by affecting the power generated by solar panels on the rover, its battery performance, and its heating or cooling. High-fidelity and integrated approaches for modeling and simulation of complex dynamic systems can provide more precise data on expected behavior of robotic surface and subsurface systems.

Further improvement in high-performance computing will ultimately enable the high-fidelity modeling and simulation of systems with millions of degrees of freedom to be integrated with onboard GN&C functionality. An example is the use of onboard simulation by a rover to replan its trajectory over complex terrain while negotiating obstacles (e.g., boulders, challenging illumination conditions). This onboard simulation would enable more efficient use of resources (e.g., power, mass distribution). For platforms operating in dynamic regimes, there is a need to identify realizable, multidimensional control trajectories that reflect complex system dynamics and environmental disturbances.

Physics-based, integrated modeling techniques currently in use are Multi-Body Dynamics (MBD), Finite Element Methods, Discrete Element Method (DEM), and Particle Methods. Multicore systems, Graphical Processing Units (GPUs), and FPGAs are some of the available hardware options for high-performance computing solutions. An example of this would be a Titan balloon collecting wind data (science data) and using this data in real time (planning algorithms) to optimize its trajectory. Another example is Project Chrono, an open-source multiphysics simulation engine that has been developed by the University of Wisconsin–Madison, which supports simulations that couple MBD and DEM models, in which the dynamics of the robotic parts are modeled directly with MBD while the mechanics of the soil particles are directly modeled with DEM, and which has been applied to full-scale ground vehicles interacting with complex terrains.[129, 130] Both MBD and DEM are based on Newton's laws of motion and contact mechanics. The simulation framework can be extended to account for ice particles by considering different material properties (e.g., density, modulus, friction coefficients) and ice sintering by introduction particle bonding.

Robotic vehicles that dock or manipulate objects require detailed models of the contact multi-body dynamics to enable proper control of their interactions. Contact dynamics deals with the motion of autonomous multi-body systems subjected to unilateral contacts and friction. Such systems are omnipresent in many robotic applications. The two main approaches for modeling mechanical systems with unilateral contacts and friction are the regularized approach, which makes use of differentiable models of friction and contact and leads to a set of ordinary differential equations, and the non-smooth approach, which uses set-valued force laws for higher-fidelity modeling of contact and friction but leads to a more complex system of differential-algebraic equations.

Presently, devices for sensing or detecting wheel slip, wheel sinking, and terrain hardness are among the greatest sensing needs for planetary surface robotics. There also are strong desires for viable devices that can improve existing capabilities for sensing large-scale terrain discontinuities such as cliffs, craters, and escarpments; for optical ranging in both full sun and deep shadow; and for distributed sensing in multiple-rover applications. Developing validated parametric models that accurately capture the dynamic behavior of terrain interaction would be extremely useful for wheel and vehicle state estimation and control and for terrain manipulation. Granular media modeling techniques are a promising approach for modeling these phenomena, and Project Chrono has several examples of realistic terrestrial systems being simulated, such as rovers, cars, trucks, etc.

Efficient HPC methods for integrated modeling and simulation of system behavior with GN&C functionality operating in complex environments, collision detection, and solution of the associated complementarity methods involved in the contact computation have begun to be developed that use the computational acceleration provided by the GPU on multiple processors.

Further improvement in these methods will ultimately lead to dramatic increases in computational speed that will allow the modeling of the interaction of convex and non-convex shapes in systems with millions of degrees of freedom in near real time. High-performance atmospheric modeling for aerial vehicle simulation and performance assessments is also needed for all planetary bodies with atmospheres.

6.5.5 Terramechanics and Ice Mechanics

A critical component of surface and subsurface GN&C is the effect of the extraterrestrial terrain on the robotic system. Terramechanics, as well as ice mechanics, is the study of soil properties and changes to soil due to external forces such as a rover's wheels, anchoring devices, drills, and sample mechanisms, and it will have increasing relevance to future NASA missions. Terramechanics and ice mechanics concentrate on the modeling, analysis, testing, and design of the interaction of mechanical and robotic systems, such as wheeled vehicles, landing assemblies, anchoring devices, and sampling mechanisms, with natural terrain (e.g., regolith, rocks, icy media). As NASA embarks on future surface and subsurface missions to celestial bodies, terramechanics will play a key role for developing GN&C capabilities. The response of robotic systems when interacting with extraterrestrial terrain may define the success or failure criteria for many of these missions. To design systems that are capable of operating with the required robustness and reliability, it is of utmost importance to improve our knowledge of the mechanical properties and behavior of the surface materials in relevant extraterrestrial environments. The MER, MSL, and Mars 2020 missions demonstrated our ability to safely and successfully interact with the Martian terrain.[131-134] This success has stemmed from experimental and analytical efforts in quantifying the effect of terrain mechanics on rover mobility. Similarly, the success of Viking 1 and 2, Phoenix, and the Mars rover missions in acquiring samples is the result of significant experimental and numerical studies of terrain mechanics arising from sampling systems interacting with these terrains.[82, 131-135]

To steer future missions toward more challenging and uncertain terrains, comprehensive experimental campaigns and physics-based modeling efforts have to be developed in order to raise the probability for mission success and maximize the scientific outcome. Significant uncertainty remains in our ability to characterize the surface material of small bodies and ocean worlds in our solar system.[136, 137] These terrains include icy, porous media with phase change dynamics and levitating granular media with varying levels of compaction to regolith characterized by the presence of ice fragments, gas encapsulations, electrostatically charged material, and spatially varying micro-gravitational fields. Even in higher-gravity environments such as Mars, experience has demonstrated the risks associated with our limited ability to predict mobility (e.g., Spirit embedding in soft soil) and penetration performance (e.g., InSight's HP^3 not penetrating to its target depth) across a full spectrum of terrains.[58, 138]

The development of novel mobility and sample-acquisition systems in these types of terrain remains challenging with research efforts needed to 1) quantify and reduce uncertainties in characterizing the physical properties of these terrains; 2) create analogous simulants for laboratory experimentation, requirement verification, and system validation; and 3) understand the interactions between robotic systems and the terrain in the presence of various types of physical phenomena (i.e., solid-fluid, solid-gas physics). Given the complexity in the different extraterrestrial environments and the difficulty in reproducing them in laboratory settings, it is necessary to develop robust, physics-based, deterministic models and simulation tools to lead the analysis and augment physical testing.

There is a need to continue to develop and disseminate a physics-based simulation (similar to OWLAT) to serve as a virtual testbed for the evaluation and maturation of prototype mobility system designs.[139] Significant uncertainty remains in our ability to characterize small-body terrains. These terrains range from levitating granular media with varying levels of compaction to terrain characterized by the presence of ice or ice fragments, gas encapsulations, electrostatically charged material, and spatially varying micro-gravitational fields. Robotic sample acquisition in these types of terrain remains challenging with research efforts needed to a) reduce uncertainty in characterization of these terrains, b) develop analogous simulants for laboratory testing, and c) understand the interactions between sampling systems and the terrain in the presence of the multiphysics environmental effects (i.e., solid-fluid, solid-gas physics).

Improved simulation frameworks are required that couple MBD and DEM models (Figure 19), in which the dynamics of the robotic parts are modeled directly with MBD while the mechanics of the soil particles are directly modeled with DEM. Both MBD and DEM models are based on Newton's laws of motion and contact mechanics. These simulation frameworks need to be extended to account for ice particles by considering different material properties (e.g., density, modulus, friction coefficients) and ice sintering by introduction particle bonding. Recent methodologies for modeling and simulation of anchoring processes in microgravity, and of the interaction between surface material and robotic vehicles are discussed in References 140-142.

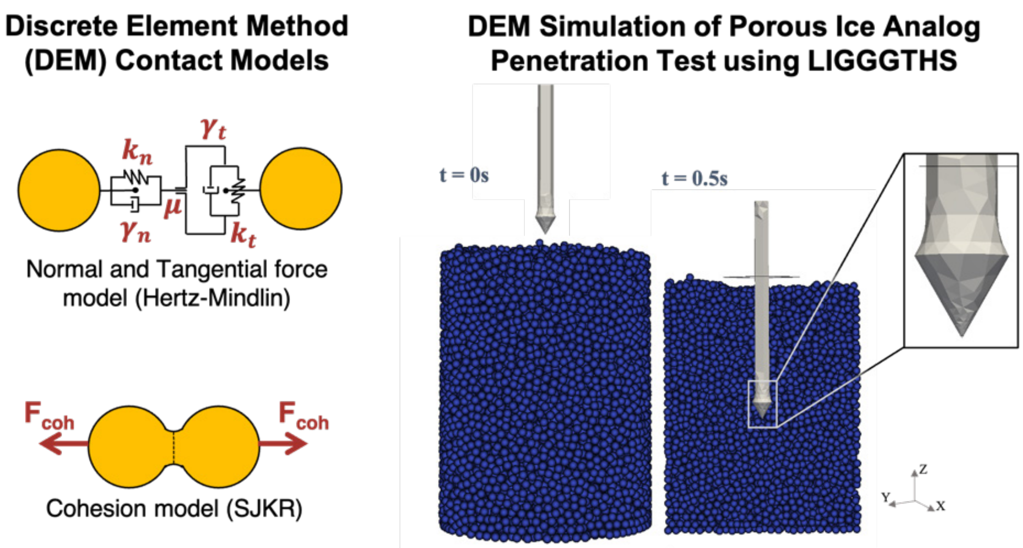

Figure 19. DEM modeling for porous media simulation.[143]

6.6 Emergent technologies

Emergent technologies considered in this report are artificial intelligence (machine learning) and quantum technologies.

6.6.1 Impact of Artificial Intelligence

In conventional studies of surface locomotion of planetary rovers, the interaction of wheels moving on terrain (terramechanics) is based in semiempirical laws. Before starting a traverse, MER or MSL rovers typically use vision to generate a path that avoids visual obstacles. In Reference 144, an assessment of existing terramechanics techniques that rely on machine learning was conducted, identifying the pros and cons of machine-learning techniques to detect wheel slip and other terramechanics metrics.

MLNav, shown in Figure 20, is a learning-enhanced path planning framework for safety-critical and resource-limited systems operating in complex environments, such as rovers navigating on Mars.[145] MLNav uses machine learning to achieve more efficient path planning while fully respecting safety constraints.

Soil Property and Object Classification (SPOC) has been proposed as a new software capability to visually identify terrain types (e.g., sand, bedrock) as well as terrain features (e.g., scarps, ridges) on a planetary surface.[146] SPOC is based on both orbital and ground-based images, and uses a deep convolutional neural network (CNN) to learn terrain information from image data.

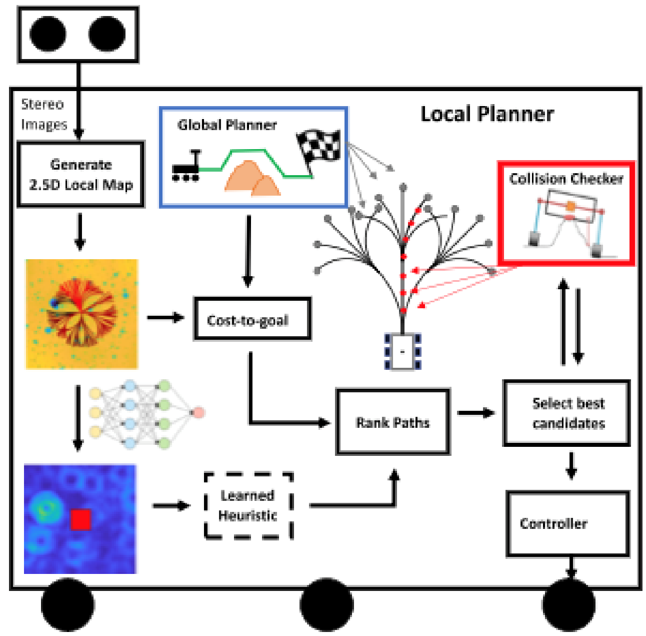

Figure 20. MLNav framework: A classical search-based planner is augmented with a learning-based heuristic to accelerate the search, where the safety of the selected path is guaranteed by a model-based collision checker, from Reference 144.

6.6.2 *Impact of Quantum Technologies*

Quantum technology is an emerging field of physics and engineering based on quantum-mechanical properties and their utilization for practical applications to deliver useful devices and processes that are based on quantum principles, such as superposition, entanglement, etc. Quantum technologies can provide unmatched possibilities at the atomic scale that can advance computation, communication, and sensing. Until recently, these areas have been investigated separately. Although significant progress is being made in regards to quantum technologies that can advance computation (i.e., hardware and software aspects, which can also potentially be applied in the algorithms associated with robotics-related processes), there is a gap between quantum technologies, which usually deal with physical processes at the atomic scale, and classical robotic systems, which usually deal with physical processes at a macroscopic scale. References 147-150 summarize recent work that has investigated the fundamental and applied aspects of integrating the quantum phenomena, such as photon quantum entanglement, and applications, such as cryptography and teleportation, with multi-agent robotics. While quantum computing is still in the early phases, there have already been many innovations and breakthroughs. It now appears that some of the most prominent and widely used AI and machine learning algorithms can be sped up significantly if run on quantum computers, which does not mean performing a task faster but rather taking a previously impossible task and making it possible or even easy. Potential applications include fully autonomous science operations in challenging environments (e.g., roving, sampling, sample processing); sensor processing and interpretation; and in situ mobility with both major assets such as rovers and aircraft as well as drones. As it pertains to AI/machine learning, there is the potential for classical and quantum machines to work together, leveraging the elastic nature of the cloud and the powerful, specific problem-solving capabilities of quantum computing. Over time, both computing formats will continue to advance, but the ability to accelerate workloads on traditional GPUs and Application-Specific Integrated Circuits while also leveraging the power of quantum computing could be a recipe for faster, more robust computational capabilities, which we can expect to see as quantum computing becomes more widely accessible. Applications of quantum technologies have shown the greatest potential in the advancement of engineering systems in recent decades, including with computational speedup and guaranteed security. By integrating the unmatched possibilities of quantum advantage with engineering applications, such integrated quantum and engineering systems and techniques can potentially push engineering boundaries beyond any classical technique.

7 Key Findings and Recommendations

This section describes key findings and provides recommendations for the areas that have been identified to be critical to develop new surface and subsurface GN&C capabilities to enable new NASA planetary science missions. The recommendations are made along three principal directions (covered by the NASA Office of Chief Technologist): systems studies and workshops, low TRL development, and high TRL development.

The 10 findings are organized into six major areas:

1. Surface and subsurface mobility systems
2. Sample acquisition and transfer systems
3. Modeling and simulation
4. Control and planning
5. Sensing and perception
6. Emergent technologies

7.1 Finding 1: Surface mobility systems need improvements to negotiate challenging terrains but also for ocean worlds, small bodies, and Venus

SURFACE ROVERS: Increased miniaturization and performance improvements of onboard computing architectures, navigation sensors, and communications systems, together with advances in surface navigation and localization, could open up possibilities to explore substantial planetary diversity in a single mission.

Three innovations now in progress have the potential to enhance long-range lunar rover scenarios and to enable these surface exploration scenarios. First, new driving actuators using outer rotor motors and dry lubricant have potential to increase velocity to around 30 cm/s and to eliminate the need for preheating before driving. Second, processors analogous to the smartphone computer in the Ingenuity Mars helicopter may achieve three orders of magnitude more computing throughput than the RAD750 and one to two orders of magnitude more than the VCE coprocessor used in the Perseverance rover, with far lower SWaP. Other avionics advances in progress include major size and power reductions for motor controllers, IMUs, and radios. Third, such faster autonomous navigation processing loops are required to keep up with the vehicle speed; this would be enabled by much faster avionics with low SWaP. The lack of onboard absolute position–estimation capability currently requires rovers to get position updates through GITL cycles every few hundred meters of travel. “Mobility faults” also require frequent GITL cycles for diagnosis and recovery. Both of these limitations can be greatly alleviated with better onboard autonomy.

Recommendations (near-term):

- Develop and test new GN&C planning and control algorithms for fast traverses, thereby enabling a high degree of autonomy and reliability.
- Develop methodologies to achieve the required robustness and fault-tolerance of autonomy capabilities in a cost-effective manner in harsh environments.

Recommendations (far-term):

- Address the challenges of steep slopes and operations in low gravity by developing improved environmental models and planning-and-control algorithms that are robust to significant uncertainties.
- Develop much faster autonomous navigation processing loops by much faster avionics with low SWaP to address the unique nature of operations for mobility-based missions.

EXTREME-TERRAIN MOBILITY SYSTEMS: Extreme terrains present interrelated mobility challenges that are substantially different from those of existing planetary rovers, including anchoring and de-anchoring operations, tether management, significant inertial effects (i.e., dynamic motion as opposed to static or quasi-static motion); high-lateral surface loads; and brittle terrain failure at ground contacts. Also, extreme-terrain mobility systems will be required to adapt to soil-property changes associated with solid and liquid multiphase behavior.

Recommendations (near-term):

- Develop system models of a range of systems suitable for supporting early mission concept studies and gap analyses for access to extreme terrains on Mars, the Moon, Europa, Venus, or Titan.

Recommendations (far-term):

- Develop early-stage prototypes targeted at the highest-priority mission concepts.

SMALL-BODY MOBILITY SYSTEMS: The challenges of evaluating small-body mobility systems using Earth or orbital testbeds are prohibitive and can only be addressed by simulation. Engineers need more insight into potential science objectives, while the science community needs increased awareness of mobility-system capabilities and system trade-offs.

Recommendations:

- Conduct **system studies** initiated by a workshop, bringing together engineers and scientists with the objective of reaching a consensus regarding a) the targets for which mobility provides significant science value; b) a set of science-derived mobility requirements for each target/target type (e.g., motion accuracy, instrument pointing, and surface mechanical coupling in micro-gravity); and c) the mobility strategies (e.g., random hopping versus controlled mobility) appropriate to each body.

OCEAN-WORLD MOBILITY SYSTEMS: Due to the exceptionally complex environment in ocean worlds, these challenging missions will require combined, highly integrated and multimodal technology solutions for surface, through-the-ice, and under-ice GN&C, which present many challenges in modeling, system integration, terramechanics and ice mechanics, localization, mapping, and communication.

Recommendations:

- Conduct a workshop to determine the state of the art and provide directions on GN&C technology (e.g., modeling, simulation, control, and guidance) needed by cryobots, under-ice probes, and through-the-ice mobility.

7.2 Finding 2: Subsurface mobility systems need increasingly complex autonomy for all surface missions

Subsurface voids are of interest for their potential relevance to astrobiology and potential records of geology and climate, as well as with regards to the Moon and Mars, as potential habitat locations for eventual human explorers. They also pose challenges in localization, mapping, and communication. Subsurface robotic systems will require increasingly complex autonomy, leading to better communication networks, and global localization.

Recommendations (near-term):

- Conduct a workshop to assimilate lessons learned from the DARPA SubT and RACER field tests for future underground planetary robotics involving new technologies in localization, mapping, and communication.

Recommendations (far-term):

- Develop and test system models for GN&C of tethered robotic systems with increased capability to descend, traverse, and safely return from underground destinations.

7.3 Finding 3: Sample acquisition and transfer needs more GN&C capability to navigate the widely different surfaces on planetary bodies

The wide variety of missions requires development of a range of sample acquisition and transfer technologies because few currently exist.

SAMPLING TOOLS: Including phase-change soil behavior as part of the system is also an under-developed area of investigation.

CACHING: Adopting a holistic approach with the platform and sampler target considered collectively for GN&C purposes can provide both science (e.g., sample collection) and engineering benefits.

DRILLING: More advancements are needed for deep rock and deep ice drilling.

Recommendations (near-term):

- Mature additional technology for coring and **sampling of bodies with reduced gravity** (e.g., Mars and lunar) to TRL 7.
- Develop a spectrum of low-TRL prototype sampling systems appropriate for bodies with **extreme temperatures** such as Venus (Titan missions are not in the current Decadal Survey), for bodies with low gravity (e.g., asteroids and comets), and for heterogeneous bodies (e.g., comets).
- Develop a flight-qualified, **general-purpose force torque sensor** to enable advanced sampling scenarios.

Recommendations (far-term):

- Conduct studies of ***integrated*** **mobility and sampling systems**, merging the sampling mechanism functions with the system-level functions, e.g., small-body sampling that relies on active compliance between the spacecraft and the surface.

7.4 Finding 4: Integrated system modeling and simulation needs to be more ubiquitous for all missions

Physics-Based Integrated System Modeling and Simulation Methodologies: Further improvement in high-performance computing is needed, which will ultimately enable the high-fidelity modeling and simulation of systems with millions of degrees of freedom to be integrated with onboard GN&C functionality. For all types of robotic vehicles but especially for aerial robots, advancements are needed in a) detailed modeling of actuators and sensors, including camera imaging; b) modeling of ground contact dynamics, including varied terrain and surface properties; c) flight software integration; and d) 3D visualization.

Uncertainty Quantification: NASA needs to expand the use of multiphysics–based QMU technology to enable rigorous certification of models and simulations for extrapolation to poorly testable flight conditions. QMU seeks to quantify margins and risk from both simulation and test uncertainties, and can supplement traditional margin rules when experience is sparse. Furthermore, there is a need to establish “simulation credibility” via application of rigorous process, and the QMU process is aligned to do just that.

Verification and Validation: In order to optimize system designs and reduce development cost/risk, more comprehensive system-level modeling is needed throughout the mission life cycle (technology investment and development, mission development and implementation, V&V, and training). Current modeling and simulation methodologies focus more on component-level rather than system-level techniques, with limited capability to reduce mission risk and enable system optimization. Together with advanced visualization techniques, an integrated, physics-based, system-level modeling, simulation, and visualization capability can provide for realistic training of both operations personnel and science team members.

Terramechanics and Ice Mechanics: In order to understand surface missions, there is a need for more sophisticated models of soil and ice interaction for both sampling and mobility. A distinguishing feature of many surface missions (e.g., those involving mobility and/or sampling in extreme terrain or microgravity) is a need for more sophisticated models of soil interaction. Even in high-gravity environments such as Mars, experience has demonstrated the risks associated with our limited ability to predict mobility (e.g., MER wheel becoming embedded in soft soil) and sampling performance (e.g., Phoenix) across a full spectrum of terrains. The development of high-fidelity simulations of regolith, such as granular media techniques, would facilitate improvements in surface mobility and also science. Additionally, phenomena such as complex phase changes and interactions with liquid media need to be better understood. A distinguishing feature of many surface missions (e.g., those involving landing, mobility, sampling, and/or anchoring in extreme terrain or microgravity) is a need for more sophisticated models of robot-terrain interaction. The development of high-fidelity simulations of regolith, such as multi-scale and multiphysics approaches, would facilitate improvements in surface interactions and science.

Recommendations (near-term):

- Conduct a workshop and systems study exploring the use of fully functional system **simulation to aid early-stage component and system design**.
- Continue to develop and disseminate physics-based simulations (similar to OWLAT) to serve as a **virtual testbed** for the evaluation and maturation of prototype mobility system designs.

- Conduct a workshop to explore state-of-the-art, high-performance computing methods (serial, parallel) to handle large-scale, multiple-sampling-rate, hardware-in-the-loop, and model-order reduction techniques that can enable real-time performance assessments for planetary missions in extreme environments.

Recommendations (far-term):

- Hold a series of workshops engaging scientists, terramechanics and ice-mechanics experts, and GN&C experts to identify the needed simulation capabilities and relevant surface-material properties to address a variety of bodies and mission types.
- Develop and validate a range of terramechanics models and/or simulations capable of supporting analysis of vehicle-soil interaction in both low- and high-gravity environments, and sampling and mobility in microgravity.

7.5 Finding 5: New control and planning techniques need to be adopted for future missions

CONTROL: In order to address the increasing complexity of spacecraft systems and interaction with the environment, new model-based control techniques that efficiently model dynamically evolving systems in order to control the system, and learning-based control techniques that infer the model parameters from sensor measurements in order to control the system, need to be leveraged. Computational constraints and the complexity of planetary science goals have limited the application of model-based control to date. The advent of flight-qualified, high-performance computing will address that constraint. The incorporation of model-predictive control into surface GN&C systems will lead to higher-performance operations because knowledge of the system behavior is explicitly taken into account for planning and control. Applications include the modeling of vehicles, manipulators, and task interaction dynamics in drilling or other contact with the environment or fast manipulation operations.

PLANNING UNDER UNCERTAINTY: New methods for quantifying uncertainty and risk are required to address future missions involving more uncertain environments (e.g., asteroids). A large number of the envisioned future missions involve a significantly less predictable environment than previous lander and rover missions. Be it an aerial platform operating in unknown and changing window conditions, a sampling arm digging beneath the exposed surface, a small-body hopper exerting a rapid force against a complex and poorly understood regolith, or an extreme-terrain robot applying lateral force to a rock outcrop of unknown strength, the mobility system's motion-planning component will have to take into account a level of uncertainty much greater than current rovers. Additionally, path planning in environments dominated by complex phase changes and interactions with liquid media need to be better understood.

Recommendations (near-term):

- Conduct a systems study to identify the advantages and disadvantages of model-based and learning-based predictive control to provide significantly improved performance and conduct evaluation studies.
- Hold a workshop outlining a plan and ideas and engaging experts from diverse disciplines (e.g., control theory, mechanical engineering, systems engineering). The purpose of the workshop is to explore successful techniques for robust control and planning under different types of uncertainty.

Recommendations (far-term):

- Conduct a multi-year, university-focused research program addressing planning under uncertainty while ensuring that a broad range of mobility systems are addressed, including aerial mobility, microgravity mobility, horizontal mobility in uncertain terrain, and vertical mobility of a tethered system.

7.6 Finding 6: High-speed autonomous navigation needs to leverage the advantages of HPC

The reduced speed of autonomous navigation limits both energy efficiency and the surface area reachable in a fixed mission duration. Ongoing advances in HPC will eliminate the performance penalties associated with autonomous driving. For sample return missions, improved autonomous navigation speeds will enable substantially greater sample diversity and more in-depth site characterization. Currently, autonomous navigation entails significant reductions in average drive speed. This in turn reduces energy efficiency and limits the areas reachable within a fixed mission duration.

Recommendations (near-term):

- Undertake a systems study of the benefits of HPC on planetary rovers. Pending the results, a follow-up effort to develop a prototype of a high-speed, low-mass rover should be considered.

Recommendations (far-term):

- At TRL 6 or 7, demonstrate high-speed navigation of a prototype planetary rover running on prototype flight avionics.

7.7 Finding 7: Range sensing needs improved detectors and metrology

Industry is rapidly maturing alternative active range sensing devices (LIDAR and flash LIDAR), patterned light techniques, and headlights, which require redesign for flight. The binocular stereo range sensing currently used by Mars rovers is computationally intensive, can be done only in full illumination, and has limited range. In addition, there is an opportunity to leverage rapidly advancing computation capabilities towards improved range sensing. Contact sensing, especially for confined spaces, needs to be improved.

Recommendations (near-term):

- Conduct a study to estimate development/maturation trajectories of alternative range sensors, model their expected performance (including SWaP), and quantitatively evaluate the benefits to multiple applications, including mobility.
- Undertake development of reusable, high-performance, flight-qualified implementations of multiple ranging techniques and sensors.

Recommendations (far-term):

- Develop a new generation of engineering cameras suitable for multiple applications, including deep space navigation as well as lunar and Martian surface missions.

7.8 Finding 8: Global localization needs more autonomy infusion

Small-body mobility systems, as well as Venus and Titan aerial vehicles (covered in Part IV), need the ability to determine real-time surface references for science targeting and navigation. On Mars, rovers need to use real-time localization with orbital localization data to more efficiently traverse long distances.

Recommendations (near-term):

- Develop a program to demonstrate vision-based global localization across multiple destinations.

Recommendations (far-term):

- Develop localization techniques to enable efficient low-gravity, small-body exploration.

7.9 Finding 9: Ground operations tools need better human-machine interfaces

The planning and visualization tools required for surface operations for missions other than rover missions have not yet been developed. Also, tools for interfacing to much more autonomous systems still need maturation. The evaluation of risks associated with particular command sequences for uplink is currently ad hoc. The planning and visualization tools required for surface operations for missions other than rovers have not yet been developed, and even crude simulation-based operation experiments would help identify achievable mission goals, system requirements, and technology gaps. Also, tools for interfacing to much more autonomous systems still need maturation. The evolution of the associated missions and the design of spacecraft themselves would benefit from initiating dialogue between scientists and technologists to develop at least a conceptual storyboard outlining viable operations processes and interfaces.

Recommendations (near-term):

- Conduct a study to evaluate and communicate the uncertainty and risks associated with prospective uplink sequences for an aerial platform or a rover operating in extreme terrain.

Recommendations (far-term):

- Continue to improve 3D immersive visualization environments for surface operations.

7.10 Finding 10: Emergent technologies need to be matured and adopted

AI, with its subareas of deep learning and machine learning, has progressed enormously in recent times, with potential advantages for the areas of planning, control, and navigation. New holistic frameworks have emerged for high-stakes planning that allows resource-constrained robotic systems to effectively navigate in complex environments while guaranteeing safety. There is also a gap between quantum technologies (which usually deal with physical processes at the atomic scale), and classical robotic systems (which usually deal with physical processes at a macroscopic scale), and combining the two can provide unmatched possibilities that can advance computation, communication, and sensing.

Recommendations:

- Evaluate possible and novel research directions with holistic networks to target how low-cost distributed sensing can be combined with machine learning to derive fundamental performance estimates.
- Because quantum technologies will inevitably be integrated with classical mechanical systems, conduct an evaluation of the impact of training GN&C engineers in quantum technologies, and start to infuse quantum technologies in the NASA Systems Engineering process.

8 Conclusions

This document, Part III of the *Guidance, Navigation, and Control Technology Assessment for Future Planetary Science Missions* series, has proposed a vision of surface and subsurface GN&C

development for the next 10 years or so, in which the findings described above are all part of an integrated system. This is the first time that surface and subsurface GN&C have been examined in a unified manner. This document provides a development roadmap for the next few years. The findings and recommendations presented in this document represent a spectrum of investments in cross-cutting technologies as well as systems engineering and prototype development targeted at specific mission types. Architecture and systems-engineering processes leading to a successful surface and subsurface system design are still evolving, but based on recent experience, we note the following:

- Surface and subsurface GN&C is still in its infancy.
- Surface and subsurface GN&C is a distinct area from traditional spacecraft GN&C.
- Flight missions need to treat the surface and subsurface phases with as much concern as cruise and EDL.
- Integrated modeling and simulation for surface and subsurface GN&C are not yet used to their full potential.
- Sustained system-level analyses and design of surface and subsurface GN&C need to take place well before mission definition.

Acronyms

3D	three-dimensional
ACS	Attitude Control System
ARC	Ames Research Center
ASTID	Astrobiology Science and Technology for Instrument Development
ATK	Alliant Techsystems Inc.
AVM	Adaptive Vehicle Make
BWS	Brushed-wheel Sampler
CAT	Coring Abrading Tool
COTS	commercial off-the-shelf
CSSR	Comet Surface Sample Return
DAME	Drilling Automation for Mars Exploration
DARPA	Defense Advanced Research Projects Agency
EDF	entry, descent, and flight
EDL	entry, descent, and landing
EP	electric propulsion
ESA	European Space Agency
EVA	extra-vehicular activity
FDIR	failure detection, identification, and recovery
FPGA	field programmable gate array
GCM	Global Circulation Model
GITL	Ground In the Loop
GN&C	Guidance, Navigation, and Control
GPS	global positioning system
GPU	Graphics Processing Unit
GRC	Glenn Research Center
HEOMD	Human Exploration and Operations Mission Directorate
HiRISE	High Resolution Imaging Science Experiment
HP^3	Heat Flow and Physical Properties Package
HPC	High Performance Computing
HTA	heavier than air
IMSAH	Integrated Mars Sample Acquisition and Handling
IMU	inertial measurement unit
INS	Inertial Navigation System
ISAS	Institute of Space and Astronautical Science
JAXA	Japanese Aerospace Exploration Agency
LaRC	Langley Research Center
LIDAR	Light Detection and Ranging
LSR	Lunar Sample Return
MAV	Mars Ascent Vehicle
MBE	Model-based Engineering
MER	Mars Exploration Rovers
MINERVA	MIcro Nano Experimental Robot Vehicle for Asteroid
MinSAC	Minimum Scale Sample Acquisition and Caching
MSL	Mars Science Laboratory
MSR	Mars Sample Return
NIAC	NASA Innovative Advanced Concepts
NRC	National Research Council
OSIRIS-REx	Origins, Spectral Interpretation, Resource Identification, Security-Regolith Explorer
OWLAT	Ocean World Lander Autonomy Testbed

PDP	Planetary Defense Precursor
PSD	Planetary Science Division
PSR	permanently shadowed region
QMU	Quantification of Margins and Uncertainty
R&D	research and development
RA	robotic arm
RCS	Reaction Control System
RKA	Russian Space Agency
RHBD	radiation hardened by design
RSVP	Rover Sequencing and Visualization Program
SAC	sample acquisition and caching
SAGE	Surface and Atmosphere Geochemical Explorer
SAT	Sample Acquisition Tool
SD2	Sampler, Drill, and Distribution System
SIPR	Subsurface Ice Probe
SLAM	Simultaneous Localization and Mapping
SMD	Science Mission Directorate
SPOC	Soil Property and Object Classification
SWAP	size, weight, and power
TAG	Touch and Go
TDT	Transonic Dynamics Tunnel
TGIP	touch-and-go-impregnable-pad
TRIDENT	The Regolith and Ice Drill for Exploration of New Terrains
TRN	Terrain Relative Navigation
TSSM	Titan Saturn System Mission
TRL	Technology Readiness Level
UQ	Uncertainty Quantification
USDC	ultrasonic/sonic driller/corer
V&V	verification and validation
VCO	Venus Climate Orbiter
VISE	Venus In Situ Explorer
VLBI	very long baseline interferometry
VO	visual odometry
WFF	Wallops Flight Facility

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