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

## *Part III. Surface Guidance, Navigation, and Control*

**April 2, 2013**

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 Guidance, Navigation, and Control*

**Strategic Missions and Advanced Concepts Office**
**Solar System Exploration Directorate**
**Jet Propulsion Laboratory**
**for**
**Planetary Science Division**
**Science Mission Directorate**
**NASA**

*Work Performed under the Planetary Science Program Support Task*

**April 2, 2013**

**JPL D-78106**

***Authors***
*Jet Propulsion Laboratory, Caltech*
Marco B. Quadrelli (co-lead)
Michael McHenry (co-lead)
Brian Wilcox
Jeffery Hall
Richard Volpe
Issa Nesnas
Hari Nayar
Paul Backes
Rudranarayan Mukherjee
Larry Matthies
Wayne Zimmerman
David Mittman

*Stanford University*
Prof. Marco Pavone

*Autonomous Systems Laboratory, CSIRO*
Alberto Elfes*

***Advisory Committee***
*Jet Propulsion Laboratory, Caltech*
Patricia M. Beauchamp
James A. Cutts
Rob Manning

*Carnegie Mellon University*
Prof. Red Whittaker

* Formerly with Jet Propulsion Laboratory, Caltech

# Foreword

Future planetary explorations envisioned by the National Research Council's (NRC's) *Vision and Voyages for Planetary Science in the Decade 2013–2022*, developed at the request of NASA the 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 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 to be the onboard determination of the desired path of travel from the vehicle's current 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 determination of 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, and so continuous technology 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 Guidance, Navigation, and Control—is the third, and last, in a series of 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 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 Guidance, Navigation, and Control, examines GN&C for vehicles that are not in free flight, but that operate on or near the surface of a natural body of the solar system. It should be noted that this is the first time that Surface GNC has been assessed and requirements given for future missions. Together, these documents provide the PSD with a roadmap for achieving science missions in the next decade.

Patricia M. Beauchamp

Patricia M. Beauchamp
*Strategic Missions and Advanced Concepts Office*
*Solar System Exploration Directorate*

April 2, 2013

## Acknowledgments

This work was conducted as part of the Planetary Program Support task that JPL carries out for NASA's Planetary Science Division. The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Gordon Johnston is the NASA program executive responsible for this work funded under the Technology sub-task.

Special thanks to Samantha Ozyildirim for support during preparation of this report and to Richard Barkus for development of the cover.

## Other Reports in This Series

### Power Technology

- Advanced Radioisotope Power Systems Report, Report No. JPL D-20757, March 2001.
- Solar Cell and Array Technology for Future Space Missions, Report No. JPL D-24454, Rev. A, December 2003.
- Energy Storage Technology for Future Space Science Missions, Report No. JPL D-30268, Rev. A, November 2004.

### Planetary Protection Technology

- Planetary Protection and Contamination Control Technologies for Future Space Science Missions, Report No. JPL D-31974, June 2005.

### Extreme Environments Technology

- Extreme Environment Technologies for Future Space Science Missions, Report No. JPL D-32832, September 2007.
- Assessment of Planetary Protection and Contamination Control Technologies for Future Science Mission, Report No. JPL D-72356, January 2012.

### Guidance, Navigation, and Control Technology

- Guidance, Navigation, and Control Technology Assessment for Future Planetary Science Missions: Part I. Onboard and Ground Navigation and Mission Design, Report No. JPL D-75394, October 2012.
- Guidance, Navigation, and Control Technology Assessment for Future Planetary Science Missions: Part II. Onboard Guidance, Navigation, and Control (GN&C), Report No. D-75431, January 2013.

# Table of Contents

## List of Tables

## List of Figures

## Executive Summary

This document provides an assessment of 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. ***It should be noted that this is the first time that such an assessment and recommendations have been provided for surface GN&C technology.*** The organization of the document closely follows the process used to arrive at the findings and recommendations. Specifically, the document is organized into four sections: 1) a review of potential future missions involving significant surface components; 2) an outline of capabilities required for successful implementation of those missions; 3) a review and assessment of key technology areas addressing those capabilities; and 4) a set of findings and recommendations for future GN&C technology investments.

Even though we have successfully placed four rovers on Mars, GN&C development for planetary surface missions is still in its infancy. Surface 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. Secondly, the operational environments are both very complex and yet only partially known. Finally, the variability of technology needs across the expanse of prospective surface missions is immense yet technology development funding is extremely limited. Note that the scope of this document includes, in addition to ground systems, platforms operating in atmospheres, oceans, and lakes.

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 missions will demand much more precise interaction with the terrain soil; examples include Mars sample caching, mobility systems operating on extreme slopes, or sampling systems collecting soil in micro-gravity. And since 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 missions makes cost-effective technology development a particular challenge. Greater reliance on system modeling and simulation will reduce costs through 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 GN&C technology development program. ***One overarching recommendation is that flight missions treat the surface phase with as much rigor as cruise and entry, descent, and landing (EDL). Similarly, surface 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 GN&C technology development should be a sustained effort with a portfolio that includes both 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. Finally, flight projects should treat surface GN&C as a distinct discipline from traditional GN&C.***

The 12 technology findings and recommendations discussed in this report are given below:

### *Finding 1: Integrated System Modeling and Simulation Methodologies*

In order to optimize system designs and reduce development cost/risk, there is a need for more comprehensive system-level modeling throughout life cycle (technology investment & development, mission development and implementation, Verification and Validation [V&V], and training).

***Recommendation 1:*** Conduct a workshop and systems study exploring the use of fully functional system simulation to aid early-stage component and system design.

***Recommendation 2:*** Based on the results of the above, conduct two pilot studies—one focused on pre-phase A design needs for a particular mission type (e.g., aerial mobility with surface sampling capability) and another focused on mid-mission V&V.

***Recommendation 3:*** 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.

### *Finding 2: Terramechanics*

More sophisticated models of soil interaction for both sampling and mobility are required to better understand surface missions.

***Recommendation 1:*** Hold a series of workshops engaging scientists, terramechanics experts, and the GN&C experts to identify the needed simulation capabilities and relevant surface material properties to address a variety of bodies and mission types.

***Recommendation 2:*** Develop and validate a range of terra-mechanic models and/or simulations capable of supporting analysis of wheel-soil interaction in both low- and high-gravity environments, and sampling and mobility in micro-gravity.

### *Finding 3: Model-Based Control*

In order to address increasing complexity of the spacecraft systems and the interaction with the environment we need to leverage new control techniques that model dynamically evolving systems.

***Recommendation 1:*** Conduct a systems study to identify candidate operational scenarios where model-predictive control could provide significantly improved performance and conduct evaluation studies.

### *Finding 4: Planning Under Uncertainty*

New methods for quantifying the uncertainty and risk are required to address future missions involving more uncertain environments (e.g., asteroids).

***Recommendation 1:*** Hold a workshop, outlining a plan and ideas, engaging experts from diverse disciplines (control theory, mechanical engineering, systems engineering). The purpose of the workshop is to explore successful techniques for robust planning and control under different types of uncertainty.

***Recommendation 2:*** Fund 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, micro-gravity mobility, horizontal mobility in challenging terrain, and vertical mobility of a tethered system.

### Finding 5: High-Speed Autonomous Navigation

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. Ongoing advances in high-speed computing will eliminate the performance penalties associated with autonomous driving.

***Recommendation 1:*** Undertake a systems study of the benefits of high-speed computing on planetary rovers. Pending the results, a follow-up effort to develop a prototype of a high-speed, low-mass rover should be considered.

***Recommendation 2:*** Demonstrate at TRL 6 or 7, high-speed navigation of a prototype planetary rover running on prototype flight avionics.

### Finding 6: Ground Operations Tools

The planning and visualization tools required for surface operations for missions other than rover missions have not yet been developed.

***Recommendation 1:*** Conduct a small study to evaluate the cost and benefits of the development of a simulated operations system capable of supporting one or more future missions such as a Mars Sample Return (MSR), small body operations, or a Titan aerial platform.

***Recommendation 2:*** Fund 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.

***Recommendation 3:*** Establish and fund a multi-center team to coordinate development of three-dimensional (3-D) immersive visualization environments for surface operations.

### Finding 7: Range Sensing

Industry is rapidly maturing alternative active range sensing devices (Light Detection and Ranging [LIDAR] and flash LIDAR), patterned light techniques and headlights, which require redesign for flight.

***Recommendation 1:*** Conduct a study to estimate development/maturation trajectories of alternative range sensors, model their expected performance (including size, weight, and power [SWAP]), and quantitatively evaluate the benefits to multiple applications including mobility.

***Recommendation 2:*** Undertake development of reusable, high-performance, flight-qualified implementations of multiple ranging techniques and sensors.

***Recommendation 3:*** Fund the development of a new generation of engineering cameras suitable for a range of applications including deep space navigation as well as lunar and martian surface missions.

### Finding 8: Global Localization

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

***Recommendation 1:*** Develop a program to demonstrate vision-based global localization.

***Recommendation 2:*** Develop techniques to enable low-gravity small body exploration.

### *Finding 9: Extreme Terrain Mobility Systems*

Extreme terrains, such as steep slopes, present mobility challenges that are substantially different from those of existing planetary rovers.

***Recommendation 1:*** 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.

***Recommendation 2:*** Develop early stage prototypes targeted towards the highest priority mission concepts.

### *Finding 10: 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.

***Recommendation 1:*** Conduct system studies initiated by a workshop, bringing together engineers and scientists with the objective of reaching a consensus regarding:

- The targets for which mobility provides significant science value
- 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)
- The mobility strategies (e.g., random hopping vs. controlled mobility) appropriate to each body.

***Recommendation 2:*** Develop and disseminate a physics-based simulation to serve as a virtual testbed for the evaluation and maturation of prototype mobility system designs.

### *Finding 11: Aerial Mobility Systems*

Higher fidelity simulation tools and prototype field testing are needed to design robust systems.

***Recommendation 1:*** Extend existing modeling and simulation tools for planetary environments and robotic ground vehicles to make them suitable for exploration of aerial vehicle designs and early performance assessments.

***Recommendation 2:*** Fund the development of prototypes (based on the systems study) and evaluate performance of vehicle deployment, localization, surface sampling, onboard autonomous science, and aerial vehicle mission operations interfaces.

### *Finding 12: Sample Acquisition and Transfer*

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

***Recommendation 1:*** Mature technology for coring and sampling of bodies with gravity (e.g., Mars and lunar) to TRL 7.

***Recommendation 2:*** Fund a spectrum of low TRL prototype sampling systems appropriate for bodies with extreme temperatures (Venus and Titan), for bodies with low gravity (e.g., asteroids and comets), and for heterogeneous bodies (e.g., comets).

***Recommendation 3:*** Conduct studies of *integrated* mobility and sampling systems, merging the sampling mechanism functions with the system-level functions; for example, small body sampling that relies on active compliance between the spacecraft and the surface.

***Recommendation 4:*** Develop a flight qualified, general-purpose force torque sensor.

***Recommendation 5:*** Endorse the Astrobiology Science and Technology for Instrument Development (ASTID) workshop in 2013, and ensure that there is sufficient and adequate GN&C participation.

This document proposes a vision of technology development for the next few years and is the first time that surface GN&C has been examined to this breadth. The findings and recommendations represent a spectrum of investments both in cross-cutting technologies as well as systems engineering and prototype development targeted to specific mission types. One over-arching finding is that because surface 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 GN&C must be recognized as a distinct field rather than a sub-set of spacecraft GN&C.
- Flight missions must treat the surface phase with as much concern as the cruise and EDL phases.
- Integrated modeling and simulation can be better utilized to reduce risks, costs, and development timelines.
- Sustained system-level analyses and design of surface GN&C systems must be undertaken well before mission definition.

# 1 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 technology in guidance, navigation, and control (GN&C), and mission design that are needed to achieve the goals of future planetary science missions. The two previous documents in this series are "Part 1: Navigation and Mission Design"[1] and "Part II: Onboard Guidance, Navigation, and Control."[2] This document addresses the post entry, descent, and landing (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 the "Part II: Onboard Guidance, Navigation, and Control" document.

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. Figure 1-1 depicts an artist's conception of planetary robots: the Mars Science Laboratory (MSL); lunar exploration with robots and humans; a picture of a possible undersea robot that would explore Europa's oceans for life; and a Venus altitude-cycling balloon based on phase-change buoyancy fluids. 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.

**Figure 1-1.** Artist's conception of planetary robots: (top, left) Mars Science Laboratory; (top, right) lunar exploration with robots and humans; (bottom, left) picture of a possible undersea robot that would explore Europa's oceans for life; and (bottom, right) Venus altitude-cycling balloon based on phase-change buoyancy fluids.

While we have had recent successes with the Mars Exploration Rovers (MERs) and the Phoenix lander, significant improvements are possible to enable 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 soils and the resulting interactions with the vehicle, present critical challenges. Findings presented in this document represent a spectrum of needs both in cross-cutting technologies as well as systems engineering and prototype development targeted to specific mission types.

### 1.1 Definition of Surface GN&C

Surface 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. Some of the terminology associated with surface mobility systems can differ from that adopted for general 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."

## 2 Missions from 2011 Decadal Survey Requiring New Surface GN&C Capabilities

This section contains descriptions of the missions identified in the 2011 Decadal Survey[3] followed by a description of specific surface GN&C technology needs for each.

### 2.1 Mars Sample Return

Both the roving/sample gathering and caching segment, as well as the cache retrieval/Mars Ascent Vehicle (MAV) launch segments of a potential Mars Sample Return (MSR) mission, would contain substantial requirements for new surface GN&C technology. The need to collect samples from a rich and diverse set of well-characterized sites within a limited mission duration requires faster and more energy-efficient rover navigation. Better prediction of vehicle mobility via improved terrain sensing will improve mission safety and enable operation on more extreme terrains. When combined with methods to plan under uncertainty, quantitative measures of the uncertainty associated with terrain sensing and predicted vehicle mobility will enable more efficient operations, improve mission safety, and potentially enable access to more challenging terrain. Improvements in global localization will enable greater leveraging of orbital data in traverse planning, thereby enabling more efficient long traverses. Sampling acquisition and handling methods need to be matured and updated based on more demanding mechanical designs and constraints.

### 2.2 Comet Surface Sample Return (CSSR)

The New Frontiers Comet Surface Sample Return (CSSR) mission is one of several potential missions to small primitive bodies. There have been prior cometary missions beginning with the European Space Agency (ESA) Giotto (fast flyby) and continuing with ESA's Rosetta mission, which will rendezvous with a comet and place a lander on it in 2015. Many of these new missions will require technologies such as Touch and Go (TAG), a type of autonomous rendezvous and docking GN&C system that can make close, controlled approaches and gentle contact with the rotating surface of the body, or different types of penetration systems such as harpoons, darts, or drilling end-effectors. Since ground testing of systems operating in microgravity is extremely costly, innovative approaches for integrated modeling and simulation of proximity operations will be needed to test system performance. Similar to the MSR mission, CSSR will require advances in the areas of sampling and sample handling, efficient operation methodologies, precise global localization, and advanced options for surface mobility in the cometary microgravity environments.

### 2.3 Lunar Sample Return (LSR)

The Lunar South Pole-Aitken Basin Sample Return is another potential New Frontiers mission. A soft landing on the Moon, probably in rugged terrain to ensure a sampling of material from the mantle, will require several novel surface GN&C elements. These include vision-based Target Relative Navigation (landmark modeling and tracking), fast and energy-efficient roving capability, precise global localization, efficient operations, advanced sample collection and sample handling capabilities, and automated path planning and optimization.

## 2.4 Venus

A variety of Venus missions have been proposed with very distinct science objectives, mobility systems, and GN&C requirements. The 2011 Decadal Survey includes an atmospheric-focused Venus Climate Orbiter (VCO) Mission based on an uncontrolled wind-driven balloon with global localization needs. In addition to the balloon, there is a mini-probe and two drop sondes.

The surface-centric Venus In Situ Explorer (VISE) mission would place a lander on the surface capable of sample acquisition and analysis with extended mission duration. The New Frontiers Surface and Atmosphere Geochemical Explorer (SAGE) mission would require an autonomous surface excavation system in an extreme environment (450°C, 92 bars) and in situ instrumentation for geochemical analysis.

## 2.5 Titan

There are two potential missions to explore Titan via different mobility systems: 1) based on a wind-driven Montgolfière, and 2) based on a lake lander.

The Titan Saturn System Mission (TSSM), in which a wind-driven Montgolfière is used to survey the moon, and a lake lander is used to explore the methane and ethane lakes, require unique localization capabilities, assisted by efficient operations, and a sophisticated set of technologies in the areas of aerial mobility (for the balloon) and surface mobility (for the lake lander). All these capabilities will also need to rely on high-performance computing hardware and software, particularly in the path planning and management and correlation of science data collected by heterogeneous sensors.

On the other hand, alternative mission concepts using passive elements such as floaters will not likely require precise localization. In general, all balloons require localization, but balloons operating near the surface require even higher levels of precision to avoid collisions and acquire surface samples from small terrain features. There is a range of possible Titan balloon missions going from uncontrolled, all-passive, helium, super-pressure balloons to sophisticated motorized blimps. There is a corresponding range of GN&C requirements associated with this aerial mobility. Besides a lander and an orbiter, the TSSM includes a hot air balloon (Montgolfière) that might require a vertical ascent/descent control system and accurate localization ability. More advanced versions of this balloon are possible in which the balloon changes altitude to catch favorable winds and go to desired locations above the ground. This wind-assisted navigation was not part of the original TSSM, but is a logical extension. Also, it is an example of the impact of GN&C technology on a mission on a planetary scale, since innovative mission planning strategies for long-duration flights might have to be developed while keeping in mind the limited lifetime of vehicle resources.

Finally, challenges common to virtually all planetary science missions beyond the orbit of Mars include limited bandwidth and high-latency communications, which preclude real-time teleoperation, thus requiring a high degree of autonomy and reliability.

### 2.6 Europa Lander

Studies of a Europa lander were conducted by JPL as part of a Europa option study completed earlier in 2012. The lander option was ruled out as too costly in the current environment. However, it was recognized that a future Europa lander is important and that more information about the surface will be needed to design the lander. Accordingly, the Europa Clipper mission, consisting of multiple fly-bys, will be equipped to perform landing site characterization. This future lander mission will require advanced capabilities in the areas of efficient operations, sampling, and potentially deep drilling, all using rad-hard technology.

### 2.7 Near Earth Objects (NEOs)

This is a class of missions that would investigate NEOs for general planetary science purposes, for planetary defense purposes, for pre-mission surveys, and reconnaissance for human exploration and retrieval. These missions will share characteristics of other small body missions, including the need for autonomous surface GN&C, precise global localization, small body mobility, and sample collection and handling. If surface contact is going to be made, precision sample collection and handling subsystems will be required (TAG, darts, harpoons, and others), which will also require interaction with the surface regolith.

Initial planetary defense missions such as Planetary Defense Precursors (PDPs) will explore alternative defense strategies. These may be small investigatory surveyors to assess physical characteristics of the small body and leave precision-clock-based radio beacons for precise global localization and/or mitigation technology demonstrations incorporating one or more deflection methods such as electric propulsion (EP) systems or gravity tractors. Such missions will share all of the surface GN&C new technology needs of the sample return missions.

Many future small body missions are likely to be micro-spacecraft missions. Aside from the already discussed technology requirements associated with small body missions in general, micro-missions will require specialized micro-spacecraft subsystems. Because of the small, compact, and inexpensive nature of micro-missions, these spacecraft will likely need more extensive autonomous capability than simple TAG functions, including better ways to manage operations, and to handle samples collected from different locations.

## 3 Surface GN&C Capabilities

This section describes some key capabilities that will enable or enhance the missions outlined in the previous section.

The list of missions outlined above demonstrates the multitude of challenges presented by future surface missions. Challenges general to virtually all of the surface missions include:

- Limited bandwidth and high-latency communications preclude real-time teleoperation (except to 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.
- 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, cryo-lakes, thermal extremes in shadows, etc., can require novel system designs and autonomy algorithms tailored for these new environments. Many of the future missions detailed above involve levels of interaction with the environment (terrain and soil, atmosphere, and lakes) far beyond those previously demonstrated. 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.
- Closely related to the challenge of environmental uncertainties is the unique nature of operations for mobility-based missions. Figure 3-1 and Table 3-1[4] depict a summary of past and present mobility system technology categorized by mobility type, as well as a classification of advantages and disadvantages offered by several mobility systems. Mobility-based missions involve a rapid and continuous evolution of the understanding of the environment, system performance, communication windows, and science objectives, all of which are reflected in a rapid turnaround operational pace.

Table 3-2 maps each identified capability (rows) to the mission types (columns) discussed above. The capabilities will be discussed in detail in the next section.

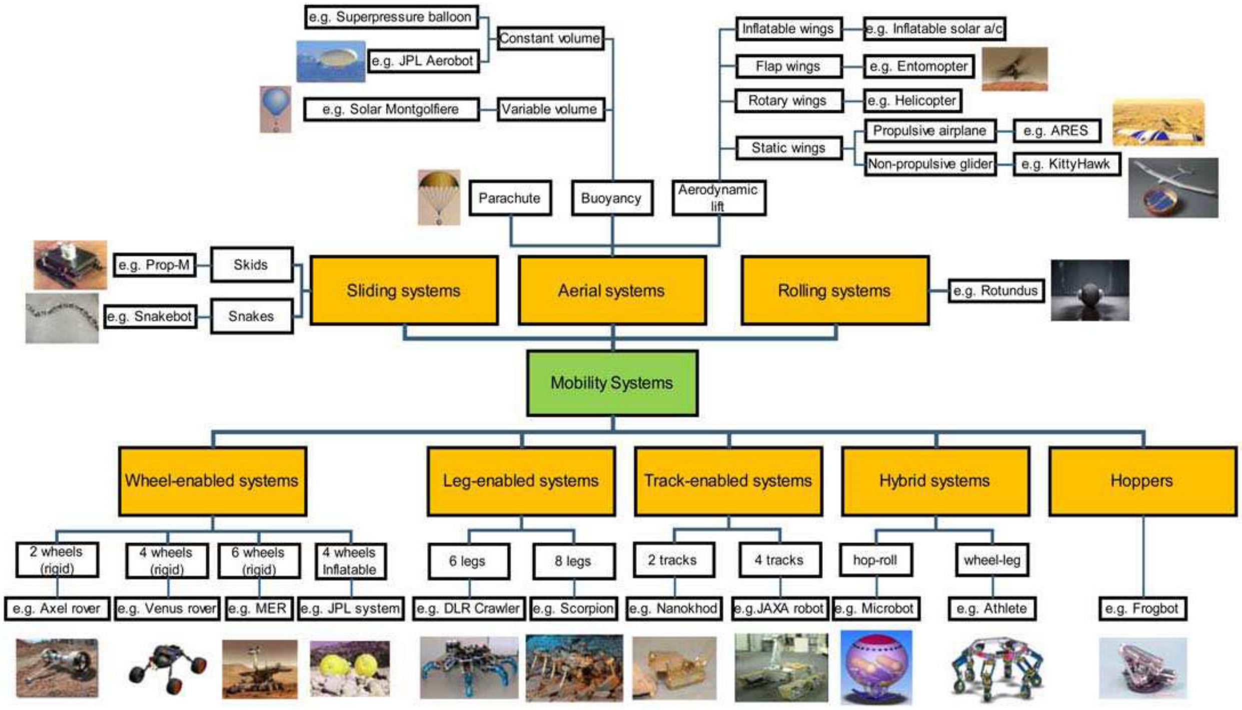

**Figure 3-1.** Summary of past and present mobility system technology categorized by mobility type. Reprinted from *Robot Mobility Systems for Planetary Surface Exploration – State-of-the-Art and Future Outlook: A Literature Survey*.[4]

**Table 3-1.** Advantages and disadvantages of mobility systems. Reprinted from *Robot Mobility Systems for Planetary Surface Exploration – State-of-the-Art and Future Outlook: A Literature Survey*.[4]

| **System** | **Advantages** | **Disadvantages** |
|---|---|---|
| Wheels | • Better speed in even terrain<br>• Simple and mature technology<br>• Adequate redundancy (mobility)<br>• Payload weight-to- mechanism weight ratio high<br>• Relatively low power consumption rates and energy efficient | • Relatively low slope climb capacity due to wheel slippage<br>• Obstacle traverse capability relatively less compared to other concepts |
| Tracks | • Good terrain capability<br>• Technology well understood in terrestrial applications<br>• Better traction capability on loose soil • Handles large hinders, small holes, ditches better<br>• Good payload capacity | • Inefficient due to friction of tracks<br>• Low speed operation<br>• Slip turning and friction<br>• Low redundancy, jamming of parts and prone to failure |
| Legs | • Highly adapted to uneven terrain and hence better obstacle and slope traverse capability | • Mechanically complex<br>• Control of walking is complex<br>• Slow mobility<br>• Impact after each step<br>• Poor payload weight-to-mechanism weight ratio |
| Hoppers | • Better obstacle traverse capabilities<br>• If power availability is flexible, can enable large scale exploration due to better speed | • Impact during landing after hopping had large risk of failure |
| Hybrids | • Shares the advantages of two locomotion concepts<br>• Miniaturized hybrid hop-roll systems operating as swarm, enables exploration of larger area in a short time | • More complexity<br>• Low technology maturity |

**Table 3-2.** Mission types benefiting from proposed surface GN&C capabilities.

| | **Mars Sample Return** | **Comet/ Small-Body Sample Return** | **Lunar Sample Return** | **Venus Climate Orbiter** | **Venus In Situ Explorer** | **Titan Missions** | **Europa Lander** | **NEO Missions** |
|---|---|---|---|---|---|---|---|---|
| More Capable Rovers | √ | | √ | | | | | |
| Extreme Terrain Mobility | √ | | | | | √ | | √ |
| Aerial Mobility | | | | √ | | √ | | |
| Small Body Mobility | | √ | | | | | | √ |
| Sampling and Sample Handling | √ | √ | √ | | | √ | √ | √ |
| Efficient Operations | √ | √ | √ | | √ | √ | √ | √ |
| GN&C Modeling and Simulation | √ | √ | √ | | √ | √ | √ | √ |

## 3.1 Planetary Rovers

While the MERs and the MSL rover have amply demonstrated the value of mobile surface exploration, there are two needed GN&C-based enhancements: 1) greater traverse speeds and energy efficiency, and 2) more sophisticated hazard detection. Note that within this document, rover is used to refer to MER- and MSL-like vehicles designed for horizontal mobility on bodies with significant gravity. Other ground vehicles designed for vertical mobility or small bodies are discussed in subsequent sections.

Computational limitations constrain the traverse speed of existing rovers when performing vision-based autonomous navigation and slip detection. The constraints reduce the distances that can be traversed in a given day and over the entire mission duration. For example, the vision processing that underlies autonomous navigation and slip detection requires between one or two minutes of processing on current flight-qualified processors (e.g., RAD750). The rover must stop during these computations, resulting in a small ratio of driving to thinking and associated reductions in average traverse speed. The overall result is that MER and MSL autonomous driving is on the order of 3–4 times slower than blind drives commanded explicitly by ground operators.[5] Note that since the additional power required to drive the wheels is a fraction of the overall rover avionics power, the reduced driving duty cycle reduces the overall energy efficiency (meter/Watt-hr) by approximately a factor of 2 as compared to a manually commanded drive. As a result of these time and energy penalties associated with autonomous navigation, ground operators are forced to ration the use of hazard and slip detection that would otherwise increase mission safety.

The benefits of developing faster and more energy-efficient rovers are particularly relevant to potential MSR missions. 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. For a mission utilizing the MAV, faster autonomous driving would enable shorter mission duration (an important factor given concerns regarding the potential degradation of the MAV rocket fuel). Another benefit is improved mission safety by enabling always-on hazard avoidance and slip detection. Improvements are needed in autonomous navigation speeds to enable future Mars rovers that are faster, can drive further, and can operate more safely than current rovers.

Not only does the limited onboard computational power limit rover traverse rates and energy efficiency, it also constrains the fidelity and sophistication of the hazard detection and autonomous navigation algorithms that can be fielded. Figure 3.1-1 illustrates the basic hazard avoidance strategy used by the MERs and MSL rover. 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 areas of high slip before the rover enters. In addition, the autonomous navigation functions rely on simple heuristics to try to minimize path length and

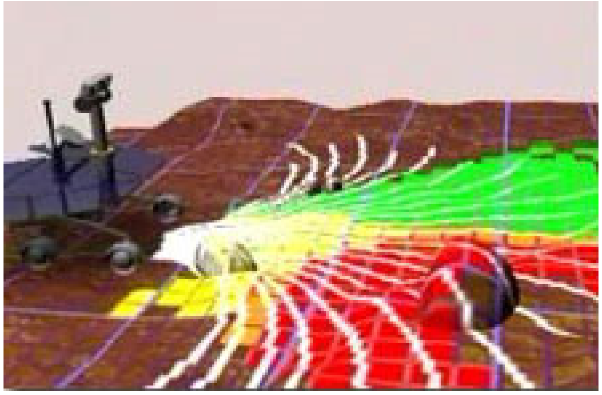

**Figure 3.1-1.** MER/MSL autonomous navigation technique of evaluating terrain traversability along discrete arcs in the imaged terrain. This algorithm is called GESTALT (Grid-based Estimation of Surface Traversability Applied to Local Terrain).

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
- 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.

## 3.2 Extreme Terrain Mobility

Extreme terrain mobility refers to surface mobility over extreme topographies and different soil 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. Liquid environments as found in Titan can also be considered extreme terrains. While other extreme environmental conditions may also be present at sites, such as high temperatures on Venus, technologies to address these extreme environmental conditions are not addressed here but in an earlier assessment in this series.[6]

Extreme terrain mobility covers capabilities that enable access to the sites, in and out of those terrains, 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.

Figure 3.2-1 shows the Axel rover descending a 20-meter cliff face with slopes ranging from 65° in angle to near vertical at a quarry in Canyon Country, California.

While progress has been made with extreme terrain mobility for terrestrial applications, and the MERs have explored the sides of craters, to date, there has been no planetary mission that has attempted access to geologic features such as cliffs. State-of-the-art surface exploration

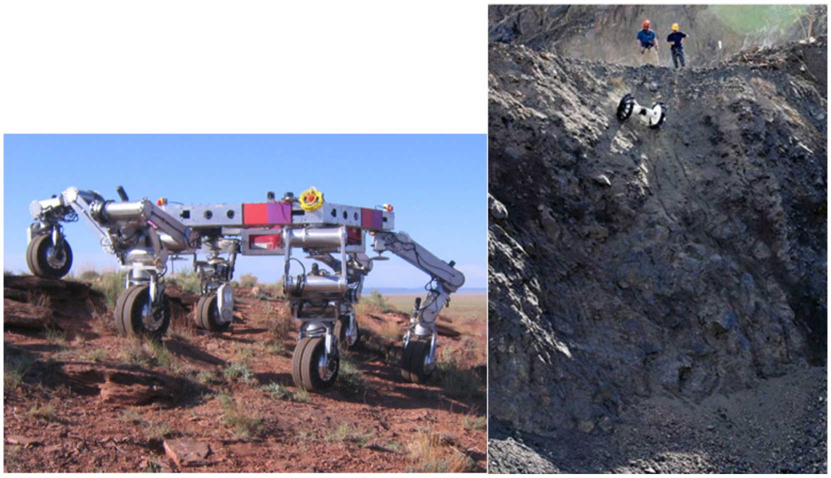

**Figure 3.2-1.** ATHLETE and Axel rovers descending steep slopes.

platforms are designed to operate on relatively flat terrain (less than 20° for the MERs and less than 30° for the MSL rover).

As was noted in the National Research Council (NRC) report, "higher degrees of mobility serve to complement autonomy."[7] Additionally, technologies such as precision and pin-point landing 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 soil properties may be critical. Unique localization requirements exist for a floating vehicle on a Titan lake because of the lack of surface references.

Many of the most scientifically compelling sites are found in terrains that are currently inaccessible to state-of-the-art planetary surface explorers. Most significantly, the ground mobility systems deployed to date are focused on horizontal mobility. There are many science investigations that require vertical access.

The key areas of technology needs for extreme terrain access include traverse to designated targets in extreme terrains, retro traverse for captured samples, traversability analysis and motion planning, anchoring and de-anchoring, docking and undocking, control of tethered platforms, and high-fidelity terrain modeling and simulation of extreme terrain mobility.

## 3.3 Aerial Mobility

Aerial vehicles (HTA = heavier than air, LTA = lighter than air) are in situ mobility platforms that can support science investigations of planetary atmospheres and near-surface regions at a regional or global scale. Typical measurements include atmospheric structure (composition, temperature, pressure, wind fields, solar and infrared fluxes), atmospheric phenomena (storms, lightning), aerosols, magnetic and electrostatic fields, surface imaging and subsurface radar soundings, and surface sampling for onboard analysis.

There have been two aerial vehicles flown outside of the Earth's atmosphere, the two VEGA balloons deployed at Venus in 1985 by the Soviet Union. These were helium-filled, super-pressure balloons that successfully flew at an altitude of 51–53 km for two days. The VEGA vehicles were uncontrolled, wind-driven balloons that travelled for thousands of kilometers during their missions. Localization and wind measurements were provided by radiometric tracking from Earth-based ground antennas.[8]

There have been many proposals for other aerial vehicle missions to Venus, Mars, and Saturn's moon Titan (Figures 3.3-1, 3.3-2, and 3.3-3), including different kinds of LTA vehicles, airplanes,[9,10,11,12] and rotorcraft.[13] No such missions have been attempted, but research on different kinds of LTA vehicles and on Mars airplanes have achieved substantial technology development. One conception of a Mars airplane is shown in Figure 3.3-2. Generally, LTA vehicles are more suitable for long-duration missions as they do not expend limited onboard energy staying aloft. Options for LTA vehicles include free-flying balloons such as the VEGA probes mentioned earlier, Montgolfière or hot-air balloons that have some degree of


**Figure 3.3-1.** Titan blimp.

altitude control, airships (blimps) that have onboard engines and flight control, and hybrid systems such as a Montgolfière with engines for horizontal control.

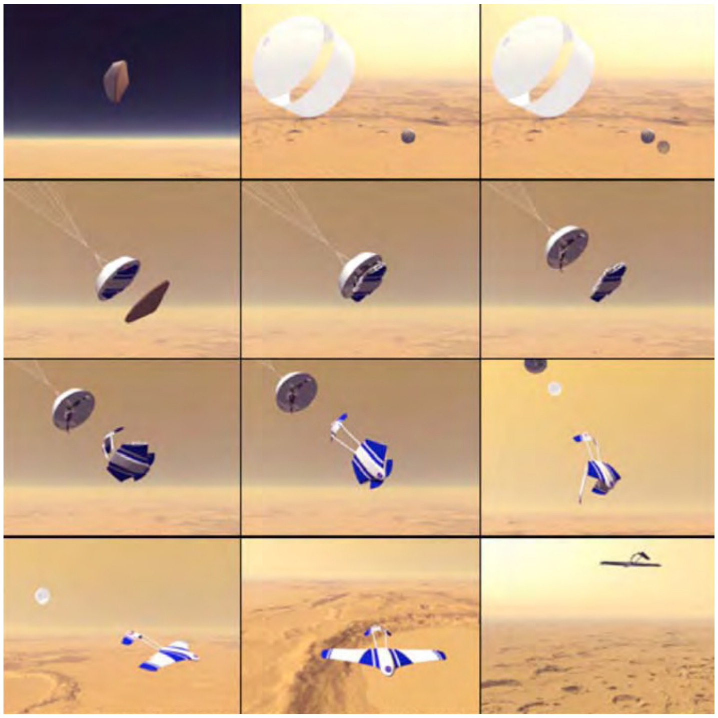

**Figure 3.3-2.** Mars airplane.

Montgolfière balloon technology is used to provide altitude control in missions to Titan (see Figure 3.3-3, also showing a depiction of the lake lander). The analogous technology for Venus is the reversible fluid aerobot. This exploits the unique conditions in the middle atmosphere of Venus where temperature and pressure conditions permit two low molecular weight fluids (water and ammonia) to be in gaseous state at lower altitudes and return to a liquid state at higher altitudes. The balloon cycles between those altitudes enabling sampling in different cloud layers. Aerial deployment is also a more efficient solution to a mechanical-based deployment in terms of the payload fraction with respect to Venus entry mass.

**Figure 3.3-3.** Montgolfière circumnavigating Titan, with lake lander.

A key challenge is adapting aerial vehicle technology developed for Earth to the extreme environments found on other worlds—Mars has a very low-density atmosphere (~7% of Earth), Titan is cryogenically cold with a surface temperature of 94°K, and Venus has sulfuric acid in the atmosphere and extremely high pressures (92 atm) and temperatures (450°C) close to the surface. Therefore, much of the technology development has focused on the mechanical and thermodynamic aspects of aerial vehicles, such as suitable materials for extreme environments, robust designs for long-duration missions, and insertion, deployment, and inflation in the atmosphere. Figure 3.3-4 shows the operational scenario of a proposed Titan Montgolfière mission. Some work has been done on GN&C, concentrated primarily on autonomous flight control, image-based motion estimation and localization, and surface sampling for powered flight vehicles, as well as on wind-assisted mission planning for LTA vehicles.

Table 3.3-1 summarizes the GN&C-related characteristics of different aerial mobility systems.

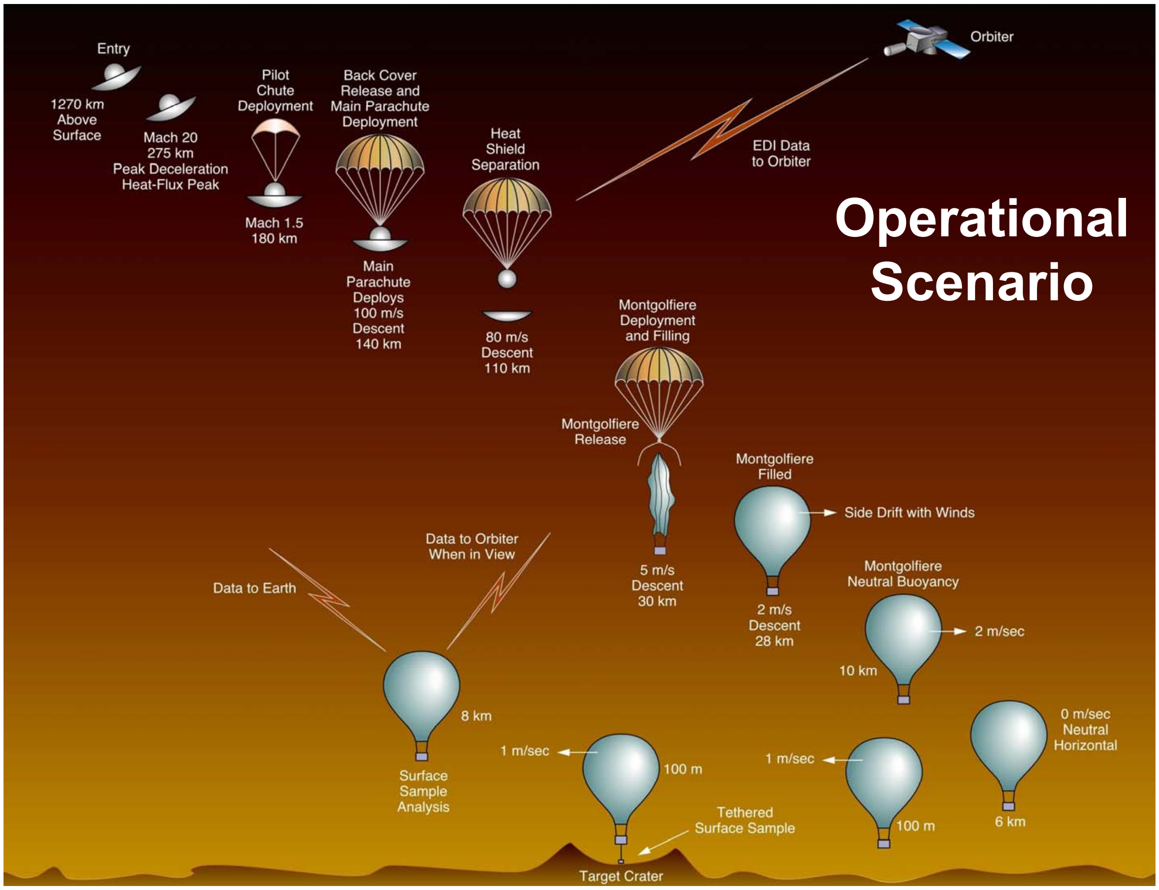

**Figure 3.3-4.** Titan Montgolfière operational scenario. Reprinted from "Titan Montgolfière Mission Study."[14]

**Table 3.3-1.** GN&C-related characteristics of different aerial mobility systems.

| | Venus Balloon | Titan Balloon | Airship | Airplane | Rotorcraft |
|---|---|---|---|---|---|
| Precise Global Localization | √ | √ | √ | √ | √ |
| Altitude Control (ascent control) | √ | √ | | | |
| Autonomous Flight Control (6 dof) | | | √ | √ | √ |
| Efficient Operations | | | √ | √ | √ |
| Planning with Uncertainty | √ | √ | √ | √ | √ |
| Long-term Wind-assisted Navigation | √ | √ | | | |
| Hazard Detection and Avoidance (Ground and Atmospheric) | | | √ | √ | √ |
| Modeling and Simulation | √ | √ | √ | √ | √ |
| Pointing and Stabilization of Antenna for Communication | | √ | √ | √ | √ |
| Aerial Vehicle Deployment in the Atmosphere | √ | √ | √ | √ | √ |

GN&C technology needs for aerial vehicles span a broad range depending on the mission scenario. The very simplest balloons require no onboard GN&C capability at all. These are the passive, wind-driven balloons that fly wherever the winds take them and that have no ability to control their flight path or to actively steer onboard instruments or antennae. The VEGA balloons were in this category. One important caveat is that even these simple balloons typically require after-the-fact knowledge of the trajectory of the balloon in order to allow geographical registration of the scientific data acquired. The VEGA approach was to track the balloon with Earth-based radio antennas using the balloon's own radio transmissions. Although of not particularly high accuracy, this approach is certainly possible for future aerial vehicle missions to Venus and Mars. The large distance to Titan will likely require an alternative approach based on tracking from an orbiter coupled with onboard localization techniques.

Any aerial vehicle that can control its trajectory requires a collection of GN&C capabilities to enable stable and safe flight. Autonomous operation is a central requirement given the long round-trip communication latencies, bandwidth limitations, and communication blackouts due to rotation of the planet or moon being explored, such as occultation of Titan by Saturn. These issues preclude effective teleoperated control from Earth. The list of required capabilities includes vehicle flight control, robust vehicle safing, regional and global localization, path planning and trajectory following, surface and atmospheric hazard detection, identification and avoidance, close-to-surface operation for surface sampling, and wind-assisted navigation. While terrestrial experience with unmanned aerial vehicles (UAVs) can inform planetary aerial GN&C, Earth-bound UAVs are typically navigated using a global positioning system (GPS), autonomous control can be overridden by remote human pilots, flight missions are only launched when atmospheric conditions are favorable, and vehicles can return to base for maintenance. Planetary aerial vehicles must operate without GPS or any of these other favorable conditions mentioned, and this places a much greater burden on developing autonomous navigation and guidance functionality.

The GN&C needs become even more challenging if the aerial vehicle will be operating near, or even landing on, a planetary surface. Various Terrain Relative Navigation (TRN) techniques are required including precision altitude estimation (barometric or radar altimeter) and vision-based approaches for hazard detection, motion estimation, science site selection and identification, and landing and/or surface sampling. Near-surface aerial vehicle control systems must be robust to the effects of atmospheric turbulence, especially for large balloon or airship vehicles that are very sensitive to wind gusts.

Some types of LTA vehicles achieve a limited form of trajectory control without propulsion systems. The classic example is an altitude-controlled hot air balloon (Montgolfière) that changes altitude by opening a valve on top of the balloon to release hot air and thereby modulate the buoyancy. Since a planetary wind field has different wind velocities at different altitudes and geographic locations, it is possible to target distant locations for over-flight by following the right combination of winds over time. This is an unusual path planning function that requires real-time localization, continuously updated wind predictions, and robustness to the stochastic nature of planetary winds. To enable this approach, information from Global Circulation Models (GCMs) has to be combined with wind field updates obtained in situ. This kind of wind-driven navigation capability is also of value to optimize the flight of self-propelled aerial vehicles, given the large effect of winds on trajectories spanning hundreds or thousands of kilometers.

As already mentioned, another key challenge for aerial exploration vehicles is determining their location in global coordinates and in real time. While Earth-based radio tracking methods could provide rough localization estimates for Mars, accurate global registration will increase substantially the value of the science data being collected. For aerial vehicles capable of active flight control, this is even more essential, as it will enable the vehicle to plan trajectories to specific science sites (chosen from orbital imagery, for example), and subsequently approach, survey, and potentially collect surface samples from these sites. For Venus and Titan, where the atmosphere is optically thick, radar-based imagery has been proposed. It is likely that a different mix of methods will be used depending on the target (Mars, Venus, or Titan) and on the orbital assets in place. An aerial vehicle on Titan, for example, could combine tracking data from an orbiter, from an onboard Earth-pointing communications antenna, and from a multi-resolution and multi-modal image registration system, where low-altitude local visual maps, high-altitude regional visual maps, and orbital radar and/or thermal imagery would be registered to each other. Additional sources of information that could be explored include visual identification of the centroid of the silhouette of Saturn in the sky.

Another GN&C need is for attitude estimation and control. This can be for pointing of scientific instruments at surface targets, orienting the vehicle properly for propulsive flight or aiming high-gain radio antennas for communication. All but the simplest balloon missions (like VEGA) will require one or more of these pointing abilities.

Because very little is known of the environments on Venus and Titan, there will be uncertainties about the actual performance of an aerial vehicle that has been inserted into their atmospheres. Extensive Earth-based testing, as well as modeling and simulation of aerial vehicle performance in a different atmosphere and gravity, is essential. However, online estimation of system parameters and performance measurements of the vehicle will have to be conducted in situ once it has been deployed. For long-duration missions, where the vehicle characteristics and performance can be altered by wear and/or environmental conditions, system identification and performance measurements will need to be repeated on a regular basis.

Airborne vehicles operating below the cloud cover would provide the first opportunity to conduct very high-resolution mapping surveys of Venus and Titan. While this by itself is of great scientific interest, the ability to interact with the surface and extract samples that could be analyzed onboard would add enormous science value to these aerial missions. Surface sampling is difficult to execute with fixed-wing aircraft, but LTA vehicles that fly more slowly and can potentially hover (airships or powered Montgolfière balloons) or be anchored for a period of time (balloons) are ideal for this purpose. Surface access will require the vehicle to operate at relatively close distances to the ground (probably on the order of tens to hundreds of meters) and be able to deploy and retrieve sampling devices. Other required technologies include accurate navigation, so that pre-selected science sites can be approached, and/or some degree of autonomous science, namely the ability to detect desirable sampling sites in real time and in flight and to deploy sampling devices as appropriate.

Obstacle and hazard detection for aerial vehicles is also quite different from surface vehicles. Flight trajectory planning and control has to take into account both the local topography and the atmospheric conditions. Hills or mountains, for example, can generate up- or downdrafts, and close-surface sampling operations should not be done under turbulent conditions. More broadly, storms such as those observed on Titan can create wide-scale changes in wind patterns and potentially endanger the vehicle, so that early detection and avoidance maneuvers would be essential. Safe trajectory planning and control presuppose availability of orbital and onboard instruments that can help detect atmospheric events.

Another major challenge is the insertion of the aerial vehicle in the atmosphere. Although there are some similarities between EDL of ground platforms and entry, descent, and flight

(EDF) of aerial platforms, there are others aspects that are unique. Many mission scenarios foresee that airborne platforms would not be brought down to the planetary surface and then inflated (if relevant) and released, but would instead be inflated during descent (if relevant) and then released into the atmosphere before touching the surface. This approach is generally seen as less risky and the only practical alternative than having an airborne platform operationalized on an unknown surface. While EDL is beyond the scope of this document, EDF is within its scope, as it involves the very complex interactions between the aerial system that is descending and is being rendered operational, and the atmosphere within which it is being deployed.

## 3.4 Small Body Mobility

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 NEOs, asteroids, comets, and planetary moons (e.g., Phobos, Deimos, Enceladus, and Phoebe).

The NRC has designated technologies for small body mobility as a high priority for NASA given its destination potential for human spaceflight, which would likely require precursor robotic missions. 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 (SBAG).[15] Specific technology needs include novel mobility systems together with associated control techniques and novel localization techniques.

For science missions, an in situ spatially extended exploration of small bodies would mainly fulfill the objectives in the Building New Worlds theme.[16] 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.[16]

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. Microgravity mobility could include hoppers, wheeled, legged, hybrid, and other novel types of mobility platforms. 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. Figure 3.4-1[17] shows several design choices of various surface locomotion systems in different gravitational fields.

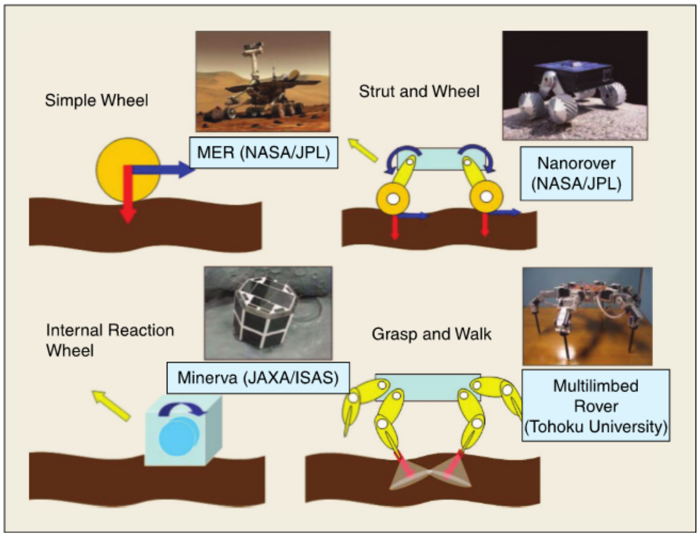

**Figure 3.4-1.** Design choices of various surface locomotion systems in different gravitational fields. © 2009 IEEE. Reprinted, with permission, from "Achievements in Space Robotics," *IEEE Robotics & Automation Magazine*.[17]

While there have been several attempts at small body surface mobility, to date, no such system has successfully explored the surface of a small body. In 1988, the Soviet Union's Phobos 2 mission hosted a 41-kg PROP-F robotic hopper, which would have used spring-loaded legs to hop around Phobos's surface. Unfortunately, when Phobos 2 was within 50 meters of the Martian moon, communication with the spacecraft was lost before PROP-F was deployed. A second mission, Japanese Aerospace Exploration Agency's (JAXA) Hayabusa, was originally planning to carry JPL's Nanorover, a four-wheeled rover with articulated suspension that was capable of roving and hopping. However, due to budgetary reasons, the rover was canceled. Subsequently, JAXA/Institute of Space and Astronautical Science (ISAS) developed the MINERVA rover, which was a 591-gram hopping rover that used a single flywheel mounted on a turntable to dynamically shift the center of gravity and control the direction of the hop. Both the Nanorover and the MINERVA hopper were solar-powered systems and hence had very limited power and computation. Unfortunately, the deployment of the MINERVA rover failed.

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. 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 mission 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 and 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, which hops from place to place on the surface, or a legged or wheeled vehicle that remains in contact with the surface. This should be the subject of a trade study where issues like the size of the body, the surface material composition, the ease of sampling, and the types of science that are being studied are all part of the assessment.

Novel mobility systems together with associated control techniques would be capable of operating on a range of heterogeneous terrain types. They would also include techniques for localization of surface assets given the discrete nature and pose uncertainty resulting from hopping and tumbling operations. Since surface assets are likely deployed by a host spacecraft, advances in control strategies that would exploit synergistic operations between the mother-craft and the deployed surface assets could enhance asset localization, mapping, and motion planning, and reduce the computational requirements on the power-constrained surface assets. Furthermore, algorithmic advances that reduce computational requirements while improving perception, mapping, localization, and navigation, are key elements for exploration and surface operations of small body assets. For tumbling platforms, advances in controls that enable more precise control of the orientation of assets on the surface would allow greater flexibility in placing instruments and acquiring measurements at designated locations. Data fusion between surface assets and the mother-craft in light of uncertainty of the information from the surface asset would be critical. Unlike typical rover developments for larger bodies, development of microgravity technologies requires specialized testbeds, which are expensive and have operational constraints. As a result, the development of high-fidelity simulations and the cross-validation of the simulations with results from the experimental testbeds and microgravity test environments would be critical.

### Anchoring

Anchoring and de-anchoring are two of the key areas of technology investments for small body mobility and extreme terrain access. Some proposed anchoring scenarios are depicted in Figure 3.4-2. Effective small body and extreme terrain exploration requires vehicle/astronaut anchoring due to extremely low gravity or extreme topography. Simulation and testing must be carried out with implications on system/mission design, system verification and validation, design of combined vehicle/human/robot teams, and design of proximity operations such as landing, tethered operations, surface mobility, drilling, and sub-surface sampling. Extra-vehicular activity (EVA) requires innovative tethering/anchoring techniques for the astronauts to move in the vicinity of a small body. In all these cases, a motorized winch network could provide support for astronaut surface operations. A motorized winched network also provides the vertical reaction force needed for drilling and sample collection. Robot arm sampling device interactions with terrain during sample collection also need to be understood. Hopping/crawling robots may interact with regolith material on the surface of the planetary body and can hop at various angles with adjustable strengths to achieve a desired vertical height or horizontal distance. In all these cases, an anchoring process is involved. Anchors may be used as hand- or footholds, or possible attach points for ropes that hold an astronaut or equipment to the surface.

All the asteroids that have been observed at close range appear to be covered by meters of weakly bound regolith, in which case the anchor pull-out capacity is dependent on the weight of the overlying material. Large asteroids typically spin slowly and may have more loose material on the surface than small bodies, which tend to spin faster. This understanding implies that, in general, slow anchoring methods such as those based on drilling or frozen soil melters will require the spacecraft Attitude Control System (ACS) to be involved for vehicle stabilization. Conversely, fast anchoring methods such as those based on tethered spikes, telescoping spikes, and legged platforms with tethered or telescoping spikes will likely require less spacecraft ACS involvement, but more GN&C involvement from a dedicated mobility control system. Early

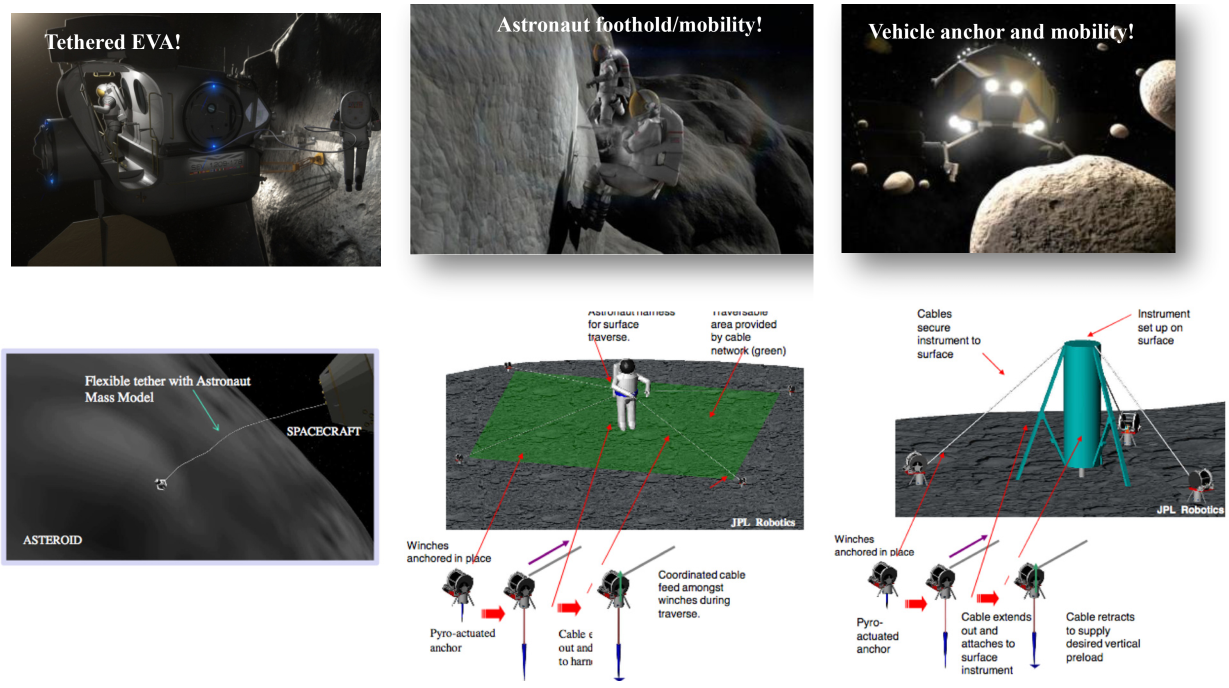

**Figure 3.4-2.** Anchoring scenarios.

studies on anchoring for the ST4/Champollion mission selected a 1-kg, 1.9-cm-diameter truncated cone penetrator for anchoring onto the surface on materials of strength up to 10 Mpa with a 45 degree impact angle within a reasonable velocity range (100–200 m/s) and a minimum pullout resistance of 450 N in any direction.

Several anchoring deployment/retrieval issues that can impact the GN&C subsystems and mission design must be carefully considered. An anchor may ricochet adversely on the surface instead of solidly emplacing within the ground. Also, drilling a helical anchor requires a torque transfer to another object. For example, Philae's landing gear uses ice screws and three landing legs with two pods in each. Harpoons can be easily launched before landing. More than one anchor needs to be deployed from the spacecraft to ensure static stability. Spacecraft ACS [reaction wheels, not Reaction Control System (RCS)] will probably need to be on during the anchoring phase to avoid slack cables and vehicle stability problems. Some anchor designs will allow them to be pulled out, others will not.

## 3.5 Sampling Acquisition and Transfer

The process of retrieving, collecting, and packaging a sample for a purpose such as sample return must be distinguished from the kind of manipulation used in an in situ mission. 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 is safely placed for subsequent analysis (either in situ, or for transfer back to the Earth). Figure 3.5-1 indicates how the principal GN&C functions are integrated in a sample collection event. The yellow box denotes the functional areas relevant to this report, and the number of red dots indicates those areas requiring more technology development than others. Furthermore, there are significant differences between sampling on bodies with significant gravity and sampling on small bodies with little gravity. Amongst small bodies, there are differences between sampling comets and sampling asteroids. For instance, sampling of small bodies takes place in an environment where

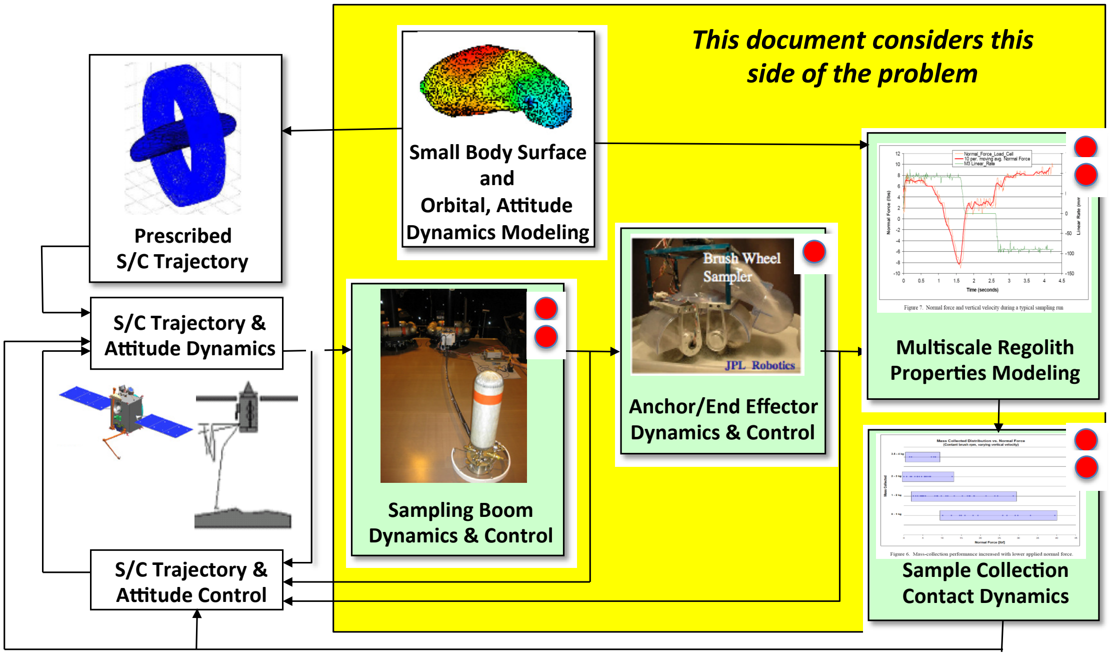

**Figure 3.5-1.** Integration of GN&C functions in small body sampling. Reprinted from "Modeling and Simulation of Anchoring Processes for Small Body Exploration,"[18] Copyright © 2012 AIAA.

**Table 3.5-1.** Differences between NEO and Moon. Reprinted from "Modeling and Simulation of Anchoring Processes for Small Body Exploration,"[18] Copyright © 2012 AIAA.

| Phenomena | Moon | NEO |
|---|---|---|
| Gravity | Higher order harmonics from mascons (at the milliGal level) | Polyhedral gravity models |
| Surface Acceleration | Same as gravity acceleration | Order of magnitude variations |
| Orbital stability | Long term drift due to mascons | Mix of stable and unstable orbit "families" |
| Target Body Orbital Period | ~30 day period | Hours |
| Porosity | Small | 30-50 % |
| Morphology | Planet-like | Rubble pile |
| Regolith mechanical properties | Friction dominated – like sand / rocks | Cohesion dominated - like bread flour ? |
| Interesting surface features | Rocks, craters | Rocks; electro-statically generated dust ponds; large-scale cohesively bound structures |

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) micro-gravity and solar radiation dominate system behavior prior to end-effector soil engagement/anchor penetration. Table 3.5-1 shows the differences between the environment at a NEO and at the Moon. Conversely, for sampling at the surface of bodies with significant gravity fields (Moon, Mars, and Venus), the weight of the sampling device and the landing platform can be used as an advantage in sample acquisition. Table 3.5-2 summarizes the GN&C-related characteristics of different sampling mechanisms discussed in this section.

The technology for sample acquisition and handling could be classified according to: a) Continuous Drill Depth (Very Shallow [<20 cm], Shallow [20 cm–3 m], Moderate [3–5 m], Deep [>5 m]); b) Required Sample Type (Powder, Cuttings, Core, Down-hole Measurements); c) Gravity (Microgravity, Low Gravity [e.g., Moon], Moderate Gravity [e.g., Mars]); d) Degree of Human Interactivity (Autonomous Operation, Tele-robotic Operation, Real-time Human-in-the-Loop); e) Physico-chemical Cleanliness (Cross-contamination Tolerated, Minimal Cross-Contamination, No Cross-Contamination); and f) Biological Cleanliness.

**Table 3.5-2.** GN&C-related characteristics of different sampling mechanisms.

|  | Close Proximity Sampling |  |  |  | Projectile-Based Sampling |  |
|---|---|---|---|---|---|---|
|  | Brushed Wheel Sampler | Sticky Pad | Drill | Corer | Tethered Harpoon | Dart and Pellet Gun |
| Force-torque Sensing | √ | √ | √ | √ |  |  |
| Efficient Operations | √ |  | √ | √ | √ | √ |
| Planning with Uncertainty |  |  |  |  | √ | √ |
| Terramechanics | √ | √ | √ | √ | √ | √ |
| Modeling and Simulation | √ | √ | √ | √ | √ | √ |
| Anchoring |  |  | √ | √ |  |  |
| Onboard Sampling Control | √ |  | √ | √ |  |  |

### 3.5.1 Integration of GN&C Functions with Sampling Acquisition and Transfer

**Figure 3.5-2.** The Phoenix lander pushed a rock 0.5 m into a trench excavated below it using the scoop, to reveal the surface underneath. Reprinted from "The Phoenix Mars Lander Robotic Arm,"[19] Copyright 2009 IEEE.

Figure 3.5-1 summarizes the integration of the various GN&C functions in small body sampling in the form of a functional block diagram. The block diagram shows each element of the integrated model of spacecraft and end-effector dynamics, which includes the models of the planning function, where the spacecraft trajectory and attitude are specified; the vehicle attitude and orbital dynamics; the vehicle GN&C functions, including orbital and attitude estimator and navigation filters; the deployable manipulator dynamics and hinge actuation; the end-effector, anchoring, or in situ sampling device dynamics and actuation; the small body shape, orbital dynamics, and polyhedral gravity models; the communication, power, and lighting geometric analysis; the multi-scale properties of the surface regolith; and the interaction of the end-effector, anchoring, or in situ sampling device with the surface regolith. The block diagram includes feedback loops to the spacecraft controller from the hinge states of a deployed robotic manipulator, the end-effector states, and the amount of mass collected, assuming all these states are known. If not known, they could be estimated. The reason for including these additional functions is that sensing these states are all possibilities in a scenario where an algorithm is needed to monitor the duration of the sample event (dwell time), and a change in each one of these states can be used as a trigger to terminate the event.

The approach used by the Phoenix lander is an example of integration of 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 the paper "The Phoenix Mars Lander Robotic Arm,"[19] which highlights the methodology used in controlling the motion of the arm and executing complex trenching operations while efficiently handling faults and anomalous events. Figure 3.5-2[19] shows an image taken by the Phoenix lander, which pushed a rock 0.5 m into a trench excavated below it using the scoop, to reveal the surface underneath. Since hardened soil material frequently impeded motion of the arm during digging and scraping activities, autonomous recovery from these events was enabled in the flight software and command sequences. This permitted subsequent arm operations to continue without ground operator intervention saving valuable sols that would otherwise have been used for recovery operations. The Phoenix robotic arm (RA) was used to point the robotic arm camera to take images of the surface, trenches, samples within the scoop, and other objects of scientific interest within its workspace. Data from the RA sensors during trenching, scraping, and trench cave-in experiments were also used to infer mechanical properties of the martian soil.

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."[20] In this paper, an innovative solution for sampling and mobility in near zero-g environments has been proposed, based on an omni-directional anchoring mechanism that can withstand over 100 N of force in all loading directions on natural rock surfaces.[20] 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.

Utilizing force sensing and active compliance during sample collection has also been proposed,[21] and is another example of close integration between the GN&C functions and the sample collection dynamics. This solution allows the sampler to contact and penetrate the surface while the spacecraft is far away from it, and dramatically increases the likelihood of successful sample collection and return of pristine samples to Earth, with great benefit to planetary science. Small body sampling from a long stand-off boom not only poses lower risk to the spacecraft, but allows for longer sampling durations and depths than possible with existing articulated arms and booms in closed proximity of the surface, and for sampling multiple times at multiple locations for a fixed spacecraft position.

### 3.5.2 Small Body Sampling

Most of the current prototypes for small body mobility cannot achieve targeted sampling. For example, NASA, the Russian Space Agency (RKA), ESA, and JAXA have all recognized the advantages of hopping on small bodies. However, ESA's hopper prototype 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 MINERVA lander (that hops by rotating a single flywheel mounted on a turntable and did not succeed during its deployment) do not allow for precise traverses to designated targets.

There are various architectures possible for a small body sampling mission. The use of counter-rotating brushes to acquire surface samples has been proposed for small body missions.[22,23] Figure 3.5-3 shows a typical sampling event of the brushed-wheel sampler during micro-gravity testing, which demonstrated the ability to fill the sample canisters in approximately 2 seconds.[23] Sticky pad samplers utilize an adhesive, which sticks to surface regolith.[22] 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. Similar to a sticky pad is the OSIRIS-REx mission concept of releasing a high-pressure gas into the surface upon contact and then capturing material that is forced up into the sampling tool.[24] Honeybee robotics has suggested using high-pressure gas to force regolith into a tube and then into a sample canister.[25]

Utilizing a rover-mounted harpoon to collect samples from Mars cliffs and a balloon-mounted harpoon to sample the surface of Titan has been proposed.[26] Goddard Space Flight Center (GSFC) has proposed using a harpoon sampler for comet sampling.[27] The Hayabusa mission fired a projectile into the surface to dislodge surface material, which was captured.[28]

**Figure 3.5-3.** A typical sampling event during micro-gravity testing demonstrated the ability to fill the sample canisters in approximately 2 seconds. Reprinted from "The Brush Wheel Sampler – a Sampling Device for Small-body Touch-and-Go Missions,"[23] Copyright 2009 IEEE.

Small body sampling using an untethered penetrator was proposed by Lorenz[29] and analyzed for various applications.[30]

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.

### 3.5.3 Proposed Systems for Sample Acquisition

Several sampling systems have been developed for planetary sample acquisition. Some of these systems require more autonomy than others.

#### 3.5.3.1 Soft Terrains

The Brushed-wheel Sampler (BWS) developed by JPL works by plunging down into the terrain, which is collected by the counter-rotating brushes spinning at 1000 rpm. Tests were done at variable microgravity in the KC-135 airplane parabolic flight tests. BWS is well suited for coarse terrain, and heterogeneous material of up to 3-cm-diameter rocks.

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.

#### 3.5.3.2 Hard Terrains

Another option is the pellet gun, which flew on board the MUSES-C spacecraft. The pellet gun is a sampling device used in the MUSES-C (Hayabusa) asteroid mission. Figure 3.5-4 shows the Hayabusa sampling system.[28] 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. Also, a hopping rover called MINERVA was deployed, but never made it to the surface. Since 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 second after the tip of the sampler horn touched on the asteroid surface, a projectile of 5-g mass was shot at 300 m/sec by a small projector onto the asteroid surface.[28] Impact of the projectile produces surface

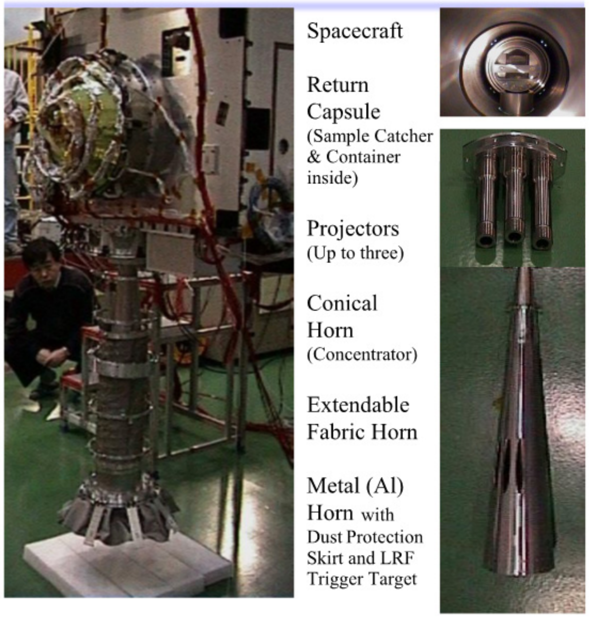

**Figure 3.5-4.** Hayabusa sampling system. Reprinted from "Sampling Systems for Hayabusa and Follow-on Missions: Scientific Rationale, Operational Considerations, and Technological Challenges."[28] Image courtesy of JAXA, Copyright 2009.

ejecta, which was concentrated through a conical capture horn toward the sample catcher. The catcher was transferred into the reentry capsule, which was hermetically sealed. Although the Hayabusa sampling mechanism did not function as planned, asteroid samples were successfully collected and returned to Earth.

For even harder terrain like basalt, a core sampling or drilling mechanism is better. Honeybee Robotics developed the MiniCorer for possible use in an MSR mission.[31] Honeybee Robotics also developed the Corer Abrader Tool (CAT) for NASA as a potential tool for the MSL mission when the mission was still considering the collection of rock cores.[32] The MSL mission drills and collects powder.[33] The MiniCorer and CAT are both rotary drag coring tools and push the sample out the front of the sampling tool using a push rod. The Sample Acquisition Tool (SAT) was developed at JPL.[34] The SAT tool utilizes rotary percussion for coring and a sample is acquired directly into a sample tube in the bit. Bit change-out transfers the sample to a caching element, which removes the sample tube and replaces it with a new sample tube.

### 3.5.4 Caching

Several concepts have been proposed to encapsulate and store the samples for return to Earth. Cadtrak Engineering proposed to insert a sample sleeve made from heat shrink tubing material into a coring bit.[35] The heat shrink tubing would be heated to encapsulate the sample. The encapsulated sample would then be transferred to a sample canister. JPL proposed to acquire a sample directly into its sample tube.[36,37,38] Honeybee Robotics proposed to return a sample in its coring bit.[39,40] A Surface Sample-Handling System was proposed for a potential ESA MSR mission.[41] An integrated scoop, sieve, and canister approach was proposed for a lunar sample return mission.[23] In situ missions prepare and transfer samples to science instruments as implemented for the ESA RoLand/Philae (Rosetta) mission,[42,43] MSL mission,[33] and proposed for the ESA ExoMars mission.[44]

There are various possible architectures for caching.[36] Three primary caching architectures have been proposed: 1) a cache canister, 2) returning the sample inside the coring bit, and 3) transferring the sample using bit change-out. First, for an architecture where a core sample is pushed out the front of the sampling tool, the sample could be pushed directly into a sample chamber in a cache canister.[38] Second, Honeybee Robotics has suggested an architecture where a sample is returned in the coring bit in which it was acquired.[39,40] Third, JPL developed the Integrated Mars Sample Acquisition and Handling (IMSAH) architecture where a sample is acquired directly into its sample tube in a sampling bit and transferred to the caching element using bit change-out.[36,38,45] The sample tubes are sealed and placed in a cache canister, which results in a high sample mass to cache mass ratio and minimized cache volume. In the Minimum Scale Sample Acquisition and Caching (MinSAC) version of the IMSAH architecture, the sampling robotic arm is also used for tube transfer operations to minimize the mass and volume of the SAC subsystem for small rovers.[46] The architecture also allows for hermetic sealing of samples.[47]

### 3.5.5 Drilling and Coring

Sampling the near-surface as well as sub-surface can be accomplished by either drilling or coring. Drilling is based on the hammering motion of a tool.[48] These mechanisms can be used in a variety of missions from Mars sampling to small body sampling. The Russian Phobos-Grunt mission had a hammering mechanism-based sampler.[48]

Deep drilling through rock and regolith has been demonstrated using the Drilling Automation for Mars Exploration (DAME) system.[49] A multi-segment, 2-meter-deep drill was developed for the ESA ExoMars mission.[50] Deep drilling through ice has been proposed for Mars ice caps and icy moons. Examples are the Cryobot,[51] Subsurface Ice Probe (SIPR),[52] and IceMole.[53] 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.[43]

The Heat Flow and Physical Properties Package ($HP^3$) on Insight is designed to penetrate up to 15 meters into the surface.[54]

An ultrasonic/sonic driller/corer (USDC) has been developed at JPL to acquire samples from various planets or small bodies (e.g., asteroid and comets) using low axial load and low power.[55] The drill bit not does require sharpening and can be made to operate at cryogenic and high temperatures; non-round cross-section cores can be created and it can be used to probe the ground as well as deliver in situ sensing down the borehole. The developed drills are driven by piezoelectric-actuated percussive mechanisms that require low preload (as low as 10 N), and can be operated using low average power. The drills were demonstrated to penetrate rocks as hard as basalt and in one of the designs, it was made as light as 400 g.

The Soviet Luna 24 mission of 1976 drilled 2 meters down and extracted 170 grams of lunar soil, which it brought back to Earth for analysis, taking every possible precaution to avoid contamination.[56,57] The scientists found that water made up 0.1 percent of the mass of the soil, and published their results in the journal *Geokhimiia* in 1978,[56] which unfortunately did not have a wide readership in the West.

While much can be learned from the challenges of drilling, collecting, and processing powder samples, acquisition and caching of core samples provides many unique challenges.

An important conclusion of the evaluation discussed in “Sampling Systems for Hayabusa and Follow-on Missions: Scientific Rationale, Operational Considerations, and Technological Challenges,”[28] is that *the sampler is not just one of the spacecraft sub-systems but the spacecraft itself*. Based on the lessons learned from the Hayabusa mission, the point is made that we can target the maximum science output with ample sample mass for mission design goal; yet, we must also define the minimum requirement that still justifies this mission in the worst 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 sub-systems, the pin-point landing accuracy and autonomous maneuvering capability dictates 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. The last table in “Sampling Systems for Hayabusa and Follow-on Missions: Scientific Rationale, Operational Considerations, and Technological Challenges”[28] 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 capable of stratigraphy.

The MSR campaign will include acquiring and caching samples. Sample acquisition and caching (SAC) will produce the cached samples in a canister that could be returned to Earth as part of an MSR mission campaign.[58] The potential multi-mission campaign will include the caching mission, which will generate the samples. The SAC capability includes acquisition of rock and regolith material, encapsulating them, and storing them in a cache canister that could be returned to Earth. For a caching mission, it is anticipated that samples will be about 1 to 1.1 cm in diameter by 6 to 8 cm long and would be encapsulated individually. The samples would be sealed; if possible, hermetically sealed.

A lunar sample return mission could use the sample acquisition and caching approach proposed for Mars sample if there were 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.[59] If acquisition and distribution of only regolith is needed, then a scooping approach similar to the Mars Phoenix mission might be used.[60,61]

The need for autonomy is also particularly important for time-critical missions like VISE, which have such a short duration, that in all likelihood, have to be completely preprogrammed.

## 3.6 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.

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 to either key opportunistic data acquisition or simply to better prioritize downlink of existing data products.[62] On the engineering side, this could involve the deployment of specific capabilities that eliminate the need for ground interaction such as autonomous instrument placement.[63]

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 towards each have been largely developed independently,[64,65] though some tools such as 3-D immersive visualization are readily applicable to both user communities (Figure 3.6-1).

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 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.

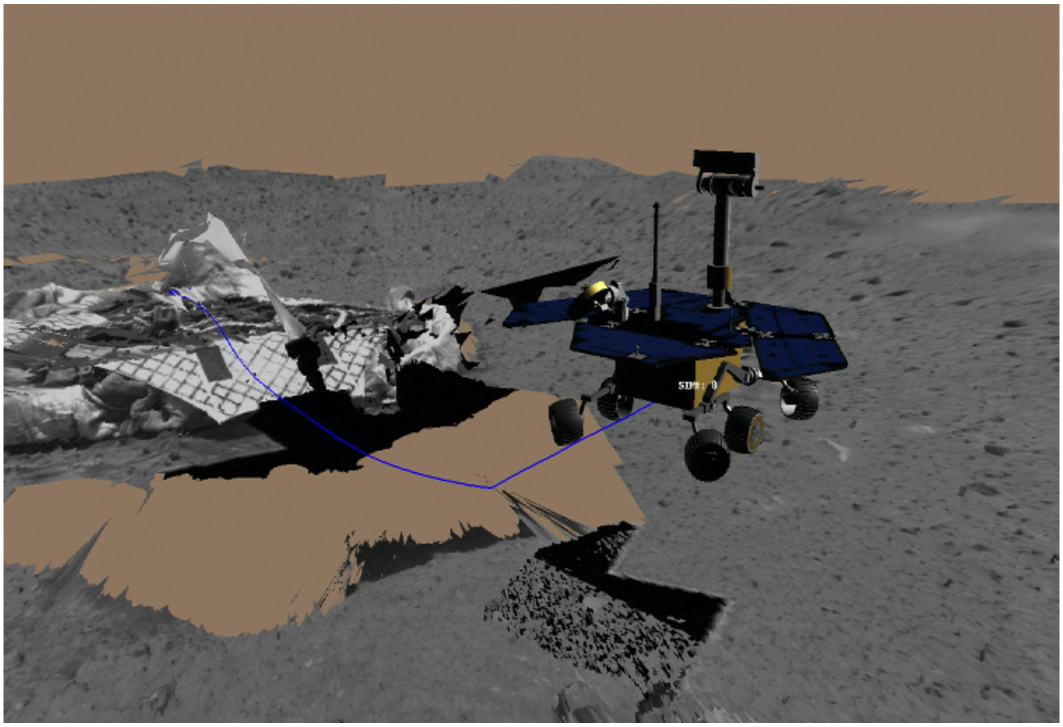

**Figure 3.6-1.** RSVP being used during MER operations to rehearse Spirit's initial drive off the landing platform. Reprinted from "Using RSVP for Analyzing State and Previous Activities for the Mars Exploration Rovers."[65]

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.[66] 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.

## 3.7 Surface GN&C Modeling and Simulation

The modeling and simulation capability is ubiquitous across all GN&C technologies. Modeling and simulation is used effectively in other fields such as aircraft design, car design, oil and gas, and other large-scale industrial processes. Such capability is mature and effective enough for spacecraft mission design.

System-level testing in a mission-relevant environment is very 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 (MBE) 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.

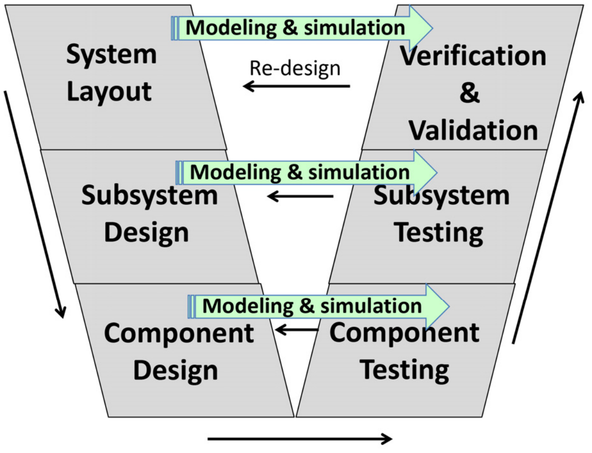

**Figure 3.7-1.** An advanced modeling and simulation capability that integrates the system behavior with the GN&C functions in the proper environment would be able to identify and retire risk early before the hardware is built.

Figure 3.7-1 depicts how an advanced modeling and simulation capability that integrates 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 Defense Advanced Research Projects Agency (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 five fold while increasing the nation's pool of innovation by several factors of 10.[67] 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.

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 (ODE), 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 (DAE).

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 will 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.

Efficient High Performance Computing (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 (Graphics Processing Unit) 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.

## 3.8 Summary

Table 3.8-1 summarizes the current and desired status of these capabilities, as well as the benefits that these desired improvements would bring to the missions outlined in the previous section.

**Table 3.8-1.** Key advances in surface GN&C capabilities.

| Surface GN&C 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<br>• 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 TRL prototypes of tethered systems<br>• JPL ATHLETE<br>• JPL Axel | • High TRL robotic prototypes capable of exploring gullies, cliffs, and caves<br>• 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 |
| Aerial Mobility | • Montgolfière balloon altitude control<br>• Autonomous flight control of terrestrial airship | • Autonomous localization and flight control<br>• Pointing and stabilization for sensing and communication<br>• Autonomous vehicle self-protection during atmospheric flight<br>• Aerial platform deployment<br>• Wind-assisted navigation and planning with uncertainty<br>• Onboard atmospheric mapping for flight planning, storm/turbulence avoidance<br>• Close-to-surface operation (for surface sampling)<br>• Efficient vision and navigation processing | • Regional and global science surveys of the surface<br>• Access to high-value science targets<br>• Close access to the surface for heterogeneous sample collection |
| Small Body Mobility | • Low TRL prototypes (e.g., NIAC hedgehog)<br>• JPL's ATHLETE<br>• JPL's Nanorover<br>• JAXA MINERVA (Hayabusa)<br>• DLR MASCOT (Hayabusa II)<br>• ESA RoLand/Philae (Rosetta) | • Instrumented mobility platforms (e.g., hover spacecraft with tethered penetrators, hoppers, wheeled, legged, or hybrid platforms)<br>• Autonomous traverses to designated targets and in situ measurements | • Access to high-value science targets<br>• Enable heterogeneous sample collection |
| Sampling and Sample Handling | • MSL SA/SPaH, PADS, DRT, CHIMRA<br>• JPL IMSAH (SHEC) prototype<br>• ASI, Honeybee, ATK designs | • Efficient cache retrieval and handoff, solid/liquid sample acquisition, handling, and distribution | • Enable heterogeneous sample collection |
| Efficient Operations | • MER/MSL state of art | • Greater operational efficiency (time and workforce)<br>• Improved situational awareness of science and operations team<br>• Greater understanding of viable operations procedures and tempo for targets with very limited communications | • Reduced mission cost and improved science |
| GN&C Modeling and Simulation | • Modeling and simulation of small mission segments<br>• Limited spatial and temporal scales | • Modeling and simulation of entire mission phases, across multiple spatial and temporal scales of operation<br>• 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 |

# 4 Surface GN&C Technologies

This section and Figure 4.1 describe key technologies that will enable the capabilities outlined in the previous section. These technologies are organized as follows:

1. Modeling and Simulation
    a. Integrated system modeling and simulation methodologies
    b. Terramechanics
2. Planning and Control
    a. Model-based control
    b. Planning under uncertainty
    c. High-speed autonomous navigation
    d. Ground operations tools
3. Sensing and Perception
    a. Range sensing
    b. Global localization
4. Mobility Systems
    a. Extreme terrain mobility systems
    b. Small-body mobility systems
    c. Aerial mobility systems
5. Sample Acquisition and Transfer

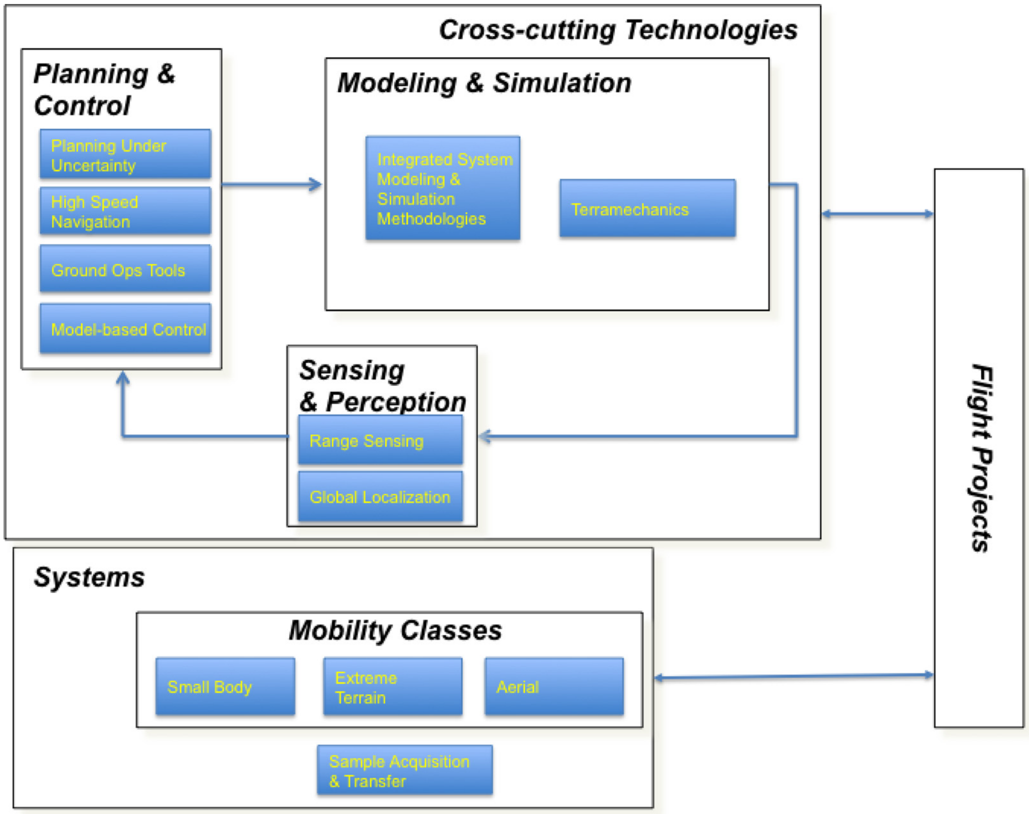

**Figure 4-1.** Relationship between findings. Cross-cutting technologies apply to all four systems in the lower box.

These technologies are defined as follows.

- *Integrated system modeling and simulation methodologies* refers to the application of mathematical modeling and software simulation technologies to functionally integrated processes that model one or more elements at various points of the design life cycle.
- *Terramechanics* encompasses the understanding of the physics of the vehicle-soil interaction.
- *Model-based control* refers to approaches to control a vehicle component or subsystem based on an understood state model of the system.
- *Planning under uncertainty* means trajectory planning that reflects quantitative estimates of sensing and control uncertainty.
- *High-speed autonomous navigation* refers to way-point guidance and hazard avoidance methodologies to navigate the vehicle.
- *Ground operations tools* encompass all the visualization and planning tools used in mission operations.
- *Range sensing* refers to sensing and computation that produce estimates of range to remote and distant features.
- *Global localization* means the determination of the position and attitude of the vehicle with respect to a specified reference frame.
- *Extreme terrain mobility systems* include unconventional mobility types targeted towards vertical access in strong gravitational fields as well as mobility on liquid and multiphase media.
- *Small-body mobility systems* include unconventional mobility types targeted towards locomotion in weak gravitational fields.
- *Aerial mobility systems* include both lighter-than-air and heavier-than-air vehicles.
- *Sample acquisition and transfer* encompasses all forms of devices and techniques to collect and place a sample from a planetary body.

Table 4-1 summarizes the mapping between those technologies and the surface GN&C capabilities discussed in the previous section.

**Table 4-1.** Technologies (rows) that impact surface GN&C capabilities (columns).

| | | Fast and Energy-efficient Rovers | Extreme Terrain Mobility | Aerial Mobility | Small Body Mobility | Sampling and Sample Handling | Efficient Operations | GN&C Modeling and Simulation |
|---|---|---|---|---|---|---|---|---|
| Modeling and Simulation | Integrated system modeling and simulation | √ | √ | √ | √ | √ | √ | √ |
| | Terramechanics | √ | √ | | √ | √ | | √ |
| Planning and Control | Planning under uncertainty | √ | √ | √ | | | | √ |
| | High-speed autonomous navigation | √ | √ | √ | | | | |
| | Ground operations tools | | | √ | | | √ | |
| | Model-based control | √ | √ | √ | √ | √ | √ | √ |
| Sensing and Perception | Range sensing | √ | √ | √ | √ | | | |
| | Global localization | √ | √ | √ | √ | √ | √ | √ |
| Mobility Systems | Extreme terrain | | √ | | | | | √ |
| | Small body | | √ | | √ | | | √ |
| | Aerial | | | √ | | | | |
| Sample Acquisition and Transfer | Sample acquisition and transfer | | √ | √ | √ | √ | | √ |

## 4.1 Modeling and Simulation

### 4.1.1 Integrated System Modeling and Simulation Methodologies

Integrated modeling of spacecraft on planetary bodies 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 spacecraft.

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 (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, multi-dimensional control trajectories that reflect complex system dynamics and environmental disturbances. High DoF robotics (ATHLETE, Robonaut) require processor-intensive control algorithms for operations in dynamic environments. Multi-core systems, GPUs, and field-programmable gate arrays (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.

Finally, while other agencies (Department of Defense [DOD], Department of Energy [DOE]) are making significant advancements in Quantification of Margins and Uncertainty (QMU) methodologies,[68] it is important to recognize here that planetary surface missions have unique environmental and autonomy requirements, which have to be defined separately. NASA should be pursuing multi-physics 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.

### 4.1.2 Terramechanics

Terramechanics, 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, will have increasing relevance to future NASA missions.

A critical component of surface GN&C is the effect of the extra-terrestrial terrain on the robotic system. How a robotic vehicle or a sampling system reacts when interacting with extra-terrestrial terrain may define the success or failure criteria for many of these missions. The MER and MSL missions demonstrate our ability to safely and successfully interact with martian terrain. This success has stemmed from significant analytical and experimental efforts in quantifying the effect of terrain mechanics on rover mobility. As future Mars missions plan to traverse more challenging terrain, quantifying effects of terrain mechanics on rover mobility will be critical for safe and successful mission execution. Similarly, modeling of terrain mechanics is critical for sample acquisition system design and operations. The success of Phoenix and the rover missions in acquiring samples is also based on significant experimental and numerical modeling of terrain mechanics arising from sampling systems interacting with these terrains. Similar experimental and modeling based efforts are needed for future Mars missions, particularly when more challenging terrains have to be considered. An example is when the wheel of the rover engages a multiphasic soil (soil with ice).

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 presence of the multi-physics environmental effects (i.e., solid-fluid, solid-gas physics). Given the complexity in the various environmental effects and the difficulty in reproducing them in laboratory settings, modeling and simulation should be effectively used to lead the analysis and augment physical testing.

## 4.2 Planning and Control

### 4.2.1 Model-Based Control

The approach in most surface 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 the 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 and ground vehicles, could greatly benefit from a model-based approach for control.

### 4.2.2 Planning Under Uncertainty

Deterministic mobility planning requires an accurate understanding of the future motion of the vehicle given a particular control input. 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 non-linear 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 very small mobility prediction error can be a very 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,[69] offline probabilistic planning methods capable of producing paths with a bounded probability of failure,[70] methods for view planning that take into account potential benefits of paths that provide improved visibility of the area towards the goal,[71] and methods specific to wind-assisted navigation planning for LTA vehicles.[72]

### 4.2.3 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 hard by design (RHBD) FPGAs, RHBD multi-core 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 recently, radiation hard FPGAs were limited to smaller fuse-based devices but Xilinx's introduction of the V5QV in 2010 offers dramatically more capable and reconfigurable devices.[73] The larger number of FPGA resources facilitates more computationally intensive processing, particularly for data parallel processing as is common in image processing. The radiation hard Maestro processor represents an alternative solution based on general purpose computing.[74] The Maestro is a 49-core RHBD processor developed by Boeing under DARPA and Defense Threat Reduction Agency (DTRA) funding and is based on the commercial Tilera processor. Lastly, the commercial world, and low-power mobile computing in particular, is pushing towards hybrid single-chip solutions that incorporate general purpose processing together with digital signal processors or FPGAs (e.g., Xilinx's Zynq and Actel's Fusion line). For some environments, the application of external fault tolerance mechanisms may enable the use of COTS components for planetary surface missions.[75] Each of these alternative means of deploying higher performance computation comes with its own set of trade-offs and the appropriate technology will vary with 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. As discussed in Section 3.1, the immediate result will be significant increases in traverse distances, energy efficiency, and mission safety. Currently, the Mars Technology Program is funding FPGA implementations of existing machine vision and autonomous navigation algorithms, and several have already been demonstrated on a research rover.[76] 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 non-geometric hazard detection (e.g., remote identification of areas of high slip), explicit consideration of uncertainty and risk in autonomous navigation, and semi-automated 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. As examples, aerial mobility-based missions can rely on significant computational horsepower to accomplish both image-based localization, as well as flight controls reflecting complex optimization criteria including quantitative measures of uncertainties in environmental conditions. 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.

### 4.2.4 Ground Operations Tools

The ground operations tools represent a critical component in optimizing science return and in attaining overall mission success, as these 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 direction 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.[66] 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),[65] are valuable for providing operators and scientists with situational awareness of the terrain in the vicinity of planetary rovers. 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 3-D 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 3-D 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.[77]

## 4.3 Sensing and Perception

### 4.3.1 Range Sensing

The MERs and MSL rover rely on fixed baseline binocular stereo imaging for both hazard detection as well as relative localization measurements.[5] Such systems have the advantage of being low power and free of moving parts. They do, however, rely on there being 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.[78] Flash LIDAR is a maturing technology that could find a role in future surface missions.[79]

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.[80,81,82]

### 4.3.2 Global Localization

Global localization will be key to a wide range of future surface missions. Much of the work to date has involved manual localization of planetary rovers[82] or TRN applied to precision landing. 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.[83,84]

For aerial missions, the spacecraft is necessarily in constant motion and hence the need for global localization is particularly acute. Relevant mission targets include Venus, Mars, and Titan. One approach is TRN, a method for estimating vehicle position and attitude by matching an observed scene against an a priori model. The models can be either actual scaled images of the intended scene or rendered views of 3-D models. Though the raw TRN kinematic data (position and pose) can be of great value, the highest value arises from the use of the raw observed feature or landmark locations in a filter that properly links all of the TRN-processed pictures through accurately modeled dynamics of the vehicle motion. Various applications of TRN techniques can address challenges such as precision altitude estimation (barometric or radar altimeter), hazard detection, motion estimation and landing, and/or surface sampling site selection.

For those environments in which the real-time sensor is of a different type from that used in forming the a priori model, more sophisticated registration methods are required. One environment where this may be required is Titan, where the thick atmosphere requires that orbital observations of the surface be taken using radar or infrared imagers. Some preliminary work on this front has been performed using mutual-information image registration techniques common in medical imaging.[85,86]

Other relevant localization technologies that require further maturation include Simultaneous Localization and Mapping (SLAM), a technique that simultaneously estimates spacecraft motion and the 3-D location of environmental features.[87] By themselves, such approaches produce only local motion estimates, but when combined with other global position measurements (such as TRN-based methods) can provide greater robustness and accuracy.

Because of the lack of surface references, unique localization requirements exist for a floating vehicle on a Titan lake, and identifying innovative navigation approaches for this type of mobility system need to be developed. One option might be a global localization system that involves a communication link with either a floating balloon or with an orbiter.

Planetary missions typically perform Earth-based radio localization and such approaches have been demonstrated to be viable for at least some surface missions. For example, the mid-1980s VEGA balloons demonstrated very long baseline interferometry (VLBI) tracking and sun sensing on Venus.[8] For terrestrial applications, there has been substantial investigation into global localization with degraded GPS measurements that fuse image-based techniques with radio-based measurements and such approaches should be investigated as well.

## 4.4 Mobility Systems and Sample Acquisition

### 4.4.1 Extreme Terrain Mobility Systems

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.

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.[88] While initial designs of the Axel robot targeted a kilometer-long tether with a 2-mm diameter, to maintain a 10-fold margin on tether strength, maintain redundancy in the number of conductors, and provide the necessary tether abrasion resistance layer, the tether ended up being 4 mm in diameter. 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.

### 4.4.2 Small Body Mobility Systems

Controlled mobility in low gravity poses very different problems from those faced by robots operating in high-gravity environments. A first challenge is the specification of mobility requirements in terms of motion accuracy, instrument pointing, and surface mechanical coupling (that is particularly problematic in micro-gravity). 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 thermo-couple, and a microscope.[89]

A second challenge is the design of motion planning algorithms for loose, dusty, and rocky terrains in low, non-uniform 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 becomes 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.[90] The JPL-developed MUSES-CN Nanorover was designed for precise mobility in micro-g 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.[91]

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 operations (in terms of perception and planning) are essentially independent of the mother ship (used as a communication “bent pipe”), which 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 usage of vision sensors, which are able to provide absolute position measurements, but could suffer from dirty optics and challenging illumination. However, by considering as an example a small hopping platform, the compact shape would severely constrain the baseline for stereo vision (hence precluding 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."[91] 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 targeted in this document, the scientific value, the magnitude of the technical challenges, and potential relevance to Human Exploration and Operations Mission Directorate (HEOMD) plans call for some early phase technology investments.

### 4.4.3 Aerial Mobility Systems

There is a large body of research and technology development for UAVs on Earth. Larger UAVs such as the Predator have been tested extensively and are flown regularly by DOD; NASA Ames Research Center (ARC) has flown a Predator modified for scientific research, the Theseus. Smaller UAVs, primarily fixed-wing (airplane) and rotary-wing (helicopter) aircraft, are used extensively both for research and for civilian applications, and a number of companies offer both UAV platforms and UAV data gathering services. Most of the commercial systems use a combination of onboard flight control for cruise with teleoperation for critical stages of flight, particularly takeoff and landing. Onboard flight control and vehicle localization typically rely on combining GPS and an Inertial Navigation System (INS), and missions are generally flown under favorable atmospheric conditions.

Far less flight control research has been done on LTA vehicles. High-altitude weather balloons (regular or super-pressure) are used very extensively on Earth, but do not have any flight control capability and are driven by the wind. Onboard instrumentation (GPS and IMU) and tracking beacons allow accurate localization of the vehicles. Experienced pilots can exert limited flight control of manned Montgolfière (hot air) balloons by controlling their altitude and taking advantage of varying wind directions at different altitudes, but very little has been done on autonomous control of Montgolfières. While some research has been done on autonomous airships (blimps), these have mostly been small vehicles not suitable for outdoor flight. Autonomous flight control of larger outdoor airships up to TRLs 4 to 5 has been demonstrated on the AURORA airships[92] and the JPL aerobots.[85,93]

A proposed rocket-driven Mars airplane would have a very short mission span and be operated more like a missile than a normal aircraft. Passive balloons for Venus, Mars, and Titan will not require autonomous flight control, as shown by the Venus VEGA balloons. A solar-powered airplane on Venus and a nuclear-powered aircraft on Titan can potentially have a long flight time in which useful planetary science data can be collected.

In 2012, Northrop Grumman Corp. initiated a feasibility study for a semi-buoyant maneuverable vehicle that could operate in the upper atmosphere of Venus. This study identified a promising approach for a maneuverable air vehicle that could explore the upper Venus atmosphere with the following characteristics: it is a semi-buoyant (6–12%) powered aircraft capable of a mission lifetime of months; the vehicle deploys/inflates in orbit and has a benign entry into Venus, requiring no aeroshell; and it has the ability to fly at altitudes between 55 and 70 km and cover a wide range of latitude, and in the event of a safe mode entry, will float at a safe altitude until recovered.

Montgolfière balloons for Venus and Titan will require altitude control, while other mission concepts, including a sun-synchronous, solar-powered, high-altitude airplane for Venus; a helicopter for Titan; and powered Montgolfières and airships for Venus and Titan will require the development of robust autonomous aerial vehicle control architectures. The requirements for an onboard autonomy architecture include the need to plan and control the flight path of the vehicle; maintain vehicle safety at all times; conduct onboard system identification and failure detection, identification, and recovery (FDIR); detect and avoid surface and atmospheric hazards; provide accurate estimates of local, regional, and global localization; and for more demanding missions, control close-to-surface operations for surface sampling, and conduct wind-assisted navigation.

Accurate localization is highly desirable for all types of aerial missions, and will require significant technology development beyond the radio tracking done for the Venus VEGA balloons. While localization on Earth is largely done fusing information from GPS and IMU devices, localization of aerial missions on Mars, Venus, or Titan will require fusion of information from multiple sources, including IMU, orbiter, and Earth fixes; multi-resolution and multi-modal image registration; and potentially other celestial fixes. At Venus, the aircraft cannot see the ground from high up, due to cloud coverage, and cannot see the Earth on the back side, where the vehicle spends most of the time, and so localization is a real problem. Today there are no COTS IMU devices that can give useful accuracy over the 2- to 3-day “ignorance” period in this scenario, and this is an area that requires further development. Perhaps there is less need at Titan provided that reasonably good feature mapping from aerial images is available, but even then, good inertial data could only help this complex problem.

Estimating aerostatic and aerodynamic performance of an aerial vehicle in an alien atmosphere will require a combination of modeling, testing in wind tunnels, Earth-based testing, and simulation of the performance on another planet or moon. Some of the existing resources that can be drawn from for this research include the high-altitude balloon flight testing program (at NASA Wallops Flight Facility [WFF] and industry), the NASA LaRC Transonic Dynamics Tunnel [TDT], and the NASA Glenn Research Center [GRC] Large Vacuum Chamber). This will have to be complemented by online, in situ system identification once the vehicle has been inserted at Venus, Mars, or Titan.

Deployment and (for balloons) inflation is done autonomously, but it is essentially a mechanical function without significant GN&C elements. However, reliable strategies need to be developed for mid-air transition from a stowed payload to a flying platform. This technology would be applicable to Venus, Mars, and Titan missions. Current HTA vehicle transition methods rely on rigid wings and empennages with hinges, latches, and energy-absorbing devices, demonstrated with high-altitude balloon Earth-based testing. LTA aerial deployment and inflation was successfully demonstrated on the VEGA balloons at Venus in 1985. More recent technology development activities involving Earth-based flight-testing have sought to extend that technology to larger Venus balloons[94] and Mars balloons.[95] Aerial deployment and inflation of balloons at Mars is much more challenging than for Venus and Titan because its very low-density atmosphere dictates the use of very lightweight balloon materials that are poorly suited to withstand the large transient structural loads experienced during the deployment process.

### 4.4.4 Sample Acquisition and Transfer

Research on technologies for sample acquisition and transfer are needed both to provide new technologies and to increase the readiness level of technologies. The IMSAH architecture will support the needs for MSR sample acquisition and caching, but there are technologies that need to be developed to implement the IMSAH architecture. The SAT coring tool from JPL provides the capability needed for MSR core acquisition but it is only TRL 4 so further work is needed to raise the technology level to TRL 6. Alternative implementations such as those developed by Honeybee Robotics also need to be matured and quantitative comparisons performed.[96] One implementation approach of the caching architecture was developed. It utilizes a tube transfer arm in the caching element. An alternative implementation, which uses the sampling manipulator to also perform sample tube transfer, is needed to reduce the mass and volume of the sample acquisition and caching subsystem. Preliminary results of hermetic sealing have been demonstrated but this technology needs to be developed to TRL 6 and effects on sample integrity and contamination control need to be assessed.

Sample acquisition and transfer technologies are needed to satisfy Planetary Protection and Contamination Control requirements for both in situ and sample return missions. For example, the contamination pathways associated with rotary actuators need to be assessed and methods for reducing the contamination need to be developed and validated.

Acquisition of samples from steep slopes is desired, such as for potential lunar or Mars missions. Mobility concepts for access to these sites have been proposed[88] but new sample acquisition and transfer technologies are needed for these concepts. An in situ sampling mission to Venus requires technologies to enable sample acquisition and transfer in the extreme temperature, pressure, and atmospheric environment of the Venus surface. 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.[97] Initial experiments using a harpoon system deployed from a prototype airship platform demonstrated the feasibility of surface sample 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.

The interaction between the spacecraft and manipulator control, the mechanical structure, and the terrain poses key technological challenges. One challenge is brought about in small body sampling due to the uncertainty in surface material properties. 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,[21] 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 responses 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 TAG scenarios.

# 5 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 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 [OCT]): systems studies and workshops, low TRL development, and high TRL development. These findings are organized into the same five major areas as the previous section:

1. Modeling and Simulation
    a. Integrated system modeling and simulation methodologies
    b. Terramechanics
2. Planning and Control
    a. Model-based control
    b. Planning under uncertainty
    c. High-speed autonomous navigation
    d. Ground operations tools
3. Sensing and Perception
    a. Range sensing
    b. Global localization
4. Mobility Systems
    a. Extreme terrain mobility systems
    b. Small-body mobility systems
    c. Aerial mobility systems
5. Sample Acquisition and Transfer

## 5.1 Modeling and Simulation

### *5.1.1 Finding 1: Integrated System Modeling and Simulation Methodologies*

In order to optimize system designs and reduce development cost/risk, the Planetary Science Division (PSD) needs more comprehensive system-level modeling throughout 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.

***Recommendation 1:*** Conduct a workshop and systems study exploring the use of fully functional system simulation to aid early-stage component and system design. Goals are to define a general architecture, identify lifecycle processes and organization, simulation modeling-based V&V, uncertainty quantification from component to system level, model re-usability, long-term maintenance, and configuration control.

***Recommendation 2:*** Based on the results of the above, conduct two pilot studies—one focused on pre-phase A design needs for a particular mission type (e.g., aerial mobility with surface sampling capability) and another focused on mid-mission V&V.

***Recommendation 3:*** 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.

### *5.1.2 Finding 2: Terramechanics*

In order to understand surface missions, there is a need for more sophisticated models of soil 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 micro-gravity) 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 (MER embeddings in soft soil) and sampling performance (Phoenix) across a full spectrum of terrains. The development of the 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.

***Recommendation 1:*** Hold a series of workshops engaging scientists, terramechanics experts, and the GN&C experts to identify the needed simulation capabilities and relevant surface material properties to address a variety of bodies and mission types.

***Recommendation 2:*** Develop and validate a range of terramechanic models and/or simulations capable of supporting analysis of wheel-soil interaction in both low- and high-gravity environments, and sampling and mobility in micro-gravity. Validation should consist of both sub-system tests in new or existing testbeds as well as system-level tests using prototype rovers.

## 5.2 Planning and Control

### *5.2.1 Finding 3: Model-Based Control*

In order to address increasing complexity of the spacecraft systems and the interaction with the environment, we need to leverage new control techniques that model dynamically evolving systems. 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 where complex dissipative mechanisms or high-frequency dynamics dominate.

***Recommendation 1:*** Conduct a systems study to identify candidate operational scenarios where model-predictive control could provide significantly improved performance and conduct evaluation studies.

### 5.2.2 Finding 4: 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 landers or 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.

***Recommendation 1:*** Hold a workshop, outlining a plan and ideas, engaging experts from diverse disciplines (control theory, mechanical engineering, systems engineering). The purpose of the workshop is to explore successful techniques for robust planning and control under different types of uncertainty.

***Recommendation 2:*** Fund 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, micro-gravity mobility, horizontal mobility in challenging terrain, and vertical mobility of a tethered system.

### 5.2.3 Finding 5: High-Speed Autonomous Navigation

The reduced speed of autonomous navigation limits both energy efficiency and the surface area reachable in a fixed mission duration. Ongoing advances in high-speed computing 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. In addition, allowing smaller vehicles to drive at higher speeds will facilitate reductions in rover mass with commensurate cost savings.

***Recommendation 1:*** Undertake a systems study of the benefits of high-speed computing on planetary rovers. Pending the results, a follow-up effort to develop a prototype of a high-speed, low-mass rover should be considered.

***Recommendation 2:*** Demonstrate at TRL 6 or 7, high-speed navigation of a prototype planetary rover running on prototype flight avionics.

### 5.2.4 Finding 6: Ground Operations Tools

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. 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.

***Recommendation 1:*** Conduct a small study to evaluate the cost and benefits of the development of a simulated operations system capable of supporting one or more future missions such as an MSR, small body operations, or a Titan aerial platform.

***Recommendation 2:*** Fund 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.

***Recommendation 3:*** Establish and fund a multi-center team to coordinate development of 3-D immersive visualization environments for surface operations.

## 5.3 Sensing and Perception

### *5.3.1 Finding 7: Range Sensing*

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 the opportunity to leverage rapidly advancing computation capabilities towards improved range sensing.

***Recommendation 1:*** Conduct a study to estimate development/maturation trajectories of alternative range sensors, model their expected performance (including SWAP), and to quantitatively evaluate the benefits to multiple applications including mobility.

***Recommendation 2:*** Undertake development of reusable, high-performance, flight-qualified implementations of multiple ranging techniques and sensors as well as localization methods.

***Recommendation 3:*** Fund the development of a new generation of engineering cameras suitable for a range of applications including deep space navigation as well as lunar and martian.

### *5.3.2 Finding 8: Global Localization*

Small body mobility systems, as well as Venus and Titan aerial vehicles, need real-time surface referencing for science targeting and navigation. On Mars, rovers need to use real-time localization together with orbital localization data to more efficiently traverse long distances.

***Recommendation 1:*** Develop a program to demonstrate vision-based global localization.

***Recommendation 2:*** Develop techniques to enable low-gravity small body exploration.

## 5.4 Mobility Systems and Sample Acquisition

### *5.4.1 Finding 9: 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.

***Recommendation 1:*** 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.

***Recommendation 2:*** Develop early stage prototypes targeted towards the highest priority mission concepts.

### 5.4.2 Finding 10: 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. Yet, developing a physics-based simulation capability of sufficient fidelity for any particular target and mobility system requires specialized expertise and significant funding. While early stage prototypes of small-body mobility systems have been developed, there is a need for greater interaction between the science community and engineers. In particular, engineers need more insight into potential science objectives, while the science community needs increased awareness of mobility system capabilities and system trade-offs.

***Recommendation 1:*** Conduct system studies initiated by a workshop bringing together engineers and scientists with the objective of reaching a consensus regarding:

- The targets for which mobility provides significant science value
- 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)
- The mobility strategies (e.g., random hopping vs. controlled mobility) appropriate to each body.

***Recommendation 2:*** Develop and disseminate a physics-based simulation to serve as a virtual testbed for the evaluation and maturation of existing prototype mobility system designs.

### 5.4.3 Finding 11: Aerial Mobility Systems

Due to the complex aerodynamics of deployment and navigation, higher fidelity testing and simulation tools are needed. Prototype field testing is needed on Earth to test and validate vehicle designs, atmospheric deployment methods, and GN&C technologies. Similar to small body and extreme terrain mobility, aerial mobility systems sampling the surface face similar challenges associated with the force back-reaction of the sampling element on the vehicle.

***Recommendation 1:*** Extend existing modeling and simulation tools for planetary environments and robotic ground vehicles to make them suitable for exploration of aerial vehicle designs and early performance assessments.

***Recommendation 2:*** Fund the development of prototypes (based on the systems study) and evaluate performance of vehicle deployment, localization, surface sampling, onboard autonomous science, and aerial vehicle mission operations interfaces.

### 5.4.4 Finding 12: Sample Acquisition and Transfer

The wide variety of missions requires development of a range of sample acquisition and transfer technologies because few currently exist. Including phase-change soil behavior as part of the system is also an under-developed area of investigation. 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.

***Recommendation 1:*** Mature technology for coring and sampling of bodies with gravity (e.g., Mars and lunar) to TRL 7.

***Recommendation 2:*** Fund a spectrum of low TRL prototype sampling systems appropriate for bodies with extreme temperatures (Venus and Titan), for bodies with low gravity (e.g., asteroids and comets), and for heterogeneous bodies (e.g., comets).

***Recommendation 3:*** Conduct studies of *integrated* mobility and sampling systems, merging the sampling mechanism functions with the system-level functions; for example, small body sampling that relies on active compliance between the spacecraft and the surface.

***Recommendation 4:*** Develop a flight qualified, general-purpose force torque sensor.

***Recommendation 5:*** Endorse the ASTID workshop in 2013, and ensure that there is sufficient and adequate GN&C participation.

# 6 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 GN&C development for the next 5 years or so in which the findings described above are all part of an integrated system. This is the first time that surface GN&C has been examined. This document provides a development roadmap for the next few years.

The findings and recommendations presented in this document represent a spectrum of investments both in cross-cutting technologies as well as systems engineering and prototype development targeted to specific mission types.

Architecture and systems engineering processes leading to a successful surface system design are still evolving but based on recent experience we note the following:

- Surface GN&C is still in its infancy.
- Surface GN&C is a distinct area from traditional spacecraft GN&C.
- Flight missions need to treat the surface phase with as much concern as cruise and EDL.
- Integrated modeling and simulation is not yet used to its potential.
- Sustained system-level analyses and design in surface GN&C needs to take place well before mission definition.
- While the focus of this report is on the relevance of surface GN&C technologies to accomplish the goals of planetary science, we want to make the reader aware that the 2013 edition of *A Roadmap for U.S. Robotics: From Internet to Robotics* (http://www.robotics-vo.us/node/332) proposes 15-year roadmaps for the entire field of robotics, including areas common to this report, and covers a much broader spectrum of technologies than those discussed in this report.

# Appendix A: Pertinent GN&C Challenges and Technologies in the NASA Space Technology Roadmap

This appendix extracts pertinent top technical challenges and high-priority technologies in the recently released document *NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space*,[7] henceforth referred to as the Roadmap. The intent is to provide convenient access to the Roadmap to better illustrate the commonalities and differences between that even broader analysis and this report.

## A.1 Top Technical Challenges

The Roadmap lists a number of technical challenges that are pertinent to this technology assessment. Challenges identified by the review panel for TA04 Robotics, Tele-Robotics, and Autonomous Systems include:[i]

> **1. Rendezvous:** Develop the capability for highly reliable, autonomous rendezvous, proximity operations, and capture/attachment to (cooperative and non-cooperative) free-flying space objects.
>
> The ability to perform autonomous rendezvous and safe proximity operations and docking/grappling are central to the future of mission concepts for satellite servicing, Mars sample returns, active debris removal scenarios, and other cooperative space activities. Major challenges include improving the robustness of the rendezvous and capture process to ensure successful capture despite wide variations in lighting, target characteristics, and relative motion.
>
> **2. Maneuvering:** Enable robotic systems to maneuver in a wide range of NASA-relevant environmental, gravitational, and surface and subsurface conditions.
>
> Current rovers cannot access extreme lunar or martian terrain, eliminating the possibility of robotic access and requiring humans to park and travel on foot in suits. In microgravity, locomotion techniques on or near asteroids and comets are undeveloped and untested. Challenges include developing robotics to travel into these otherwise denied areas, developing techniques to grapple and anchor with asteroids and non-cooperative objects, or building crew mobility systems to move humans into these challenging locations.
>
> **3. In Situ Analysis and Sample Return:** Develop subsurface sampling and analysis exploration technologies to support in situ and sample return science missions.
>
> A top astrobiological goal and a fundamental NASA exploration driver is the search for life or signs of previous life in our solar system. A significant planetary science driver exists to obtain unaltered samples (with volatiles intact) for either in situ analysis or return to Earth from planetary bodies. Terrestrial drilling technologies have limited applicability to these missions and robotic planetary drilling and sample handling is a new and different capability.
>
> **4. Hazard Avoidance:** Develop the capabilities to enable mobile robotic systems to autonomously and verifiably navigate and avoid hazards.

---

[i] Reprinted with permission from the National Academies Press, Copyright 2012, National Academy of Sciences.

Due to the large computational throughput requirements needed to quickly assess subtle terrain geometric and non-geometric properties fast enough to maintain speeds near vehicle limits, robotic systems lag behind the ability of human drivers to perceive terrain hazards at long range.

**5. Time-Delayed Human-Robotic Interactions:** Achieve more effective and safe human interaction with robotic systems (whether in proximity or remotely) that accommodates time- delay effects.

More effective and safe human interaction with robotic systems has a number of different focuses which range from the potential dangers of proxemic interactions to remote supervision with or without time delays. Remote interactions with robotic systems do not pose the same immediate potential level of danger to humans as close proximity interactions; however, it is often significantly more difficult for a remote human to fully understand the context of the environment in which the robotic system functions and the status of the system.

**6. Object Recognition and Manipulation:** Develop means for object recognition and dexterous manipulation that supports engineering and science objectives.

Object recognition requires sensing, and requires a perception function that can associate the sensed object with an object that is understood a priori. Sensing approaches to date have combined machine vision, stereo vision, LIDAR, structured light, and RADAR, while perception approaches often start with CAD models or models created by a scan with the same sensors that will later be used to identify the object. Major challenges include the ability to work with a large library of known objects, identifying objects that are partially occluded, sensing in poor lighting, estimating the pose of quickly tumbling objects, and working with objects at near and far range. Robotic hands with equivalent or superior grasping ability to human hands would avoid the added complexity of robot interfaces on objects and provide a sensate tool change-out capability for specialized tasks.

## A.2 High-Priority Technologies

The Roadmap reads:[ii]

> The roadmap for TA04 consists of seven technology subareas: sensing and perception; mobility; manipulation; human-systems integration; autonomy; autonomous rendezvous and docking (AR&D); and robotics, tele-robotics, and autonomous systems engineering. TA04 supports NASA space missions with the development of new capabilities, and can extend the reach of human and robotic exploration through a combination of dexterous robotics, better human/robotic interfaces, improved mobility systems, and greater sensing and perception. The TA04 roadmap focuses on several key issues for the future of robotics and autonomy: enhancing or exceeding human performance in sensing, piloting, driving, manipulating, and rendezvous and docking; development of cooperative and safe human interfaces to form human-robot teams; and improvements in

---

[ii] Reprinted with permission from the National Academies Press, Copyright 2012, National Academy of Sciences.

> autonomy to make human crews independent from Earth and make robotic missions more capable.
>
> For the TA04 roadmap to describe and provide supporting text for each of the level 3 technologies (like the other roadmaps), it would have to be largely rewritten, and the panel made a number of suggestions for changes to TA04 for it to parallel the other roadmaps. As a result, the steering committee and responsible panel did not have a list of well-defined technologies originally identified in the draft roadmaps, and have recommended a new set of level 3 technologies.

Table A.2-1 lists the TA04 breakdown structure specified in the Roadmap.

**Table A.2-1.** Technology area breakdown structure for TA04, Robotics, Tele-Robotics, and Autonomous Systems.[iii]

- 4.1 Sensing and Perception
  - 4.1.1 Vision
  - 4.1.2 Tactile Sensing
  - 4.1.3 Natural Feature Image Recognition
  - 4.1.4 Localization and Mapping
  - 4.1.5 Pose Estimation
  - 4.1.6 Multi-Sensor Data Fusion
  - 4.1.7 Mobile Feature Tracking and Discrimination
  - 4.1.8 Terrain Classification and Characterization
- 4.2 Mobility
  - 4.2.1 Extreme Terrain Mobility
  - 4.2.2 Below-Surface Mobility
  - 4.2.3 Above-Surface Mobility
  - 4.2.4 Small Body/Microgravity Mobility
- 4.3 Manipulation
  - 4.3.1 Robot Arms
  - 4.3.2 Dexterous Manipulators
  - 4.3.3 Modeling of Contact Dynamics
  - 4.3.4 Mobile Manipulation
  - 4.3.5 Collaborative Manipulation
  - 4.3.6 Robotic Drilling and Sample Processing
- 4.4 Human-Systems Integration
  - 4.4.1 Multi-Modal Human-Systems Interaction
  - 4.4.2 Supervisory Control
  - 4.4.3 Robot-to-Suit Interfaces
  - 4.4.4 Intent Recognition and Reaction
  - 4.4.5 Distributed Collaboration
  - 4.4.6 Common Human-Systems Interfaces
  - 4.4.7 Safety, Trust, and Interfacing of Robotic/Human Proximity Operations
- 4.5 Autonomy
  - 4.5.1 Vehicle System Management and FDIR
  - 4.5.2 Dynamic Planning and Sequencing Tools
  - 4.5.3 Autonomous Guidance and Control
  - 4.5.4 Multi-Agent Coordination
  - 4.5.5 Adjustable Autonomy
  - 4.5.6 Terrain Relative Navigation
  - 4.5.7 Path and Motion Planning with Uncertainty
- 4.6 Autonomous Rendezvous and Docking
  - 4.6.1 Relative Navigation Sensors (long, mid, and near range)
  - 4.6.2 Relative Guidance Algorithms
  - 4.6.3 Docking and Capture Mechanisms/Interfaces
- 4.7 RTA Systems Engineering
  - 4.7.1 Modularity/Commonality
  - 4.7.2 Verification and Validation of Complex Adaptive Systems
  - 4.7.3 Onboard Computing

## A.3 TA04 Mapping to Relevant GN&C Technology Objectives

Table S.2, Top Technical Challenges by Technology Objective, of the Roadmap includes the following:[iv]

**Technology Objective A: Extend and sustain human activities beyond low Earth orbit.**

A8. Mass to Surface: Deliver more payload to destinations in the solar system.

A9. Precision Landing: Increase the ability to land more safely and precisely at a variety of planetary locales and at a variety of times.

---

[iii] Reprinted with permission from the National Academies Press, Copyright 2012, National Academy of Sciences.

[iv] Reprinted with permission from the National Academies Press, Copyright 2012, National Academy of Sciences.

A10. Autonomous Rendezvous and Dock: Achieve highly reliable, autonomous rendezvous, proximity operations and capture of free-flying space objects.

**Technology Objective B: Explore the evolution of the solar system and the potential for life elsewhere (in-situ measurements).**

B2. Precision Landing: Increase the ability to land more safely and precisely at a variety of planetary locales and at a variety of times.

B3. Robotic Maneuvering: Enable mobile robotic systems to autonomously and verifiably navigate and avoid hazards and increase the robustness of landing systems to surface hazards.

B4. Life Detection: Improve sensors for in-situ analysis to determine if synthesis of organic matter may exist today, whether there is evidence that life ever emerged, and whether there are habitats with the necessary conditions to sustain life on other planetary bodies.

B6. Autonomous Rendezvous and Dock: Achieve highly reliable, autonomous rendezvous, proximity operations and capture of free-flying space objects.

B8. Mass to Surface: Deliver more payload to destinations in the solar system.

**Technology Objective C: Expand understanding of Earth and the universe in which we live (remote measurements).**

C4. Increase Available Power: Eliminate the constraint of power availability for space missions by improving energy generation and storage with reliable power systems that can survive the wide range of environments unique to NASA missions.

C5. Higher Data Rates: Minimize constraints imposed by communication data rate and range. C6. High-Power Electric Propulsion: Develop high-power electric propulsion systems along with the enabling power system technology.

C7. Design Software: Advance new validated computational design, analysis, and simulation methods for design, certification, and reliability of materials, structures, and thermal, EDL, and other systems.

C8. Structural Monitoring: Develop means for monitoring structural health and sustainability for long duration missions, including integration of unobtrusive sensors and responsive on-board systems.

C9. Improved Flight Computers: Develop advanced flight-capable devices and system software for real-time flight computing with low-power, radiation-hard, and fault-tolerant hardware.

C10. Cryogenic Storage and Transfer: Develop long-term storage and transfer of cryogens in space using systems that approach near-zero boil-off.

## Acronyms

| | |
|---|---|
| 3-D | three-dimensional |
| ACS | Attitude Control System |
| ARC | Ames Research Center |
| ASTID | Astrobiology Science and Technology for Instrument Development |
| AVM | Adaptive Vehicle Make |
| BWS | Brushed-wheel Sampler |
| CAT | Corer Abrader Tool |
| COTS | commercial off-the-shelf |
| CSSR | Comet Surface Sample Return |
| DAE | differential-algebraic equations |
| DAME | Drilling Automation for Mars Exploration |
| DARPA | Defense Advanced Research Projects Agency |
| DOD | Department of Defense |
| DOE | Department of Energy |
| DTRA | Defense Threat Reduction 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 |
| GN&C | guidance, navigation, and control |
| GPS | global positioning system |
| GPU | Graphics Processing Unit |
| GRC | Glenn Research Center |
| GSFC | Goddard Space Flight 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 |
| LTA | lighter than air |
| MAV | Mars Ascent Vehicle |
| MBE | Model-based Engineering |
| MER | Mars Exploration Rovers |
| MinSAC | Minimum Scale Sample Acquisition and Caching |
| MSL | Mars Science Laboratory |
| MSR | Mars Sample Return |
| NEO | near-Earth object |
| NRC | National Research Council |
| ODE | ordinary differential equations |
| OCT | Office of Chief Technologist |
| PDP | Planetary Defense Precursor |
| PSD | Planetary Science Division |
| QMU | Quantification of Margins and Uncertainty |
| R&D | research and development |
| RA | robotic arm |
| RCS | Reaction Control System |
| RKA | Russian Space Agency |
| RHBD | radiation hard by design |
| RSVP | Rover Sequencing and Visualization Program |
| SAC | sample acquisition and caching |
| SAGE | Surface and Atmosphere Geochemical Explorer |
| SAT | Sample Acquisition Tool |
| SBAG | Small Bodies Assessment Group |
| SD2 | Sampler, Drill, and Distribution System |
| SIPR | Subsurface Ice Probe |
| SLAM | Simultaneous Localization and Mapping |
| SMD | Science Mission Directorate |
| SWAP | size, weight, and power |
| TAG | Touch and Go |
| TDT | Transonic Dynamics Tunnel |
| TGIP | touch-and-go-impregnable-pad |
| TRN | Terrain Relative Navigation |
| TSSM | Titan Saturn System Mission |
| TRL | Technology Readiness Level |
| UAV | unmanned aerial vehicle |
| 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 |
| WFF | Wallops Flight Facility |

## References

[1] Jet Propulsion Laboratory, Guidance, Navigation, and Control Technology Assessment for Future Planetary Science Missions: Part I. Onboard and Ground Navigation and Mission Design, Report No. JPL D-75394, October 2012.

[2] Jet Propulsion Laboratory, Guidance, Navigation, and Control Technology Assessment for Future Planetary Science Missions: Part II. Onboard Guidance, Navigation, and Control (GN&C), Report No. JPL D-75431, January 2013.

[3] Committee on the Planetary Science Decadal Survey, National Research Council of the National Academies, *Vision and Voyages for Planetary Science in the Decade 2013–2022*, National Academies Press, Washington, DC, 2011.

[4] Seeni, A., B. Schafer, and G. Hirzinger, *Robot Mobility Systems for Planetary Surface Exploration – State-of-the-Art and Future Outlook: A Literature Survey*, Ed. by A.T. Arif, Aerospace Technology Advancements, January 2010.

[5] Goldberg, S.B., M.W. Maimone, and L. Matthies, “Stereo Vision and Rover Navigation Software for Planetary Exploration,” in *Proceedings of IEEE Aerospace Conference*, Big Sky, MT, 2002.

[6] Kolawa, E. et al., *Extreme Environment Technologies for Future Space Science Missions*, Report No. JPL D-32832, September 2007.

[7] Steering Committee for NASA Technology Roadmaps, National Research Council of the National Academies, *NASA Space Technology Roadmaps and Priorities: Restoring NASA’s Technological Edge and Paving the Way for a New Era in Space*, National Academies Press, Washington, DC, 2012.

[8] Cutts, J., K.T. Nock, J.A. Jones, G. Rodriguez, J. Balaram, G.E. Powell, and S.P. Synnott, “Aerovehicles for Planetary Exploration,” presented at IEEE International Conference on Robotics and Automation, 1995.

[9] Braun, R.D., H.S. Wright, and D.A. Spencer, “The Mars Airplane: a Credible Science Platform,” in *Proceedings of IEEE Aerospace Conference*, 2004.

[10] NASA Langley Research Center Website, Aerial Regional-scale Environmental Survey of Mars (ARES), available at: http://marsairplane.larc.nasa.gov/index.html.

[11] Barnes, J.W., C. McKay, L. Lemke, R.A. Beyer, J. Radebaugh, and D. Atkinson, “AVIATR: Aerial Vehicle for In-situ and Airborne Titan Reconnaissance,” presented at the 41st Lunar and Planetary Science Conference, 2010.

[12] Venus Exploration Analysis Group Website, Presentations at Fifth Meeting of the Venus Exploration Analysis Group (VEXAG), May 7–8, 2008, Greenbelt, MD, available at: http://www.lpi.usra.edu/vexag/may2008/presentations/.

[13] Young, L.A., V. Gulick, and G.A. Briggs, “Rotorcraft as Mars Scouts,” presented at the IEEE Aerospace Conference, Big Sky, MT, March 9–16, 2002.

[14] Lunine, J., R. Lorenz, T. Spilker, J. Elliot, and K. Reh, “Titan Montgolfière Mission Study,” presented to The Outer Planets Assessment Group, 4 May 2006.

[15] Small Bodies Assessment Group, SBAG Community Poll: Primitive Bodies Decadal Priorities, 2009, available at: www.lpi.usra.edu/decadal/sbag.

[16] Castillo-Rogez, J.C. and J.I. Lunine, "Astrobiology: The Next Frontier," Part IV, Chapter 10, *Small Habitable Worlds*, Ed. by Chris Impey, Cambridge University Press, 2012.

[17] Yoshida, K., "Achievements in Space Robotics," *IEEE Robotics & Automation Magazine* 16(4): 20–28, December 2009.

[18] Quadrelli, B.M., H. Mazhar, and D. Negrut, "Modeling and Simulation of Anchoring Processes for Small Body Exploration," presented at the AIAA SPACE 2012 Conference & Exposition, 2012.

[19] Bonitz, R., L. Shiraishi, M. Robinson, J. Carsten, R. Volpe, A. Trebi-Ollennu, R. Arvidson, P. Chu, J. Wilson, and K. Davis, "The Phoenix Mars Lander Robotic Arm," presented at the IEEE Aerospace Conference, Big Sky, MT, March 2009.

[20] Parness, A., "Anchoring Foot Mechanisms for Sampling and Mobility in Microgravity," presented at the IEEE International Conference on Robotics and Automation, Shanghai, China, May 2011.

[21] Quadrelli, B.M., P. Backes, W.K. Wilkie, J. Keim, U. Quijano, R. Mukherjee, D. Scharf, S.C. Bradford, and M. McKee, "Investigation of Phase Transition-Based Tethered Systems for Small Body Sample Capture," *Acta Astronautica*, 68(7): 947–973, 2011.

[22] Sears, D., C. Allen, D. Britt, D. Brownlee, M. Franzen, L. Gefert, S. Gorovan, C. Pieters, J. Preble, D. Scheers, and E. Scott, "The Hera Mission: Multiple Near-Earth Asteroid Sample Return," *Advances in Space Research* 34: 2270–2275, 2004.

[23] Bonitz, R., "The Brush Wheel Sampler – a Sampling Device for Small-body Touch-and-Go Missions," presented at the IEEE Aerospace Conference, Big Sky, MT, March 2012.

[24] Barucci, M. et al., "The OSIRIS-REx Mission – Sample Acquisition Strategy and Evidence for the Nature of Regolith on Asteroid 101955 (1999 RQ36)," presented at the Asteroid, Comets, Meteors Conference, Niigata, Japan, May 16–20, 2012.

[25] Zacny, K., L. Beegle, T. Onstott, and R. Mueller, "Marsvac: Actuator Free Regolith Sample Return Mission from Mars," presented at the Concepts and Approaches for Mars Exploration Workshop, Lunar and Planetary Institute, Houston, TX, June 12–14, 2012.

[26] Backes, P., J. Jones, and C. Gritters, "Harpoon-based Sampling for Planetary Applications," presented at the IEEE Aerospace Conference, Big Sky, MT, March 2008.

[27] Kaufman, R.,"Comet Harpoon Being Test Fired in NASA Lab," *National Geographic Daily News*, December 13, 2011, available at: http://news.nationalgeographic.com/news/2011/12/111215-nasa-comet-harpoon-sample-crossbow-space-science/.

[28] Yano, H., "Sampling Systems for Hayabusa and Follow-on Missions: Scientific Rationale, Operational Considerations, and Technological Challenges," presented at the International Marco Polo Symposium and Other Small Body Sample Return Missions, Paris, France, May 18–20, 2009.

[29] Lorenz, R., W. Boynton, and C. Turner, "Demonstration of Comet Sample Collection by Penetrator," in *Proceedings of the 5th IAA International Conference on Low-Cost Planetary Missions*, Noordwijk, The Netherlands, September 24–26, 2003.

[30] Lorenz, R., "Planetary Penetrators: Their Origins, History, and Future," *Advances in Space Research* 48(3): 403–431, August 2011.

[31] Myrick, T.M., S.P. Gorevan, C. Batting, S. Stroescu, J. Ji, M. Maksymuk, K.R. Davis, and M.A. Ummy, "The Athena Miniature Rock Coring & Rock Acquisition and Transfer System (Mini-Corer)," presented at the Workshop on Concepts and Approaches for Mars Exploration, Abstract 6105, Lunar and Planet, Institute, Houston, TX, 2000.

[32] Zacny, K., G. Paulsen, K. Davis, E. Mumm, and S. Gorevan, "Honeybee Robotics Planetary Drill Systems," presented at the 39th Lunar and Planetary Science Conference (Lunar and Planetary Science XXXIX), League City, TX, March 10–14, 2008.

[33] Anderson, R., L. Jandura, A. Okon, D. Sunshine, C. Roumeliotis, L. Beegle, J. Hurowitz, B. Kennedy, D. Limonadi, S. McCloskey, M. Robinson, C. Seybold, and K. Brown, "Collecting Samples in Gale Crater, Mars; an Overview of the Mars Science Laboratory Sample Acquisition, Sample Processing and Handling System," *Space Science Review* 170: 57–75, 2012.

[34] Klein, K., M. Badescu, N. Haddad, L. Shiraishi, and P. Walkemeyer, "Development and Testing of a Rotary Percussive Sample Acquisition Tool," presented at the IEEE Aerospace Conference, March 2012.

[35] Levitt, D. and G. Caffell,"Sample Encapsulation Technology," presented at the ASCE Earth and Space Conference, Pasadena, CA, April 15–18, 2012.

[36] Collins, C., P. Younse, and P. Backes, "Planetary Sample Caching System Design Options," in *Proceedings of AIAA Space Conference*, Pasadena, CA, September 14–17, 2009.

[37] Backes, P., R. Lindemann, C. Collins, and P. Younse, "An Integrated Coring and Caching Concept," presented at the IEEE Aerospace Conference, March 2010.

[38] Younse, P., C. Collins, and P. Backes, "A Sample Handling, Encapsulation, and Containerization Subsystem Concept for Mars Sample Caching Missions," presented at the International Planetary Probe Workshop (IPPW-7), June 2010.

[39] Zacny, K., P. Chu, J. Wilson, K. Davis, and J. Craft, "Core Acquisition and Caching for the 2018 Mars Sample Return," presented at the 42nd Lunar and Planetary Science Conference, The Woodlands, TX, March 2011.

[40] Paulsen, G., K. Zacny, A. Steele, P. Conrad, P. Chu, M. Hedlund, J. Craft, T. McCarthy, and C. Schad, "Demonstration of the Core Acquisition and Caching for the Mars Sample Return Mission," presented at the 43rd Lunar and Planetary Science Conference, The Woodlands, TX, March 2012.

[41] Jorden, T., "Testing a Robotic System for Collecting and Transferring Samples on Mars," in *Proceedings of ASTRA 11th Symposium on Advanced Space Technologies in Robotics and Automation*, Noordwijk, The Netherlands, April 2011.

[42] Glassmeier, K. et. al., "The Rosetta Mission: Flying Towards the Origin of the Solar System," *Space Science Reviews* 128(1–4): 1–21, October 2006.

[43] Finzi, A.E., F.B. Zazzera, C. Dainese, F. Malnati, P.G. Magnani, E. Re, P. Bologna, S. Espinasse, and A. Olivieri, "SD2 – How to Sample A Comet," *Space Science Reviews* 128(1–4): 281–299, 2007.

[44] Hofmann, P. et al., "Recent Progress in Designing the Sample Preparation and Distribution System of the ExoMars Mission," presented at the 10th Workshop on Advanced Space Technologies for Robotics and Automation – ASTRA, November 2008.

[45] Backes, P., J. Aldrich, D. Zarzhitsky, K. Klein, and P. Younse, "Demonstration of Autonomous Coring and Caching for a Mars Sample Return Campaign Concept," presented at the IEEE Aerospace Conference, March 2012.

[46] Backes, P., T. Ganino, and P. Younse, "A Sample Acquisition and Caching Architecture Applicable to a MER-Class Rover for Mars Sample Return," presented at the Concepts and Approaches for Mars Exploration Workshop, Lunar and Planetary Institute, Houston, TX, June 12–14, 2012.

[47] Younse, P., T. de Alwis, P. Backes, and A. Trebi-Ollennu, "Sample Sealing Approaches for Mars Sample Return Caching," presented at the IEEE Aerospace Conference, March 2012.

[48] Grygorczuk, J., M. Banaszkiewicz, A. Cichocki, M. Ciesielska, M. Dobrowolski, B. Kędziora, J. Krasowski, T. Kuciński, M. Marczewski, M. Morawski, H. Rickman, T. Rybus, K. Seweryn, K. Skocki, T. Spohn, T. Szewczyk, R. Wawrzaszek, and Ł. Wiśniewski, "Advanced Penetrators and Hammering Sampling Devices for Planetary Body Exploration," in *Proceedings of ASTRA 11th Symposium on Advanced Space Technologies in Robotics and Automation*, Noordwijk, the Netherlands, April 2011.

[49] Zacny, K., G. Paulsen, K. Davis, and B. Glass, "Drilling and Automation for Mars Exploration – 3rd Field Test on Devon Island," *Lunar and Planetary Science* XXXVIII, 2007.

[50] Re, R. et al., "ExoMars Multi Rod Drill Development and Testing," presented at the 10th Workshop on Advanced Space Technologies for Robotics and Automation – ASTRA, November 2008.

[51] Zimmerman, W., R. Bonitz, and J. Feldman, "Cryobot: An Ice Penetrating Robotic Vehicle for Mars and Europa," presented at the IEEE Aerospace Conference, 2001.

[52] Cardell, G., M. Hecht, F. Carsey, H. Engelhardt, D. Fisher, C. Terrell, and J. Thompson, "The Subsurface Ice Probe (SIPR): A Low-Power Thermal Probe for the Martian Polar Layered Deposits," presented at the 35th Lunar and Planetary Science Conference, League City, TX, March 15–19, 2004.

[53] Dachwald, B. et al., "IceMole, Development of a Novel Subsurface Ice Probe and Testing of the First Prototype on the Morteratsch Glacier," presented at the EGU General Assembly, Vienna, Austria, April 3–8, 2011.

[54] Grott, M. et al., "Measuring Heat Flow on Mars: The Heat Flow and Physical Properties Package on GEMS," *EPSC Abstracts* Vol. 6, 2011.

[55] JPL NDEAA Ultrasonic/Sonic Driller/Corer Website, available at, http://ndeaa.jpl.nasa.gov/nasa-nde/usdc/usdc.htm.

[56] Akhmanova, M.V., B.V. Dementev, and M.N. Markov, "Water in the Regolith of Mare Crisium (Luna 24)?," *Geokhimiia* 285, February 1978.

[57] Akhmanova, M.V., B.V. Dementev, and M.N. Markov, “Possible Water in Luna 24 Regolith from the Sea of Crises,” *Geochemistry International* 15(166), 1978.

[58] Mattingly, R. and L. May, “Mars Sample Return as a Campaign,” presented at the IEEE Aerospace Conference, March 2011.

[59] Trebi-Ollennu, A., K. Ali, A. Rankin, K. Tso, C. Assad, J. Matthews, R. Deen, D. Alexander, R. Toda, H. Manohara, M. Mojarradi, M. Wolf, J. Wright, Y. Jen, F. Hartman, R. Bonitz, A. Sirota, and L. Alkalai, “Lunar Surface Operation Testbed (LSOT),” presented at the IEEE Aerospace Conference, Big Sky, MT, March 2012.

[60] Arvidson, R., R. Bonitz, M. Robinson, J. Carsten, R. Volpe, A. Trebi-Ollennu, M. Mellon, P. Chu, K. Davis, J. Wilson, A. Shaw, R. Greenberger, K. Siebach, T. Stein, S. Cull, W. Goetz, R. Morris, D. Ming, H. Keller, M. Lemmon, H. Sizemore, and M. Mehta, “Results from the Mars Phoenix Lander Robotic Arm Experiment,” *Journal of Geophysical Resources* 114, 2009.

[61] Shaw, A., R. Arvidson, H. Keller, M. Lemmon, A. Trebi-Ollennu, M. Robinson, K. Siebach, and R. Volpe, “Phoenix Mission Trenching in Arctic Mars,” presented at the 40th Lunar and Planetary Science Conference, Woodlands, TX, March 2009.

[62] Estlin, T.A., B.J. Bornstein, D.M. Gaines, R.C. Anderson, D.R. Thompson, M. Burl, R. Castaño, and M.J. Estlin, “AEGIS Automated Targeting for the MER Opportunity Rover,” *ACM Transactions on Intelligent Systems and Technology* 3(3):1–19, May 2012.

[63] Fleder, M., I.A. Nesnas, M. Pivtoraiko, A. Kelly, and R. Volpe. “Autonomous Rover Traverse and Precise Arm Placement on Remotely Designated Targets,” in *Proceedings of the International Conference on Robotics and Automation*, 2011.

[64] Norris, J.S., M.W. Powell, J.M. Fox, K.J. Rabe, and I-H. Shu, “Science Operations Interfaces for Mars Surface Exploration,” 2005, available at: http://trs-new.jpl.nasa.gov/dspace/bitstream/2014/38341/1/05-1865.pdf.

[65] Cooper, B.K., F. Hartman, S. Maxwell, J. Wright, and J. Jeng, “Using RSVP for Analyzing State and Previous Activities for the Mars Exploration Rovers,” May 2004.

[66] Haldemann, A., M. McHenry, R. Petras, B. Bornstein, R. Castano, J. Cameron, T. Estlin, T. Farr, D. Gaines, A. Jain, C. Leff, C. Lim, I. Nesnas, M. Pomerantz, M. Powell, I. Shu, and R. Volpe, “Simulation to Evaluate Autonomous Behaviors for Mobile Planetary Surface Science Misions,” presented at the IEEE Aerospace Conference, Big Sky, MT, March 2007.

[67] DARPA Website, Adaptive Vehicle Make, available at: http://www.darpa.mil/our_work/tto/programs/adaptive_vehicle_make__%28avm%29.aspx.

[68] Peterson, L., “Quantification of Margins and Uncertainties for Model-Informed Flight System Qualification,” presented at the NASA Thermal and Fluids Analysis Workshop, Hampton, VA, August 16, 2011.

[69] Yahja, A., S. Singh, and A. Stentz, “An Efficient On-Line Path Planner for Outdoor Mobile Robots,” *Robotics and Autonomous Systems* 32(2–3): 129–143, August 2000.

[70] Blackmore, L., M. Ono, and B.C. Williams, “Chance-Constrained Optimal Path Planning with Obstacles,” *IEEE Transactions on Robotics* 27:1080–1094, January 2011.

[71] Nabbe, B. and M. Hebert, "Extending the Path-Planning Horizon," *International Journal of Robotics Research* 26(10): 997–1024, October 2007.

[72] Wolf, M.T., L. Blackmore, Y. Kuwata, N. Fathpour, A. Elfes, and C. Newman, "Probabilistic Motion Planning of Balloons in Strong, Uncertain Wind Fields," presented at the 2010 IEEE International Conference on Robotics and Automation, May 3–7, 2010.

[73] Swift, G., C. Carmichael, G. Allen, G. Madias, E. Miller, R. Monreal, and all active members of the XRTC, "Compendium of XRTC Radiation Results on All Single-Event Effects Observed in the Virtex-5QV," presented at the ReSpace/MAPLD 2011 Conference, August 2011.

[74] Malone, M., "On-board Processing Expandable Reconfigurable Architecture (OPERA) Program Overview," presented at the Fault-Tolerant Spaceborne Computing Employing New Technologies Workshop, May 2008.

[75] Beahan, J., L. Edmonds, R.D. Ferraro, and A. Johnston, "Detailed Radiation Fault Modeling of the Remote Exploration and Experimentation (REE) First Generation Testbed Architecture," in *Proceedings of the IEEE Aerospace Conference*, 2000.

[76] Howard, T.M., A. Morfopoulos, J. Morrison, Y. Kuwata, C. Villalpando, L. Matthies, and M. McHenry, "Enabling Continuous Planetary Rover Navigation through FPGA Stereo and Visual Odometry," in *Proceedings of the IEEE Aerospace Conference*, 2012.

[77] Potter, K., "Uncertainty Visualization State of the Art," presented at the USA/South America Symposium on Stochastic Modeling & Uncertainty Quantification, August 3, 2011.

[78] NASA PDS Imaging Node Website, Rover Camera Instrument Description, available at: http://pdsimg.jpl.nasa.gov/data/mpfr-m-rvrcam-2-edr-v1.0/mprv_0001/document/rcinst.htm.

[79] Advanced Scientific Concepts, Inc. Website, DragonEye 3D Flash LIDAR Space Camera, available at: http://www.advancedscientificconcepts.com/products/dragoneye.html.

[80] Kirk, R.L. et al., "Ultrahigh Resolution Topographic Mapping of Mars with MRO HiRISE Stereo Images: Meter-Scale Slopes of Candidate Phoenix Landing Sites," *Journal of Geophysical Research: Planets* 113(E3), March 2008.

[81] Hwangbo, J., Y. Chen, and R. Li, "Precision Processing of HiRISE Stereo Orbital Images for Topograpic Mapping on Mars," presented at the ASPRS 2010 Annual Conference, San Diego, CA, April 26–30, 2010.

[82] Li, R., J. Hwangbo, Y. Chen, and K. Di, "Rigorous Photogrammetric Processing of HiRISE Stereo Imagery for Mars Topographic Mapping," *IEEE Transactions on Geoscience and Remote Sensing* 49(7), July 2011.

[83] Carsten, J., A. Rankin, D. Ferguson, and A. Stentz, "Global Planning on the Mars Exploration Rovers: Software Integration and Surface Testing," *Journal of Field Robotics* 26(4): 337–357, April 2009.

[84] Stentz, A., "Optimal and Efficient Path Planning for Partially-Known Environments," in *Proceedings IEEE International Conference on Robotics and Automation*, May 1994.

[85] Elfes, A., J. Hall, E. Kulczycki, D. Clouse, A. Morfopoulos, J. Montgomery, J. Cameron, A. Ansar, and R. Machuzak, "An Autonomy Architecture for Aerobot Exploration of the Saturnian Moon Titan," *IEEE Aerospace and Electronic Systems Magazine* 23(7): 16–24, July 2008.

[86] Lamassoure, E.S., S.D. Wall, and R.W. Easter, "Model-Based Engineering Design for Trade Space Exploration throughout the Design Cycle," presented at the AIAA Space Conference and Exposition, San Diego, CA, September 28–30, 2004.

[87] Fairfield, N., G. Kantor, and D. Wettergreen, "Real-Time SLAM with Octree Evidence Grids for Exploration in Underwater Tunnels," *Journal of Field Robotics*, 2007.

[88] Nesnas, I. et al., "Axel and DuAxel Rovers for the Sustained Exploration of Extreme Terrains," *Journal of Field Robotics, Special Issue on Space Robotics*, Part II, Vol. 29, Issue 4, pp. 663–685, July/August 2012.

[89] Pavone, M., J. Castillo, J. Hoffman, and I. Nesnas, *Spacecraft/Rover Hybrids for the Exploration of Small Solar System Bodies*, NASA NIAC Final Report, 2012.

[90] Bellerose, J. and D. Scheeres, "Dynamics and Control for Surface Exploration of Small Bodies," in *Proceedings of AIAA/AAS 2008 Astrodynamics Specialist Conference*, Honolulu, HI, August 18–21, 2008.

[91] Allen, R., M. Pavone, C. McQuin, I. Nesnas, J. Castillo, T.N. Nguyen, and J. Hoffman, "Internally-Actuated Rovers for All-Access Surface Mobility: Theory and Experimentation," presented at the ICRA Conference, 2012.

[92] Elfes, A., S. Bueno, M. Bergerman, E. DePaiva, J. Ramos, and J. Azinheira, "Robotic Airships for Exploration of Planetary Bodies with an Atmosphere: Autonomy Challenges," *Autonomous Robots* 14(2–3): 147–164, 2003.

[93] Elfes, A., J.F. Montgomery, J.L. Hall, S.S. Joshi, J. Payne, and C.F. Bergh, "Autonomous Flight Control for a Planetary Exploration Aerobot," presented at the AIAA Space Conference, Long Beach, CA, August 31, 2005.

[94] Hall, J.L, A.H. Yavrouian, V.V. Kerzhanovich, T. Fredrickson, C. Sandy, M.T. Pauken, E.A. Kulczycki, G.J. Walsh, M. Said, and S. Day, "Technology Development for a Long Duration, Mid-cloud Level Venus Balloon," *Advances in Space Research* 48(7): 1238–47, 2011.

[95] Hall, J.L., M. Pauken, V.V. Kerzhanovich, G.J. Walsh, D. Fairbrother, C. Shreves, and T. Lachenmeier, "Flight Test Results for Aerially Deployed Mars Balloons," in *Proceedings of AIAA Balloon Systems Conference*, Williamsburg, VA, 2007, pp. 21–24.

[96] Zacny, K., J. Wilson, P. Chu, and J. Craft, "Prototype Rotary Percussive Drill for the Mars Sample Return Mission," in *Proceedings of IEEE Aerospace Conference*, March 5–12, 2011, pp.1–8.

[97] Willis, P.A., H.F. Greer, A.M. Fisher, R.P. Hodyss, F.J. Grunthaner, H. Jiao, D. Mair, and J.D. Harrison, "Development of In Situ Microchip-Based Liquid Chromatography for Titan Lake Sample," presented at the Astrobiology Science Conference, 2010.

National Aeronautics and Space Administration

**Jet Propulsion Laboratory**
California Institute of Technology
Pasadena, California

JPL D-78106 4/13