Spacecraft Autonomy Challenges for Next-Generation Space Missions

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Abstract

In early 2011, NASA's Office of the Chief Technologist released a set of technology roadmaps with the aim of fostering the development of concepts and cross-cutting technologies addressing NASA's needs for the 2011-2021 decade and beyond. NASA reached out to the National Research Council (NRC) to review the program objectives and prioritize the list of technologies. In January 2012, the NRC released its report entitled "Restoring NASA's Technological Edge and Paving the Way for a New Era in Space." While the NRC report provides a systematic and thorough ranking of the future technology needs for NASA, it does not discuss in detail the *technical* aspects of its prioritized technologies (which lie beyond its scope). This chapter, building upon this framework, aims at providing such technical details for a selected number of high-priority technologies in the autonomous systems area. Specifically, this chapter focuses on technology area TA04 "Robotics, Tele-Robotics, and Autonomous Systems" and discusses in some detail the technical aspects and challenges associated with three high-priority TA04 technologies: "Relative Guidance Algorithms," "Extreme Terrain Mobility," and "Small Body/Microgravity Mobility." Each of these technologies is discussed along four main dimensions: scope, need, state-of-the-art, and challenges/future directions. The result is a unified presentation of key autonomy challenges for next-generation space missions.

I. Introduction

In early 2011, in an effort to streamline future resource allocation and refine its plans, NASA's Office of the Chief Technologist (OCT) released a set of technology roadmaps with the aim of fostering the development of concepts and cross-cutting technologies addressing NASA's needs for the 2011-2021 decade and beyond (Committee on the Planetary Science Decadal Survey, 2011; NASA OCT, 2013). This set was organized into 14 technology areas (TA01 through TA14), divided into a total of 64 technology subareas. In an attempt to engage the external technical community and enhance the development program in light of scarce resources, NASA reached out to the National Research Council (NRC) to review the program's objectives and prioritize its list of technologies. In January 2012, the NRC released its report entitled "Restoring NASA's Technological Edge and Paving the Way for a New Era in Space," which reviewed an initial 320 technologies (Steering Committee for NASA Technology Roadmaps, 2012). The NRC report revolved around three technology objectives:

- **Technology Objective A**: *Extend and sustain human activities beyond low Earth orbit*. Invest in technologies to enable humans to travel throughout the solar system, including surviving longer space voyages, arriving and working effectively at specific extraterrestrial destinations, and finally returning to Earth safely.
- **Technology Objective B**: *Explore the evolution of the solar system and the potential for life elsewhere (in situ measurements)*. Investigate technologies that enable humans and robots to perform in situ measurements on other planetary bodies as well as on Earth analogues (i.e. astrobiology).
- **Technology Objective C**: *Expand understanding of Earth and the universe (remote measurements)*. Develop technologies for capturing remote measurements from platforms that orbit or fly-by Earth and other planetary bodies, and from other in-space and ground-based observatories.

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In its study, the NRC defined evaluation criteria that included assessments of technological benefit, alignment with NASA, non-NASA aerospace, and non-aerospace national needs, technical risk and reasonableness, sequencing and timing (factoring in requisite technologies), and development time and effort required to achieve each goal. By the final ranking, the NRC had whittled the selection to a group of 16 top priorities for technology.

While the NRC report provides a systematic and thorough ranking of the future technology needs for NASA, it does not discuss in detail the *technical* aspects of the prioritized technologies (which is clearly beyond the scope of the report). This chapter, building upon the NRC report and an earlier assessment of NASA's needs in terms of guidance, navigation, and control technologies (Beauchamp et al., 2013), aims at providing such technical details for a selected number of high-priority technologies in the autonomous systems area. Specifically, this chapter focuses on technology area TA04 "Robotics, Tele-Robotics, and Autonomous Systems" and discusses in some detail the technical aspects and challenges associated with three high-priority TA04 technologies: "Relative Guidance Algorithms," "Extreme Terrain Mobility," and "Small Body/Microgravity Mobility."

This chapter is structured as follows. The rest of this section provides a high-level description of the high-priority technologies for TA04. Then, Sections II, III, IV focus, respectively, on technical discussions of "Relative Guidance Algorithms," "Extreme Terrain Mobility," and "Small Body/Microgravity Mobility," each categorized as top priorities of TA04 and which represent the key areas of expertise of the authors. Finally, Section V draws conclusions with a summary of the technical challenges facing the engineering community and the unsolved technical areas that must be addressed to help NASA meet its vision. Each technology section follows the same structure: *Scope*, *Need*, *State of the Art*, and *Challenges and Future Directions*.

A. High-level Challenges and High-Priority Technologies for Space Autonomous Systems

While the guidance, navigation and control of spacecraft has resulted in numerous successful space missions, its use in fully autonomous operations has thus far been limited, with mission planners often opting for ground-in-the-loop interventions for maneuver refinements and corrections, wherever possible. Where ground-in-the-loop control is not feasible, as in the cases of rendezvous about other planets or atmospheric entry, descent and landing for instance, autonomous operations are often restricted to minimal scope in order to minimize the impact of a very costly validation and verification process. In spite of numerous autonomous operation successes, a number of anomalies have occurred during shuttle operations (Goodman, 2007) and other recent autonomous demonstration missions, e.g. (Kawano et al., 2001), (DART Mishap Investigation Board, 2006), (Davis and Melanson, 2004), and (Howard et al., 2008), that point to the need for development and maturation in this area.

NASA has repeatedly identified robotic, autonomous, and sensing systems as enabling technologies over its history, spanning as far back as the Gemini program in the 1960's (Polites, 1998). For spaceflight, many valuable proposed technologies, including real-time autonomous decision-making, opportunistic science, and human-robotic cooperation, are being investigated but have not yet been flight-tested. Analogously, for roving applications, the capability does not yet exist for traversing extreme lunar, Martian, or dusty terrains, including polar cold traps, high-grade surfaces, and microgravity environments (Bajracharya et al., 2008). The advancement of robotics and autonomous systems will be central to the transition of space missions from current ground-in-the-loop (geocentric) architectures to self-sustainable, independent systems, a key step necessary for outer-planet exploration and for overcoming the many difficulties of interplanetary travel (Truszkowski et al., 2006). Drawing similar conclusions in their technological report, the NRC highlighted TA04 "Robotics, Tele-Robotics, and Autonomous Systems" specifically as a high-priority technology area, recognizing its importance in broadening access to space and expanding humanity's presence in the solar system.

The roadmap for TA04 was broken into 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. Within this context, the NRC identified the following six top challenges for robotics and autonomous systems (quoted from (Steering Committee for NASA Technology Roadmaps, 2012)):

- **Rendezvous**: Develop the capability for highly reliable, autonomous rendezvous, proximity operations, and capture/attachment to (cooperative and non-cooperative) free-flying space objects.
- **Maneuvering**: Enable robotic systems to maneuver in a wide range of NASA-relevant environmental, gravitational, and surface and subsurface conditions.
- **In Situ Analysis and Sample Return**: Develop subsurface sampling and analysis exploration technologies to support in situ and sample return science missions.
- **Hazard Avoidance**: Develop the capabilities to enable mobile robotic systems to autonomously and verifiably navigate and avoid hazards.
- **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.
- **Object Recognition and Manipulation**: Develop means for object recognition and dexterous manipulation that support engineering and science objectives.

This list is consistent with the recommendations of NASA's previous Vision for Space Exploration (NASA, 2004), the recommendations referenced for NASA Automated Rendezvous and Capture operations (Polites, 1998), the lessons learned from Apollo Guidance Navigation and Control (GN&C) (Major et al., 2009), and the technology priorities described for the future of rovers (Bajracharya et al., 2008).

In light of these six challenges, and of the general technology objectives presented at the beginning of this section, eight specific high-priority technologies were identified in the TA04 Roadmap:

- **Technology 4.2.1**, *Extreme Terrain Mobility*.
- **Technology 4.2.4**, *Small Body/Microgravity Mobility*.
- **Technology 4.3.2**, *Dexterous Manipulation*.
- **Technology 4.3.6**, *Robotic Drilling and Sample Processing*.
- **Technology 4.4.2**, *Supervisory Control*.
- **Technology 4.5.1**, *Vehicle Systems Management and Fault Detection Isolation and Recovery (FDIR)*.
- **Technology 4.6.2**, *Relative Guidance Algorithms*.
- **Technology 4.6.3**, *Docking and Capture Mechanisms/Interfaces*.

Technology advances in these areas will help towards accomplishing Technology Objectives A, B, and C by improving access to space, increasing available mass-to-surface, and enhancing robotic maneuvering capabilities, autonomous rendezvous and docking, and precision landing, all of which were labeled top engineering roadblocks that must be overcome to meet NASA's goals.

The remainder of this chapter is devoted to clarifying precisely what needs to be addressed for the three specific subcategories "Relative Guidance Algorithms," "Extreme Terrain Mobility," and "Small Body/Microgravity Mobility," according to the best knowledge and expert opinions of the authors. The benefits, current state of the art techniques, and technical aspects and challenges of each are discussed in detail to better prepare the technical community for delivering on these advancements and meeting the needs of next-generation space missions.

II. Relative Guidance Algorithmic Challenges for Autonomous Spacecraft

Relative guidance algorithms were categorized by the NRC as the top-ranked technology for robotics, tele-robotics, and autonomous systems; their improvement would mark a tremendous milestone for robustifying and augmenting current capabilities in autonomous guidance and control.

A. Scope

Guidance is the process of real-time planning of spacecraft state trajectories in both translational and rotational motion. This involves computing desired sets of translational and rotational states and corresponding control forces and torques as a function of time. Control, or more specifically feedback control, is responsible for following these trajectories based on real-time state updates in the presence of disturbances, measurement noise, and model uncertainties. Together they are referred to as Guidance, Navigation, and Control (GN&C, or just G&C). This section addresses the technical details and challenges for *relative guidance* of autonomous spacecraft in four key space-based areas:

- **Planetary Entry, Descent, and Landing (EDL)**
- **Proximity Operations for Primitive Bodies**
- **Autonomous Rendezvous and Docking (AR&D)**
- **Autonomous Inspection and Servicing (AIS)**

In each of these applications, the guidance problem can be posed as an optimal control problem with dynamics describing the motion of the spacecraft as well as constraints on the vehicle state and controls. This can be expressed generically as follows:

Problem $\mathcal{G}\&\mathcal{C}$: *Generic Autonomous Spacecraft Guidance Optimal Control Problem*

$$\begin{aligned} \min_{t_f,u} \quad & J(x(t),u(t),t) = K(x(t_f),t_f) + \int_{t_0}^{t_f} L(x(t),u(t),t)\mathrm{d}t \\ \text{subject to} \quad & \dot{x}(t) = f(x(t),u(t),t) \\ & u(t) \in \mathcal{U}(t) \\ & x(t) \in \mathcal{X}(t), \quad \text{for all } t \in [t_0, t_f] \end{aligned}$$

where $x \in \mathbb{R}^n$ is the state of the spacecraft, $u \in \mathbb{R}^m$ is the control input, $t \in \mathbb{R}$ is time, $J : \mathbb{R}^{n+m+1} \to \mathbb{R}$ is the cost-functional (which combines terminal and incremental additive cost functions K and L), $f : \mathbb{R}^{n+m+1} \to \mathbb{R}^n$ defines the dynamics, and $\mathcal{U} : \mathbb{R} \to \mathbb{R}^m$ and $\mathcal{X} : \mathbb{R} \to \mathbb{R}^n$ are set-valued maps defining spacecraft control and state constraints. Due to the existence of system dynamics and constraints, the resulting optimal control problem must be solved numerically (Betts, 1998; Fahroo and Ross, 2002) via an optimization algorithm after a proper discretization (Hull, 1997; Vlassenbroeck and Dooren, 1988). To meet the guidance challenges of next-generation space missions, onboard algorithms will need to meet the following specifications:

- **Real-time implementability**: Algorithms must be implemented and executed on real-time processors in a reasonable amount of time.
- **Optimality**: Given that feasible solutions exist, an optimal solution $x^*(t)$ that minimizes (at least approximately) the cost function J is desired.
- **Verifiability**: There must be design metrics that accurately describe the performance and robustness of GN&C algorithms, with accompanying methods for verifying these metrics.

B. Need

Autonomous spacecraft maneuvering, especially in *proximity* of artificial objects (e.g. satellites, debris, etc.) or solar system bodies (e.g. asteroids, comets, irregular satellites, etc.), is a key enabler for the majority of future NASA missions (NASA OCT, 2013; Steering Committee for NASA Technology Roadmaps, 2012). In some cases this arises from obvious physical mission constraints, notably signal transmission delays to and from Earth. A very good example is Mars atmospheric Entry, Descent, and Landing (EDL), arguably one of the most tightly-constrained control sequences in modern spaceflight, which prohibits human intervention due to a nearly 26 minute two-way signal communication time that far exceeds the typical seven-minute descent duration. Similarly, close proximity operations around small bodies, many of which travel beyond the extent of Mars orbit, require autonomous guidance for the same reason. In other instances, the need for autonomy derives from a desire to increase mission frequency, robustness, and reliability. This includes Low Earth Orbit missions, such as Autonomous Rendezvous and Docking (AR&D) and Autonomous Inspection and Servicing (AIS). As space access improves through commercialization, the increased scheduling conflicts and labor overhead associated with ground-in-the-loop spacecraft guidance are expected to become prohibitively expensive. The risk of human error will increase as well. Spacecraft autonomy can circumvent these issues, as well as enable greater mission variety and improve the commercial and scientific return from space.

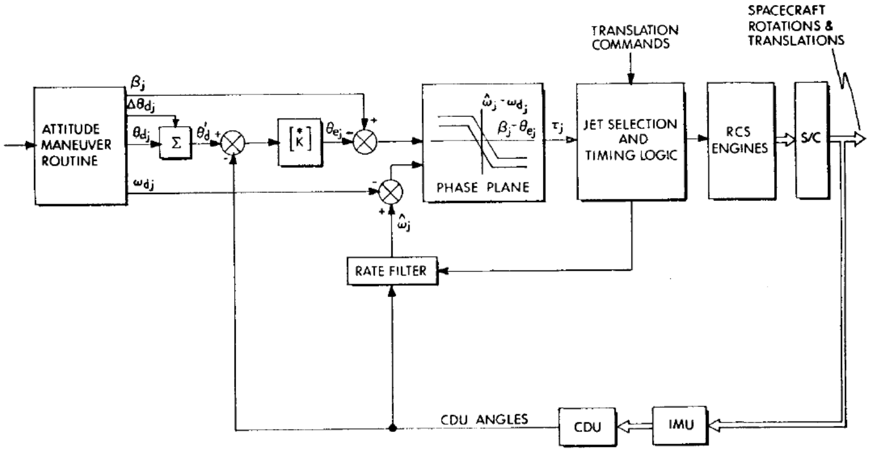
C. State of the Art

Current state-of-the-art techniques for autonomous spacecraft maneuvering include Apollo guidance (particularly phase-plane logic, glideslope, and sliding-mode controllers), Model Predictive Control (MPC) (Açikmeşe et al., 2011; Bevilacqua et al., 2011b; Carson III et al., 2011; Nolet et al., 2005; Park et al., 2011), and Artificial Potential Functions (APFs) (Badawy and McInnes, 2008; Bevilacqua et al., 2011a; McInnes, 1995). Unfortunately, such techniques, while valuable in static uncluttered settings, appear to fall short in scenarios where time-varying constraints (such as neighboring debris or other spacecraft), logical modes (e.g., safety modes), and complex maneuvering (e.g., terrain sampling or manipulation) become key features of the problem setup. In these cases, robotic motion planning techniques, though currently unproven in spaceflight, could provide a valuable alternative (LaValle and Kuffner, 2001; Starek et al., 2015); they are hence discussed here as well. Brief synopses of each these methods are presented in Subsections II-C1–II-C4 below, together with highlights of recent autonomous demonstration missions in Subsection II-C5.

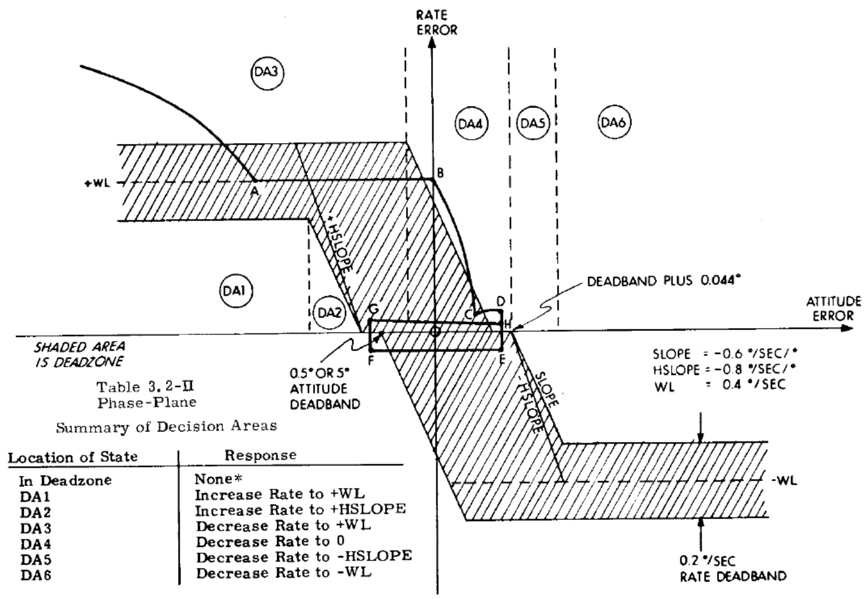
1) Apollo Guidance: The COLOSSUS Program, developed by MIT for NASA's Apollo Program, called upon three Digital AutoPilot (DAP) systems to stabilize and control the Apollo Command Service Module (CSM) as part of its Primary Guidance Navigation and Control System (PGNCS) (Widnall, 1968). The techniques used, now considered part of *classical* control, formed one of the earliest successful deployments of spacecraft autonomy. Block-diagram schematics of the Apollo CSM control logic can be seen in Figure 1. These Digital AutoPilot systems are each briefly described to provide context for more modern control techniques:

- **Orbital Re-entry Digital Autopilot (ENTRY DAP)**: Assumed control of the Command Module (CM) after separation from the Service Module (SM) and handled all Command Module flight maneuvers beginning with reorientation into Entry attitude up until drogue chute deployment. The autopilot called pairs of thrusters distributed along the rim of the base of the Command Module, as well as an additional pair near the tip for pitch-down control. The first phase of operation marked exoatmospheric mode, using various combinations of rate damping, attitude-hold, and attitude-control depending on the pitch angle value. Phase-plane logic controllers[1] (attitude rate versus attitude error) with biased deadzones drove the system to desired error tolerances. Once drag rose above 0.05g, atmospheric mode was initiated. In this regime, roll control was maintained using a complex phase plane incorporating a straight control line, maximum velocity boundaries, and constant-acceleration switching lines, while yaw and pitch reverted to rate-damping using a yaw rate versus roll rate phase plane logic and a simple relay with deadband, respectively. The purpose of ENTRY DAP was to maintain the component of lift in the trajectory plane needed to target a desired landing site given the vehicle's current position and velocity.
- **Reaction-Control System Digital Autopilot (RCS DAP)**: Responsible for controlling the attitude and attitude rates of the Command Service Module during coasting flight, both with or without the Lunar Module (LM) stage attached. The Digital AutoPilot employed for pitch, yaw, and roll control four clusters, called quads, of four Reaction-Control System thrusters each, using a phase-plane logic controller with nonlinear switching lines, a central deadband, and built-in hysteresis. The timing and firing commands of individual thrusters were issued by a thruster-selection logic responsible for

[1]Phase-plane controllers are typically used to determine stabilizing on-off control inputs for one degree-of-freedom differential systems by defining a coordinate plane of two state variables (typically a state error and its corresponding state rate error) and a set of *switching curves* with accompanying "deadband," "hysteresis," etc. in such a way as to partition the space into disjoint control regions that drive the system to within certain limits of the coordinate plane origin. Figure 1 shows a schematic of the phase-planes used by the Apollo missions.



(a) Apollo PGNCS RCS Automatic Control Logic.



(b) Apollo PGNCS Phase Plane.

Fig. 1. Illustrations of one of the earliest successful spacecraft autonomous control systems for the NASA Apollo Command Service Module (CSM). Figure (a): Block diagram logic used by Reaction Control System thrusters to control CSM attitude. Here θ_d represents the reference attitude angle, θ_e the attitude error, β an attitude bias, ω the attitude rate, and $\hat{\omega}$ the attitude rate estimate. Figure (b): Phase-plane logic schematic. For double-integrator models, this design can be shown to drive the rate and attitude errors plotted on the x- and y- axes to the box-like area near the origin. The logic works by breaking the plane into disjoint zones, inside of which the spacecraft is pre-programmed to torque positively or negatively (solid white areas) or coast (shaded region); horizontal lines represent zero-acceleration trajectories or "coasting arcs," while parabolas represent lines of constant acceleration.
Images courtesy of (Widnall, 1968)

resolving Digital AutoPilot rotation commands with translation commands and executing them as economically as possible according to the distribution of functional thrusters available. A second-order angular-rate Kalman filter was used to compute estimates of angular velocity by weighted sum of (1) extrapolated values of previous estimates and (2) derivations from gimbal angle measurements.

- **Thrust-Vector-Control Digital Autopilot (TVC DAP)**: Used to control the Command Service Module during powered flight, both with or without the Lunar Module attached. Pitch and yaw were adjusted by actuating the gimbal servos of the main engine, while a separate autopilot called TVC ROLL DAP controlled the Command Service Module attitude and rate about the roll axis during powered flight via the Reaction-Control System thruster quads. TVC DAP fed estimates of attitude rate and angle errors to pitch and yaw compensation filters, with various combinations of attenuation and phase stabilization depending on the configuration of the Command Service Module due to the changes in overall center-of-mass position, bending modes, and fuel slosh instabilities. TVC ROLL DAP used an adaptation to the phase-plane switching logic of RCS DAP in free flight, modified with ideal parabolic switching curves for roll axis attitude-hold within a small tolerance. A number of logical constraints were additionally enacted in order to conserve fuel and minimize the risk of thruster failures.

2) Model Predictive Control: Model predictive control (MPC) is a feedback law based on the repeated solution of an optimal control problem (i.e. Problem $\mathcal{G}\&\mathcal{C}$) that uses an assumed dynamics model f and the current state set as the initial condition. This problem is solved to yield a finite-horizon control trajectory that optimizes the predicted state response over the duration of a planning period or *time horizon*. Once solved, however, only the initial control segment is actually applied, after which the problem is reinitialized and the process repeats until convergence to the goal. This characteristic renewal procedure over a repeatedly updated horizon is what gives MPC its other common names: *receding horizon optimal control* or *moving horizon optimal control*. This concept allows one to design a feedback controller on the basis of nearly any open-loop optimal control approach, improving its robustness and imparting it the ability to handle disturbances and mitigate error growth. Even without prior disturbance modeling, one can demonstrate under appropriate assumptions that MPC can lead to closed-loop stability and state convergence to the target (Mayne et al., 2000). Other advantages of MPC include the ability to handle pointwise-in-time state and control constraints, the capability to withstand time delays, and reconfiguration in the presence of degradations and failure modes (Camacho and Bordons, 2007; Carson et al., 2008). As the robustness properties of MPC are contingent on fast resolvability, open-loop controllers for vehicle guidance for the most part must be restricted to convex optimization routines. Another common choice for use with MPC schemes in autonomous spacecraft guidance is Mixed-Integer Linear Programming (MILP) (Breger and How, 2008; Richards et al., 2002), which are essentially solvers for linear optimization problems with embedded discrete variables to handle simple logical constraints such as mode switching and collision-avoidance.

3) Artificial Potential Functions: The artificial potential function (APF) method (Badawy and McInnes, 2008; Bevilacqua et al., 2011a; McInnes, 1995) transforms the guidance problem into particle motion within a potential field. Attractive potentials are used for goal regions, while repulsive potentials are used for obstacles; the value of occupying a particular state is then represented by the sum of individual terms. A gradient ascent/descent routine is often called to trace a feasible path from any initial state, which, when tuned appropriately, will safely circumnavigate neighboring obstacles and converge to a goal. Alternatively, an optimal control problem may be formed to plan a path that minimizes the path integral along the gradient force field (analogous to minimum-work in physical systems). The approach benefits greatly from the ability to react in real-time to environmental changes through adjustments in individual potential functions. Some difficulty lies in adjusting each function such that the spacecraft behaves as desired (i.e. ensuring sufficient margin from obstacles, rapid convergence, etc). However, the main drawback of APFs is their well-known susceptibility to converge to local minima, which cannot be avoided without additional heuristic techniques. This tendency can be mitigated by attempting random walks out of local wells, or instead relying on a global optimization routine for open-loop control, with an artificial potential function method called for closed-loop feedback (i.e. trajectory-following, bubble methods (Quinlan and Khatib, 1993), or real-time path modification (Brock and Khatib, 2000), for instance).

4) Spacecraft Motion Planning: Motion planning constitutes a class of algorithms used to generate sequences of decisions, called *plans*, that safely navigate robots from given initial states to a set of target states called *goals*. The framework is sufficiently general that it applies equally well to spacecraft and rovers as it does traditional robots (LaValle, 2006). Motion planning techniques can be classified into two categories: *exact* (combinatorial) algorithms and *approximate* (sampling-based) algorithms. Exact approaches develop a strategy based on an explicit representation of the unsafe region of the state space, which allows them to guarantee a solution if one exists. Techniques typically involve the formation of roadmaps, which are topological graphs that efficiently capture the connectivity of points in the obstacle-free state space. Exact algorithms are often limited to problems of low-dimensionality, polygonally-shaped obstacles, and static environments. Sampling-based algorithms, on the other hand, forgo explicit construction of the unsafe state space and instead explore pathways via a sampling procedure, with safety verified by a “black-box” collision-detection routine. In many ways this idea is computationally advantageous; however, it has the obvious drawback that weaker notions of correctness and completeness must be tolerated — existence of solutions cannot be guaranteed in finite time without drawing an infinite set of samples. Prominent examples of sampling-based algorithms include Probabilistic Roadmaps (PRM) (Kavraki et al., 1996), the family of Rapidly-Exploring Random Tree (RRT) algorithms (LaValle, 2006; LaValle and Kuffner, 2001), and Fast Marching Trees (FMT*) (Janson and Pavone, 2013) together with its kinodynamic versions (Schmerling et al., 2015a,b). Sampling-based motion planning algorithms such as these have been shown under mild conditions to quickly and uniformly explore the collision-free state space. Some of them (e.g., RRT* (Karaman and Frazzoli, 2010) and FMT* (Janson and Pavone, 2013)) have the added benefit of *asymptotic optimality*; that is, they guarantee convergence to an optimal solution as the number of samples goes to infinity.

5) Recent Demonstration Missions: A handful of autonomous maneuvering missions have demonstrated at least a few of these state-of-the-art methods (combined with digital logic). Prominent examples include JAXA’s ETS-VII (Kawano et al., 2001; Oda, 2001), AFRL’s XSS-10 (Davis and Melanson, 2004), DARPA’s Orbital Express (Howard et al., 2008), NASA’s DART (Rumford, 2003), and JAXA’s Hayabusa (Fujiwara et al., 2006; Yano et al., 2006). Sadly, notable guidance and control anomalies and mishaps occurred during the latter three missions, in some cases spelling their end (DART Mishap Investigation Board, 2006; Kawano et al., 2001; Yano et al., 2006). The DART spacecraft, for instance, began using much more propellant than expected during proximity operations and initiated a series of maneuvers for departure and retirement, but eventually collided with the MULBCOM satellite (DART Mishap Investigation Board, 2006). This suggests that presently autonomous spacecraft navigation and maneuvering, even in static environments with well-understood dynamics, is still in its technological infancy (Breger and How, 2008; Steering Committee for NASA Technology Roadmaps, 2012).

D. Challenges and Future Directions

Many technical hurdles remain to be solved before autonomous spacecraft relative guidance can become a mature technology. This section begins in Subsection II-D1 with a summary of the most important relative guidance challenges concerning general spaceflight, from which the discussion is specialized to two key areas: Planetary Entry, Descent, and Landing (EDL) in Subsection II-D2, and Proximity Operations in Subsection II-D3, a blanket term that encompasses Autonomous Rendezvous and Docking (AR&D), Autonomous Inspection and Servicing (AIS), and close-range operations about primitive bodies.

1) General Relative Guidance Challenges: The main guidance challenge for next-generation autonomous spacecraft is to solve the guidance and control problem (Problem $\mathcal{G}\&\mathcal{C}$) with the appropriate dynamics and constraints onboard and in real-time. This onboard capability will enable the execution of missions with a much higher level of autonomy, ultimately prolonging mission times, increasing mission frequencies, decreasing costs, and returning more scientific data. Furthermore, it will allow the spacecraft designer to fully utilize the performance envelope, thereby maximizing achievable performance.

The most important technical challenges to meet this ambitious goal are:

- **Implementability**: Developing robust, real-time implementable, and verifiable onboard optimization algorithms for the solution of Problem $\mathcal{G}\&\mathcal{C}$;
- **Verifiability**: Developing design metrics and verification and validation methods for real-time optimization-based guidance and control algorithms;
- **Formation Flight**: Extending guidance techniques to multiple collaborative vehicles;
- **Testing**: Demonstrating next-generation autonomous algorithms in representative flight testing.

Meeting these challenges will require development of new mathematical formulations and algorithms for *robust, real-time implementation* and for ground analysis. For example, if one can express Problem $\mathcal{G}\&\mathcal{C}$ as a convex optimization problem for a given application, then one can employ Interior Point Method algorithms (IPMs) to achieve globally-optimal solutions (Boyd and Vandenberghe, 2004; Nesterov and Nemirovsky, 1994), as well as improve runtime execution speeds by 2-3 orders of magnitude (Mattingley and Boyd, 2010). This clearly motivates the use of real-time convex optimization for relative guidance whenever possible, either in the ideal case through lossless convexification (as in (Harris and Açıkmeşe, 2014a), for example) or through reasonable convex approximations, particularly for complex, difficult, or hazardous problems where the important need is a reasonably-good feasible solution obeying all mission constraints.

Verifiability of solution methods is also another interesting and important challenge. In classical linear feedback control, one has prescribed design metrics such as “phase” and “gain” margin specifications that serve as useful targets in the design of feedback controllers. It is relatively straightforward to check whether these requirements are satisfied at design time. In the case of more complex guidance algorithms, on the other hand, such general metrics do not exist. A good example can be given in the context of Mars precision landing, for which the trajectory designer must direct a vehicle from any initial state at the end of the parachute phase to a target on the Mars surface with zero velocity. Suppose the expected set of initial conditions at the start of powered descent is $\mathcal{I}_{pd}$. Define $\mathcal{I}_c$ as the set of all initial conditions from which the lander can reach the target, assuming fixed control parameters such as propellant mass fraction, thrust-to-weight ratio, fuel consumption rate, etc. Then verification simply requires checking whether the following set inclusion relationship holds:

$$\mathcal{I}_{pd} \subseteq \mathcal{I}_c \ ?$$

The next question is how to generate $\mathcal{I}_c$ for a given set of design parameters. Exact approaches devised for discrete systems conduct systematic searches through a finite state-space, collecting information about reachable sets and the properties of the states traversed (Clarke et al., 1994; Yu and Cheng, 2010). However, due to the exponential growth in state-space size with dimension, this is infeasible for continuous or high-dimensional systems. In such instances, one must resort to approximate techniques, collectively called *reachability analysis*, for computing the set I_c. Clearly one approach is exhaustive search of sample points in the set; however, this is very time consuming and not usable at design time. Many efficient alternatives have been developed, however, including (1) optimal control and Lyapunov-based theory (Gayek, 1991), (2) state abstraction, in which state-space size is reduced by grouping states together through omission of less useful details (Lefebvre and Guéguen, 2006), (3) propagation of conservative over-approximations to the true sets (Stipanovic et al., 2004), and (4) convexification of Problem $\mathcal{G}\&\mathcal{C}$ through exploitation of the problem structure.

The next challenge is to extend guidance techniques to *multiple collaborative vehicles*. This complicates problem formulation and solution methods, rendering complex problems even more so when real-time solutions are demanded. The difficulty lies in the coupling between the safety of each vehicle to the future trajectories of all of its neighbors. This is often resolved in the literature by forming a hierarchy in planning, in which one vehicle neglects its neighbors and develops a plan, the second then develops a plan assuming the first’s path is fixed, the third designs a path under the consideration of the first and second, and so on. However, this technique makes the key assumption that all current and future state information of each vehicle is freely communicable to all other vehicles. As this illustrates, multiple vehicle collaboration and guidance entails the need for communication and scheduling. This generates the question of which control architecture, or rather communication architecture, is most suitable to the application. Control architectures vary from either fully individualized control called *distributed control*, or fully dependent control called *centralized control*, in which one vehicle or mothership determines the plans for all other vehicles. A number of methods have been developed to handle multiple spacecraft guidance, including specialized formation or coordination controllers (e.g. (Beard et al., 2001; VanDyke and Hall, 2006)), passive/active relative orbit formulations (e.g. Clohessy-Wiltshire-Hill equations, halo orbits about libration points) (Ardaens and D'Amico, 2009; Gill et al., 2007), optimal formation reconfigurations (Scharf et al., 2004), rigid body or quasi-rigid body rotation planning (Blake, 2008), potential-based methods (Chang et al., 2003) and behavioral planning (Izzo and Pettazzi, 2007). Much of the literature focuses on simple formation flight architectures, such as leader-follower formations. Formation flight and collaborative decision-making remain highly active areas of research.

In summary, the key for autonomous relative guidance is having robust solution techniques that can be made efficient for real-time implementation. Though some of these techniques may not be implementable on current space-qualified flight computers, the natural increase in onboard computational power and the use of multiple processors with algorithm parallelization could enable their use in the not-too-distant future. Therefore, priority in research must first be to develop robust solution methods for the right problems with appropriate constraints. Subsequently, these algorithms should be customized for flight implementation. Finally, a rigorous process (preferably combined with flight testing) should be established for solution verification and validation.

The following subsections II-D2–II-D3 specialize the general challenges of this subsection to planetary EDL and proximity operations, each illustrating the types of difficult, mission-critical control maneuvers that typically lie at the cutting edge of modern spacecraft autonomy research.

2) Challenges for Planetary Entry, Descent, and Landing: This subsection focuses on the GN&C challenges associated with planetary missions, first highlighting the difficulties of Mars and Moon landings before extending to other planetary bodies.

The main purpose of any planetary landing GN&C system is to execute a controlled deceleration from orbital or interplanetary velocities to near-rest conditions. For a typical Mars EDL mission, this begins with an entry phase (see Figure 2) that cancels most of the planetary relative velocity. Once slowed to supersonic speeds, a parachute is deployed. Then at a prescribed altitude (e.g. approx. 2 km for the Mars Science Laboratory (MSL)), the parachute is discarded and the Powered Descent (PD) phase is initiated. At this point, passive descent during the parachute phase coupled with atmospheric density and weather uncertainties cause the predicted positions and velocities relative to the target to disperse significantly (e.g. on the order of 8-10 km with a velocity trigger (used during the MSL mission) or 5-6 km with a range trigger at the start of the parachute phase (Way, 2011)). To achieve precision landing (roughly 1 km of position error or less at touchdown), an autonomous, real-time Powered Descent Guidance (PDG) algorithm is required to continuously redirect the vehicle towards the surface target. In manned missions,

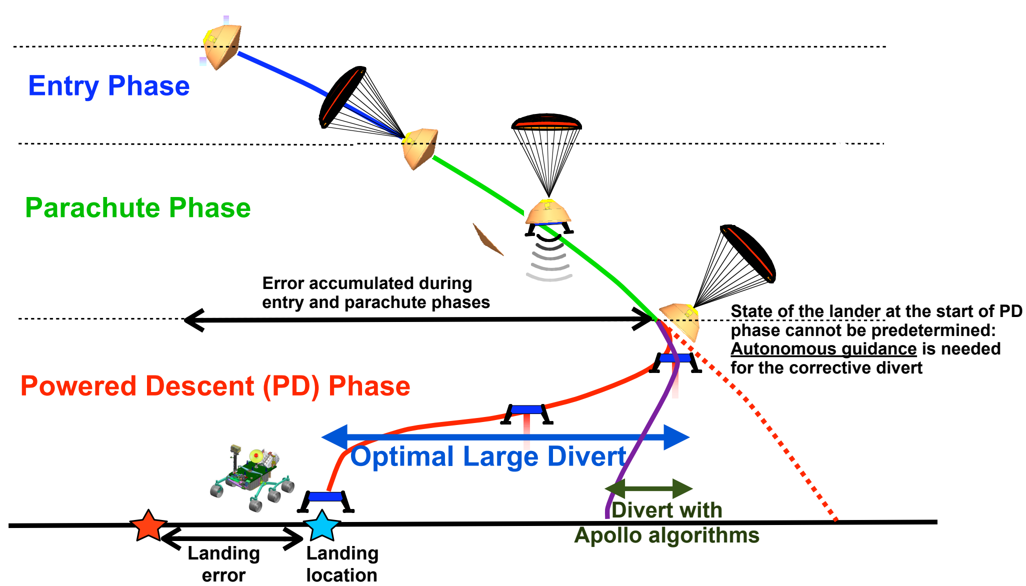


Fig. 2. Optimal Powered Descent Guidance (PDG) will enable planetary precision landing. These algorithms search over all physically possible diverts to find a fuel optimal one, significantly improving divert capability over current state-of-the-art onboard algorithms.

the challenges are magnified and still largely unsolved. Though robotic landers can weigh as little as about 2 metric tons, they are expected to require as much as 50 metric tons in the manned case, which essentially precludes any passive means of deceleration. Successful planetary descent of such heavy landers will necessitate active control starting at supersonic speeds early in the EDL entry phase.

For planets or moons without an atmosphere, a solid rocket is typically used for lander deceleration in a Braking Burn phase, which is then followed by a Powered Descent controlled by liquid fuel propulsion for final landing. The process is complicated by the fact that solid rockets must burn all of their fuel to completion once initiated. Significant uncertainty generally exists in the associated burn-time, leading to uncertainty in the vehicle state relative to the target at the end of the burn phase. Analogous to atmospheric entry and descent, the Powered Descent phase is designed to correct for any error accumulated during the solid rocket phase; autonomous PD guidance algorithms must be called to guide the lander as close as possible to the given surface target in order to achieve optimal landing accuracies.

In all planetary or lunar landing missions, the associated autonomous guidance problems for translational motion can be expressed as highly-constrained optimal control problems (Açıkmese and Ploen, 2007; Blackmore et al., 2010; Steinfeld et al., 2010). Written in terms of Problem $\mathcal{G}\&\mathcal{C}$, the guidance equations can be represented as follows: Let $x = (x_1, x_2, x_3)$, where $x_1 \in \mathbb{R}^3$ and $x_2 \in \mathbb{R}^3$ are the position and velocity, respectively, relative to the target in the rotating frame of Mars, and $x_3 > 0$ is the lander mass. The guidance problem can be formulated as,

$$
\begin{aligned}
\dot{x} &= f(t,x,u) = A(\omega)x + B\left(g(x_1) + \frac{u}{x_3}\right) \\
\mathcal{X}(t) &= \begin{cases} \{x \mid x(t) = x_0\} & \text{for } t = t_0 \\ \left\{x \mid \gamma \hat{n}^{\mathrm{T}} x_1(t) \geq \|Tx_1(t)\| \text{ and } \|x_2(t)\| \leq \bar{V}\right\} & \text{for } t \in (t_0, t_f) \\ \{x \mid Hx(t) = a\} & \text{for } t = t_f \end{cases} \\
\mathcal{U}(t) &= \left\{u \mid \rho_1 \leq \|u\| \leq \rho_2 \text{ and } \hat{n}^{\mathrm{T}} u \geq \|u\| \cos\beta\right\}
\end{aligned}
$$

where $A(\omega)$ defines the Newtonian motion in a rotating frame with fixed rotation rate ω and $g : \mathbb{R}^3 \to \mathbb{R}^3$ defines the gravitational field. Here $\mathcal{X}(t)$ captures initial and final state constraints, along with constraints during the maneuver (known as "glide slope" constraints (Blackmore et al., 2010)). The control vector norm has both an upper bound ρ_2 and a nonzero lower bound ρ_1 due to the fact that the thrusters cannot be operated reliably below a prescribed value. The other constraint on the thrust vector is that it has to remain in a cone defined by the unit surface norm, $\hat{n} \in \mathbb{R}^3$, and half-angle β in order to avoid any possibility of rotating the lander excessively, which could interfere with sensors that must be directed towards the surface. Note that the vehicle is assumed to be a point mass with a thrust vector attached to it. This simplification is a valid one since the attitude control authority and bandwidth are much higher than those for translation, so that the vehicle can quickly adjust its orientation any time a thrust vector is commanded.

As one does not know with certainty the initial relative state x_0 into which the lander will inserted from interplanetary flight, this problem must be solved autonomously in real-time on-board the spacecraft. To accommodate this, some authors have developed simplified, approximate versions of this problem that lend themselves to analytical solutions (D'Souza, 1997; Klumpp, 1974; Meditch, 1964; Najson and Mease, 2006; Topcu et al., 2007); however, to certify precision guidance across the entire landing envelope (the initial conditions from which it is physically possible to land), one must explicitly account for the full set of constraints. Unfortunately, the control constraints $\mathcal{U}(t)$ define a non-convex set (due to $\rho_1 > 0$), which further emphasizes, as previously described, the benefits of lossless convexification techniques (Açıkmeşe and Blackmore, 2011; Açıkmese and Ploen, 2007; Blackmore et al., 2010; Harris and Açıkmeşe, 2014b) and convex relaxations that are solvable using Interior Point Methods (IPMs). The lossless convexification-based algorithm (Açıkmese and Ploen, 2007) has already been demonstrated successfully by NASA JPL. See (JPL and Masten Space Systems, 2012a,b,c) for flight videos. These test flights successively demonstrated increasingly aggressive optimal divert maneuvers, starting from 100 meters for unoptimized flight and ending with the longest possible optimal divert of 750 meters, showing strong evidence that performance boundaries can be pushed to the ultimate physical limits via onboard optimization.

3) Challenges for AR&D, AIS, and Proximity Operations about Primitive Bodies: In AR&D, AIS, and close proximity operations near space objects (such as spacecraft or primitive celestial bodies) that are cooperative or otherwise, the primary guidance objective is to compute a state trajectory that safely brings the spacecraft as close as needed (including docking) to its target object while consuming as little fuel as possible and avoiding any nearby hazards. In general, this introduces many difficult, non-convex trajectory constraints into the optimal control problem given by Problem $\mathcal{G}\&\mathcal{C}$ (Richards et al., 2002). A detailed list of examples are included here to illustrate the point:

- **Constraining sensor field-of-view**: Often in proximity operations it is necessary to keep the target, spacecraft or primitive body in the field-of-view (FOV) of onboard sensors. This can be represented mathematically as:

$$\hat{n} \cdot (r - r_T) \geq \cos\alpha \|r - r_T\|$$

  where $\hat{n}$ is the unit vector describing the sensor boresight, r is the position vector of the spacecraft, r_T is the position vector of the target body, and α is the half-cone angle defining the FOV. This constraint *couples* the attitude and translational dynamics through $\hat{n}$, which is determined by the orientation of the spacecraft. To see this explicitly, if the position vectors are resolved in a rotating reference frame, e.g. LVLH (Local-Vertical-Local-Horizontal), and $\hat{n}$ is resolved in a spacecraft fixed frame, then the equation above can be re-expressed as,

$$(r - r_T)^{\mathrm{T}} C(q)\hat{n} \geq \cos\alpha \|r - r_T\|$$

  where q is the quaternion describing the attitude of the spacecraft, and $C(q)$ is the directional cosine matrix that takes a vector in the spacecraft body reference frame to the LVLH frame.

- **Avoiding plume impingement**: Impingement of thruster exhaust plumes on neighboring spacecraft poses a serious threat that can jeopardize sensitive optical devices, generate large force perturbations and disturbance torques, and disrupt thermal blankets and coatings (Goodman, 2006). Prevention requires restricting thrusters that are pointed towards neighboring vehicle(s) from firing below a prescribed relative distance. Unfortunately, this imposes a loss of control authority and necessitates special guidance or escape plans that never apply thrust forces directed away from the target when in close proximity. This constraint exists for primitive bodies as well due to scientific contamination concerns, i.e. during sample return.
  Represented mathematically, plume impingement constraints can be stated as, for $i = 1, \ldots, n_t$,

$$u_i = 0 \quad \text{when} \quad \begin{cases} (r - r_T)^{\mathrm{T}} C(q)\hat{t}_i \geq \cos\beta_p \|r - r_T\| \\ \|r - r_T\| \leq R_p \end{cases}$$

  where n_t is the number of thrusters, u_i is the thruster force command, $\hat{t}_i$ is the unit vector for the thruster direction in a spacecraft fixed frame, β_p is the plume cone angle, and R_p is the maximum effective plume radius (plume is effective if the target is in this radius).

- **Handling thruster force upper and lower (impulse bit) bounds**: Due to fuel energy storage limitations and nozzle design constraints, it is evident that all thrusters have finite upper bounds on the amount of force that they can provide. There is also a minimum nonzero force or impulse (impulse bit) that imposes a lower bound on deliverable thrust; this means that arbitrarily small forces cannot be applied using thrusters. This limits the control precision that can be achieved, which can be critical during docking or proximity operations.
  These constraints, when using force commands, can be expressed as, for $j = 1, ..., n_t$,

$$u_j \in \{0\} \cup [u_{j,1},\, u_{j,2}] \quad \text{where } u_{j,1} > 0 \text{ and } u_{2,j} > u_{j,1} \text{ are min. and max. thrusts}$$

- **Avoiding collisions**: Nothing can be more catastrophic to a spacecraft mission than collisions, which damage or destroy participating vehicles and often mark an immediate mission failure. For AR&D and AIS, the collision avoidance constraint can be described as follows,

$$r - r_T \notin \Omega_c$$

  where r_T is the position vector for the target and Ω_c is a set of relative positions that lead to collisions. For a two-spacecraft scenario as in AR&D and AIS, this can be simply a collision ball defined as $\Omega_c = \{z : \|z\| \leq R_c\}$ for some prescribed value of R_c. In proximity operations around primitive bodies, this region can be much more complicated due to their irregular and often ill-defined shapes.
- **Providing required thruster silence times**: As thrusters fire, large errors are introduced into the state estimation due to process noise at the instance of firings. Often after each burn there must be a prescribed period of thruster silence to allow the state estimator to filter this noise and re-converge to a prescribed level of accuracy.
  One approach to impose prescribed thruster silence is to have zero controls in prescribed time periods during a maneuver, i.e.,

$$F_i(t) = 0, \;\; \forall i = 1, ..., n_t \quad \text{when} \quad t \in \bigcup_{j=1,\ldots,n_s} \mathcal{T}_j, \tag{1}$$

  where $\mathcal{T}_j, \; j = 1, ..., n_s$ form a disjoint set of zero-thrust time intervals.
- **Using minimal fuel**: Every spacecraft mission is constrained by a finite supply of fuel that must be transported with the scientific payload. The high cost of access to space currently inhibits the ability to refuel or resupply spacecraft, for the most part isolating them and imposing a mission lifetime synonymous with remaining fuel. This not only affects mission lifetime but also mission capability. For example, AIS missions seek to maximize total inspection time, which has a direct correspondence with maximizing fuel efficiency. For primitive bodies, using fuel efficiently implies longer observation times and more attempts for surface contact.
- **Guaranteeing safety**: A trajectory solution is needed that can ensure spacecraft and mission safety at all times, for both the vehicle and its neighbors. Guarantees are typically classified into two forms: *passive safety*, in which coasting arcs emanating from points along the nominal guidance trajectory are certified as safe, or *active safety*, in which safe actuated abort sequences called collision avoidance maneuvers (CAMs) are enforced (Fehse, 2003, 4.4). In either case, hard (deterministic) safety constraints are required to guarantee viable escape options in the event of thruster allocation errors (misfirings, stuck-on or stuck-off valves, canted nozzles, etc), unexpected environmental changes and disturbances, or even complete system shutdown. Often in practice this is achieved through ad-hoc open-loop trajectory design (guided by significant technical expertise). However, an automated approach, potentially using optimal control techniques (Breger and How, 2008), positively-invariant sets (Carson et al., 2008; Gaylor and Barbee, 2007; Weiss et al., 2013), motion planning with safe samples (Frazzoli, 2003), or some combination of all three (Starek et al., 2015), will be needed in the future in order to achieve truly autonomous AR&D and AIS capability.
- **Handling uncertainties**: Thruster firings, aerodynamic drag in low Earth orbits, solar radiation pressure, and camera measurements can introduce uncertainties in relative state knowledge and control accuracy. As the spacecraft nears its target, these uncertainties can induce violations in any of the aforementioned mission constraints. Conversely, relative state accuracy typically improves as relative separation decreases. Hence one should embed in autonomous guidance and control algorithms the capability to handle any expected uncertainty directly, i.e. one should incorporate strategies to handle all "known unknowns."

Due to potential coupling between translational and attitude dynamics, one must consider both sets of dynamics in Problem $\mathcal{G}\&\mathcal{C}$. This complicates the problem due to the inherent nonlinearity in the attitude dynamics, leading to nonlinear equality constraints after discretization. Having nonlinear equality constraints means having non-convex constraints, causing the resulting parameter optimization problem to be a non-convex optimization problem. This complicates the numerical solution of Problem $\mathcal{G}\&\mathcal{C}$ significantly. Another source of non-convexity is the collision avoidance constraint; its incorporation can also dramatically complicate the solution algorithm for the same reason.

As a consequence of the nature of these constraints, convexification approaches for AR&D, AIS, and proximity operations appear less suitable in this case than for Entry, Descent, and Landing problems due to the errors incurred through relaxation. Hence new tools will be needed.

It is in this context precisely that motion planning algorithms (Subsection II-C4) have the potential to shine. Numerous studies have already been conducted assessing their feasibility for realistic spacecraft proximity operation scenarios (Frazzoli, 2003; Frazzoli et al., 2001; LaValle and Kuffner, 2001; Phillips et al., 2003; Starek et al., 2015). Though not yet flown on spacecraft hardware, their efficacy has already been proven in real-world systems with challenging dynamics, namely onboard real-time guidance of urban vehicles during the 2007 DARPA Urban Challenge. Several winning entrants to the 60-mi autonomous urban driving race used motion planning as their primary guidance logic, including CMU's winning Boss car with Anytime-D^*, Stanford's 2nd-place Junior car with hybrid A^*, and MIT's 4th-place Talos car with RRTs (Buehler et al., 2010; Kuwata et al., 2009; Leonard et al., 2008; Montemerlo et al., 2008; Urmson et al., 2008). The ability of these algorithms to handle such diverse constraints while providing robustness certificates in real-time applications is promising for autonomous spacecraft control.

III. Extreme Mobility

Among the top technical challenges of technology area TA04 is *maneuvering* in diverse NASA-relevant environments – a task that encompasses a wide range of environmental, gravitational, and topographical conditions. Space exploration in such environments is enabled by three types of maneuvering: surface mobility, above-surface mobility, and below-surface mobility. We focus here on the part of surface mobility called *extreme-terrain mobility*, which pertains to terrains with extreme topographies, large distributions of hazards, and/or unique regolith types. During the 2012 NRC review process, two different review boards ranked "extreme-terrain mobility" a high-priority[2] technology for NASA to develop within the next five years. This section discusses the technical aspects and challenges associated with meeting this goal.

A. Scope

Extreme-terrain mobility refers to surface mobility over a range of terrain topographies and regolith properties on bodies with substantial gravity fields. Examples of such topographies and regolith types include highly-sloped crater walls and floors, cold traps, gullies, canyons, very soft and friable terrains, and terrain with extreme rock densities. It is worth noting that other extreme environmental conditions may also be present at such sites, such as extreme temperatures or pressures. Extreme-terrain mobility covers capabilities that enable access and egress to such extreme terrains, safe traverses to designated targets, loitering for in situ measurements, and sample collection and extraction. Extreme-terrain mobility encompasses diverse platforms that may include wheeled, legged, snake, hopping, tracked, tethered and hybrid platforms. Surface guidance, navigation and control for such diverse platforms depend in part on the nature and constraints for the mobility approach. While access to and sampling from extreme terrains can also be accomplished through above-surface mobility, a key feature of extreme-terrain access is loitering at targets of interest for in situ measurements. Since the NRC defined and prioritized above-surface mobility separately from extreme mobility, we only address the latter in this section.

[2]The National Research Council study panel ranked extreme-terrain mobility 6th, while its steering committee ranked it 8th (Steering Committee for NASA Technology Roadmaps, 2012, Table 3.7, p. 88)

B. Need

Extreme-terrain mobility would be an enabling technology for both science and human space exploration missions. For science missions, some of the most compelling targets for future exploration within our solar system lie in terrains that are inaccessible to state-of-the-art robotic platforms, including NASA's Mars Exploration Rovers (NASA, 2011b) and the Mars Science Laboratory (NASA, 2011a) rover.

For example, the recent discovery of recurring slope lineae (RSL), such as those observed in Newton crater on Mars, are on steep slopes (25°–40°) that are hundreds of meters down from the crater rim. *In situ* analysis and sample capture of these out-flow deposits align with the science priorities that are described in both the Decadal Survey (Committee on the Planetary Science Decadal Survey, 2011) and the goals of MEPAG (Mars Exploration Program Analysis Group (MEPAG) Goals Committee, 2010). Similarly, successive flybys by the Mars Global Surveyor revealed dynamic processes in the form of bright gully deposits on the walls of two separate unnamed Martian craters[3]. *In situ* samples of these flows would likely lead to new insights into Martian geology. Moreover, methane plumes that have been discovered over hazardous terrain on Mars are intriguing researchers who are now attempting to ascertain whether the source is geological or biological in nature[4]; this represents another question that extreme-terrain mobility could potentially answer.

Another compelling scientific site that lies within extreme terrain was discovered by NASA's Cassini spacecraft, which revealed what scientists believe to be a cryovolcano on the surface of Titan[5]. Direct sampling of cryovolcanic ejecta along its steep slopes would shed new light on the processes underlying cryovolcanism, as well as provide valuable access to material from Titan's interior.

A third example is from the LCROSS experiment. By impacting the lunar surface and analyzing the ejected debris, the LCROSS mission found evidence of water ice in the Moon's permanently shadowed Cabeus Crater[6] (Colaprete et al., 2010). The shadowed regions lie at the bottom of a long, steep slope. These lunar cold traps, which have never received a single photon of light, are believed to hold water ice within a few centimeters of the surface. At high-probability locales such as these, the assessment of in situ resources in terms of presence confirmation, abundance mapping, and extraction possibilities would be critical for precursor missions ahead of human exploration (Wargo, 2012). Other features such as lunar vents (Hawke et al., 2012) and lava tubes are also potential sites for future exploration. Lava tubes, through observations of skylights on the Moon and on Mars, could potentially serve as future temporary habitats for astronauts, providing them with protection from space radiation (Horz, 1985). The exploration of lava tubes could also be of scientific interest for similar reasons.

A new generation of robotic explorers is needed to explore these extreme terrains in order to access, probe, measure, extract and return samples. Traversing and loitering on steep, exposed substrate slopes reaching up to 90° would enable the examination of stratigraphic layers of exposed bedrock (Mars Exploration Program Analysis Group (MEPAG) Goals Committee, 2010) and icy bodies. While current practice relies on long traverses across the surface to access these layers (Figure 3), direct access of exposed strata enables close examination of the interface between stratigraphic layers, which, due to substantially less weathering, would offer more details compared to what may be obtained through horizontal traverse alone (Conrad, 2009).

Traversing and loitering on slopes of granular and mixed media up to the angle of repose enables access to locales such as the sites of putative "water" seeps on Mars (Figure 4). Traversing across and through alluvial fans for in situ examination would further our understanding of the underlying physical

[3]New Gully Deposit in a Crater in the Centauri Montes Region (2006). URL: http://www.nasa.gov/mission_pages/mars/images/pia09028.html. Retrieved January 14th, 2011.

[4]Martian Methane Reveals the Red Planet is Not a Dead Planet (2009). URL: http://www.nasa.gov/mission_pages/mars/news/marsmethane.html. Retrieved January 15th, 2011.

[5]Flyover of Sotra Facula, Titan (2011). URL: http://www.nasa.gov/mission_pages/cassini/multimedia/pia13695.html. Retrieved January 8th, 2011.

[6]Ten Cool Things Seen in the First Year of LRO (2010). URL: http://www.nasa.gov/mission_pages/LRO/news/first-year_prt.htm. Retrieved February 3, 2011.

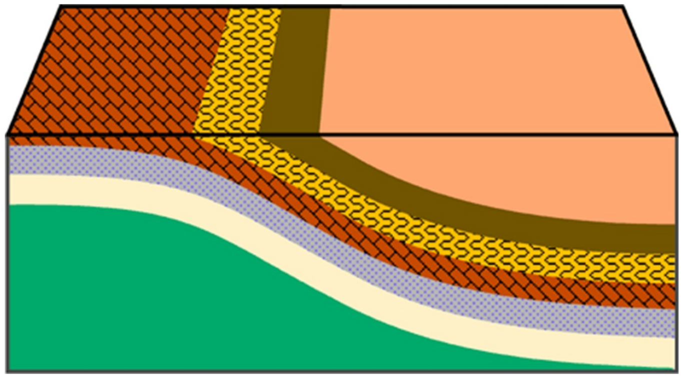


Fig. 3. Comparing horizontal and vertical access to stratigraphic layers. Some deeper layers may not be accessible via horizontal traverses.

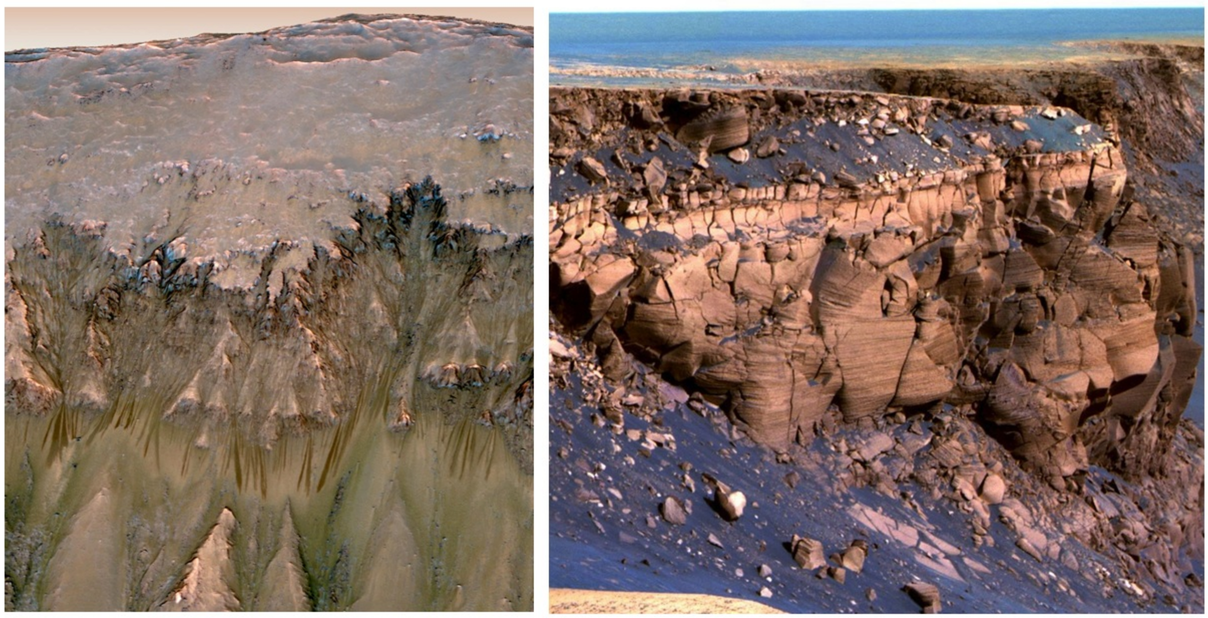


Fig. 4. Examples of extreme terrains on Mars: recurring slope lineae (RSL) in Newton crater hypothesized to be briny seeps (left: NASA/JPL-Caltech/Univ. of Arizona - Mars Reconnaissance Orbiter HiRISE, 2011), and a false-color image of Mars' Victoria crater showing steep slopes, scattered rocks, bedrock, and tall cliffs (right: NASA/JPL/Cornell - Mars Exploration Rover: Opportunity 2007).

processes and composition of the ejected material (Mars Exploration Program Analysis Group (MEPAG) Goals Committee, 2010). As detailed topography of such fans may not be well-known *a priori*, robust and versatile mobility platforms are required for their exploration. Unfortunately, through the course of accessing such extreme terrain, hazards such as sinking into soft regolith or falling via landslides could be encountered. The ability to reliably avoid or survive such events in order to maintain an acceptable risk posture becomes a key feature of these platforms.

Extreme-terrain exploration could be embarked upon with remote robotic assets or could very well be part of human exploration missions. Extreme-terrain robots would extend astronaut surface access to regions deemed too risky for human access. They would also enable robotic precursor missions to explore hazardous sites likely to harbor needed resources for future habitation. Lunar robotic missions to extreme terrain could be operated from cis-Lunar orbit. Future human missions to Mars could tele-operate robotic assets from stations on Phobos, a body significantly more accessible than the Martian surface that would also provide astronauts relatively better protection from solar radiation.

In short, extreme mobility technologies enable access to otherwise denied areas. This provides NASA with the capability to maneuver its surface vehicles in extreme terrain in order to “follow the water” — a high-priority science focus for Martian and lunar science missions that generalizes to many extraterrestrial surface exploration missions, human or robotic (Steering Committee for NASA Technology Roadmaps, 2012).

While the primary motivation and focus here has been on planetary and lunar exploration, robotic vehicles that can traverse extreme terrain may have ample terrestrial applications as well, including in scientific research such as sampling of active volcanoes and Antarctic slopes, in civil applications such as search-and-rescue, or in commercial ventures such as mining.

C. State of the Art

Significant progress in terrestrial robot mobility has been made in recent years towards handling more challenging terrains. However, efforts have primarily focused on human-traversable terrains applicable to military purposes. For example, Boston Dynamics’ BigDog and LS3 used dynamically-stable gaits to negotiate rough terrain and slopes of up to 35° grade under rough and slippery conditions (Boston Dynamics, 2012a,b). They also demonstrated robustness to external force disturbances sufficient to throw the platform off-balance.

For space robotics, the constraints on mass and power as well as the desire to traverse more extreme terrain have limited the adoption of such technologies. Nevertheless, a number of developments have aimed at contributing to our current understanding of the potential strategies for extreme-terrain mobility on planetary bodies. Both legged and wheeled robots, as well as tethered and untethered robots, have been proposed for exploring extreme terrestrial and planetary landscapes, several of which have been built and fielded. For example, the Dante II robot (Bares and Wettergreen, 1999) was a tethered legged robot that was specifically engineered to descend into active volcanoes. Shigeo Hirose’s group has explored self-anchoring tethers and tethered tracked vehicles for emergency response (Hirose and Fukushima, 2004), as well as tethered leg vehicles for fieldwork (Fukushima et al., 2001). The JPL legged ATHLETE robot, designed to handle cargo in support of a sustained human presence on the moon, has traversed rocky and sloped terrain at a number of analog sites in California and Arizona, including Black Point Lava Flow (Wilcox et al., 2007). For slopes greater than 20°, the ATHLETE rover would also use a tether. The Axel rovers[7] (Nesnas et al., 2012), designed to explore very steep terrains, have demonstrated traversal of near-vertical slopes and sloped terrain littered with large boulders. Other robots that use leg-mounted active anchors in lieu of tethers have been proposed (Badescu et al., 2005) and developed (Parness et al., 2013).

In addition to these legged robots, a number of wheeled designs have also been proposed, of which several prototypes have been built, fielded, and flown. One promising example is a recurring mechanism configuration used in either a six-wheeled rocker-bogie suspension (e.g. the MER and MSL rovers) or in a four-wheeled scissor-like active suspension that allows each wheel to be independently lifted off the ground. Such platforms were designed to lower the center-of-mass to provide greater stability. One such example is the Nanorover (Jones and Wilcox, 1997), a grapefruit-sized rover that was proposed for exploring an asteroid surface as part of the MUSES-C mission. This rover had a symmetric design and was capable of operating in an upside-down configuration. It actively controlled its center and was even capable of hopping on low-gravity planetary bodies. Follow-on concepts included tethering the Nanorover to a Sojourner class rover for future Mars missions. The architecturally-similar SCARAB rover demonstrated an inch-worming maneuver that synchronized wheel and suspension mechanism motion to traverse high-slip terrains (Bartlett et al., 2008). Despite this ability, steeper slopes will likely require additional external stabilization, such as through a tether. A four-wheeled tethered rover was demonstrated with Cliffbot (Pirjanian et al., 2002). Unfortunately, this architecture required a minimum of three rovers. Two rovers would traverse the rim of a crater while a third rover, tethered to the other two, would descend into the crater. Lateral mobility with two tethers would generally be greater at closer distances to the rim, but

[7]Axel Videos (2011). URL: http://www.youtube.com/watch?v=Ijjo1nW94tY. Retrieved October 30th, 2014.

this advantage diminishes as the rover descends deeper into the crater. The Cliffbot used the rim rovers to manage the tethers, which, unlike designs that pay out their own tether, risks higher abrasion from constant rock-scraping. Moreover, the Cliffbot cannot recover from tip-over, and the problem of planning the motions of two tethers adds extra complexity.

Outside of four-wheeled rovers, a number of previous efforts dating to the early 1970's have recognized the potential of two-wheeled rovers for steep terrains. Several efforts have converged on a robotic body morphology consisting of a simple axial body with two wheels and a caster, as recently exemplified by the Scout robots (Stoeter and Papanikolopoulos, 2006), designed for military applications. A similar tethered rover with three large inflatable wheels was proposed for future Mars missions (Miller et al., 2000). Independently conceived, the family of Axel rovers was initially developed a decade ago to provide modularity and separation between the most failure-prone mobility elements and their respective science payloads (Howard et al., 2004; Nesnas, 2001). In 2006, the original Axel rover was retrofitted with a tether and adapted with grouser wheels for extreme-terrain mobility on slopes (Nesnas et al., 2008). Such a configuration, with its symmetric design, has demonstrated potential for robust, flexible mobility and operations on challenging terrain. Its single tether was managed by the same mechanism that controls an articulated boom. This family of rovers has also included instrument bays housed inside the wheel hubs, which could be oriented in a turret-like fashion independent of wheel rotation. The DuAxel concept included docking and undocking of the Axel rovers with a central module, enabling both untethered mobility for extreme-terrain access and tethered mobility on steep terrains (Nesnas et al., 2012).

While progress has been made with extreme-terrain mobility for terrestrial applications, at the date of this writing, there has been no planetary mission that has attempted access to extreme terrains. State-of-the-art surface exploration platforms, such as the highly successful Spirit and Opportunity rovers as well as the most recent Curiosity rover, were all designed to operate on relatively flat and shallow-sloped terrains with slopes of less than 20° and 30° grade, respectively.

D. Challenges and Future Directions

To date, planetary rovers have been designed to explore rocky but relatively flat regions and were not intended for terrains such as deep craters, canyons, fissures, gullies and cryovolcanoes. Such extreme terrains pose a unique set of challenges and requirements for a robotic explorer. Researchers developing extreme-terrain surface space robots have to contend with the system complexity that results from high degrees of articulation, tether management, and the challenges associated with limited power, communication, mass, volume, and computation, as well as with terrain variations that impact anchoring and other surface operations. Conventional, flat-topography rover designs must be completely re-evaluated in the context of high-risk terrain missions.

One of the most significant challenges associated with extreme-terrain exploration derives from having to land proximal to but outside of the target site, demanding an approach from afar over diverse topographies that may require unique mobility aids such as tethers, anchors, and higher traction devices. To illustrate, Figure 4 shows a ground-level picture of Mars' Victoria Crater as imaged by the Opportunity Rover. Typical of Martian craters, Victoria consists of steep slopes, scattered rocks, exposed bedrock, and tall cliffs. Rocker-bogie class rovers such as Spirit, Opportunity or Curiosity were not designed for such terrain, and would not likely be well-suited to navigate it. Such terrains would be very difficult to traverse since platform mobility decreases with slope grade, particularly in areas of loose regolith where traction forces can be severely diminished. Given that a sand trap on relatively smooth terrain was enough to ensnare the Spirit rover (Arvidson et al., 2010), even a small amount of loose soil on sloped terrain could prove insurmountable to traditional rovers trying to climb a crater wall against the forces of gravity. Extreme-terrain rovers must be able to operate robustly in such cases.

Another mobility hazard associated with traversing steep and rugged terrain is tip-over, a concern which must be taken into consideration when designing extreme terrain rovers. Tip-over can be caused by improper stabilization, or by other uncontrollable external factors such as wind, slippery ice, loose rocks, and many other environmental factors. In 1992, the eight-legged walking robot, Dante II, successfully descended into Alaska's Mt. Spurr volcano using a winch-cable system (Bares and Wettergreen, 1999). On the ascent trip, however, the rover fell on its side under the influence of large lateral tether forces and was unable to right itself. Extreme-terrain rovers can reduce the risk of tip-over by lowering their centers-of-mass and carefully planning safe routes around obstacles so as to avoid tether entanglement and potential tip-over conditions. Alternatively, such rovers can be designed to operate in both upright and upside-down configurations, thereby eliminating the end-of-mission dangers of tip-over altogether.

Another challenge for extreme terrain mobility is power and communication. Energy sources can be difficult to find in areas of extreme terrain. For example, the Cabeus Crater located near the Moon's south pole lies in a state of near-perpetual darkness, thus precluding the use of solar power. Even with consistent access to sunlight, cold-traps like caves and crevices along crater walls would be difficult to investigate for prolonged periods. Rough terrain consisting of tall peaks, deep craters, or canyons naturally restrict access to sunlight, and rovers charged with exploring these regions must be able to survive on a limited energy budget. Such terrains also present challenges for Earth-based communications with the rover, particularly in the absence of an orbiting communication satellite.

A problem that is unique to the robotic exploration of cold regions, such as the surface of Europa and other icy moons, is heat dissipation. In addition to traditional vehicle thermal engineering for ultra-cold climates, robotic explorers designed for these environments must minimize thermal pollution to nearby terrain so as to avoid disrupting the scientific analysis of volatile components. They must also be designed with sufficient exposed surface area to allow for adequate thermal regulation.

Due to the hazardous nature of the environments and the unique mechanical, thermal, and avionics designs likely required for extreme-terrain mobility, advanced control and autonomy strategies will be needed to operate extreme-terrain rovers safely. This will require more sophisticated onboard sensing, perception, planning and computational capabilities than for state-of-the-art flat-topography rovers due to the larger variations in terrain, more complex dynamics, and tighter operational constraints. Of all the avionics systems, flight-qualified processors typically represent the bottleneck on computational capability and hence restrict the types of algorithms and approaches that may be considered. Unfortunately, the performance gap between current standard commercial processors and flight processors remains quite large. In the commercial sector, the trend is moving toward greater parallelism and multiple-core processing. Achieving comparable levels of computation, power consumption, robustness, and reliability with a similar form factor on space-rated processors in the face of increasing cost constraints remains an open problem.

In addition to these general challenges, each platform design would offer its own range of capabilities and introduce its own sets of constraints to be addressed and risks to be retired. A concerted and focused effort would be necessary to mature technology to readiness levels acceptable for future missions. Key areas of technology investments for extreme-terrain access include: traversal to designated targets in extreme terrains, retro traverse for captured samples, control of tethered or anchoring platforms including anchoring and deanchoring, avionics equipment built for hazardous terrain, traversability analysis and motion planning, and high-fidelity terrain modeling and simulation of extreme-terrain mobility. We now discuss in greater detail the major technical hurdles and challenges of each, below.

- **Traverse Technologies**: In the absence of higher precision and pinpoint landing capabilities that could deliver a payload to the vicinity of an extreme terrain site, it becomes necessary to traverse a distance of at least several kilometers to reach them by ground. In this case, technologies that would enable faster autonomous traverse for flight systems become critically important. State-of-the-art platforms currently navigate the surface at a rate of 20-30 m/sol using a computationally-demanding procedure. They first process stereo imagery, generate three-dimensional maps, and assess terrain traversability. If feasible, they then plan their motions and finally conduct their traverse. This sequential process can take up to several minutes for every half-meter step. This is primarily driven by the limited on-board power and computation on today's flight-qualified processors and by the lack of dedicated processors for computationally-demanding applications. Recent developments have made advances in migrating computationally-intensive vision processing and some navigation functions to flight-relevant fieldprogrammable gate arrays (FPGAs). This also enables vision-based pose estimation (a.k.a. visual odometry) to run more frequently and consequently help build more accurate maps that enhance the quality of the navigation. Higher quality maps would enable rovers to handle more challenging terrain and execute tighter maneuvers in rock fields, such as thread-the-needle type maneuvers where the rover negotiates a path between two tightly-spaced obstacles. As terrain topographies become more uncompromising near extreme sites, algorithmic advances in surface navigation become more critical to reach targets of interest. One such example is driving upslope towards a crater's edge before deploying a tethered payload into the steeply-sloped interior of the crater wall. As mobility in extreme terrain is likely to become more dynamic, advances in computationally-efficient localization would be necessary to improve control and mapping. In the future, onboard sensing is likely to be fused with higher-resolution orbital imagery for assessing terrain traversability in more effective and automated ways.

- **Tethered/Anchored Mobility and Control**: This brings us to a second technology: tethered and anchored mobility. Highly-sloped terrains require strong and robust mechanical support to counteract the effects of gravity. One approach would be to use an external means of mechanical support. Research in tethered mobility has included the design and management of both single and multi-tethered platforms. Future studies would need to focus on strategies that preserve tether integrity, improve coordination, minimize damage, and reduce the risk of multiple-tether entanglement. Other technologies would include tether tension and shape sensing to assist in pose estimation and identify high stress (i.e. pinch) points. Algorithms would have to become more sophisticated to incorporate this additional sensory information for control and motion planning. Anchoring, either alone or in combination with tethering, can be another means of providing mechanical support to climbing or rappelling platforms on highly-sloped terrains. This can be particularly challenging when terrain properties vary or are not known *a priori*, and would likely require onboard sensing and assessment of anchor bearing strengths. The development of technologies that enable multiple anchoring and de-anchoring across a wide range of terrain types would also be highly beneficial.
- **Avionics and Terrain Equipment**: Given the limited communication windows and bandwidths, some level of control and autonomy would be necessary during operations. While state-of-the-art rovers have demonstrated surface navigation (obstacle detection and avoidance) for hundreds of meters at a time across the Martian surface, such technology would have to be extended to extreme terrains where system dynamics from the challenging topographies and gravity vector direction become relevant. The unique design of extreme terrain mobility may impose additional challenges and constraints on sensor configurations, which would also require further development. Platforms that sport multiple appendages would likely require tool changes when transitioning from benign to extreme terrain. A hybrid legged platform on wheels would likely call for a transition between wheels and anchors when conducting an excursion across extreme terrain. In addition, given that extreme-terrain assets are more likely to be payloads rather than primary platforms due to the overall risk, their low mass constraints would drive a need for smaller and lighter sensors, cameras, inertial measurement units, and other instruments. Miniaturization of avionics equipment would increase payload capabilities. Mission-dependent objectives in extreme terrain such as sample acquisition, caching and handling present their own unique equipment challenges. Drilling and coring require stabilization of the platform or some form of grappling to impart necessary forces for percussion or coring, for instance.
- **Traversability Analysis and Motion Planning**: Control, traversability analysis and path planning for an extreme terrain mobility platform takes on a new meaning than for traditional flat-slope mobility. In extreme terrains, motion may be more constrained (especially for tethered systems), control may require more sophisticated dynamical models given the gravity field, and knowledge of regolith properties may be more critical. As compared with state-of-the-art motion planners that primarily consider terrain geometry and wheel characteristics for traversability, long-duration excursions in extreme terrain would demand more sophisticated motion planning techniques that accurately account for gravitational forces and the effects of terrain properties. Model-predictive motion planners that

incorporate dynamics may well play an important role for executing more predictable and controllable maneuvers in some of the most difficult terrains.

- **High-Fidelity Terrain Modeling and Mobility Simulation**: As a number of challenges need to be addressed to characterize extreme-terrain mobility in a relevant environment, some elements would likely benefit from advances in physics-based modeling and simulation tools. Recent and future advances in granular media simulations may prove quite effective in characterizing the interactions of the mobility platforms (or components) with regolith across a range of terrain types and under different gravity models. Given the hazardous environments and terrains, reliable fault protection and recovery systems would become essential parts of the hardware, software, or operational scenario design. For example, recovery from tip-overs could be addressed via a mechanical design that operates from all stable states or through an alternate operational strategy. With appropriate simulation tools to inform the design, such scenarios and strategies could be more readily investigated and evaluated.

In addition to mobility technologies themselves, there are a number of related technology areas complementary to and supportive of extreme terrain mobility whose advances would have direct impact to mobility research. Brief discussions of a few of the more important of these related technology areas are provided here.

a) Entry, Descent and Landing: One example is landing precision, which falls under the Entry, Descent and Landing technology area (TA-09); see Subsection II-D2 for a detailed description of relevant challenges. The key subcategories of relevance within *entry, descent and landing* are: (a) surface access to increase the ability to land at a variety of planetary locales and times; (b) precision landing that enables space vehicles to land with reduced error, and (c) surface hazard detection and avoidance to increase the robustness of landing systems to surface hazards. Since exploring extreme terrains would first require reaching extreme sites, technologies that would reduce the traverse distance by shrinking the size of the landing ellipse would not only increase the number of potential landing sites, they would also reduce the traverse distance requirement, and hence mission duration, to visit those sites. Further advances in the terminal descent phase, such as pin-point landing (within 100 m) could change the nature of extreme terrain exploration, enabling cheaper missions where the extreme-terrain platform could then be hoisted on a lander and its resources leveraged for power and communication.

b) Below-Surface Mobility: A second related area is *below-surface mobility*, which addresses vehicles that would transit under regolith, in caves, or immersed in bodies of liquid. For certain situations, the same technologies developed for extreme-terrain mobility could be re-purposed for below-surface mobility applications. The exploration of collapsed lava tubes (caves) and lunar vents are two such potential scenarios. For example, tethered platforms originally designed for access to the interior of crater walls could also potentially be reapplied to lava tube exploration.

c) Microgravity Mobility: Technologies developed for *microgravity mobility* as discussed in Section IV, including anchoring, fixturing, and tethering, as well as articulated legged, tracked, wheeled and hybrid mechanisms, could additionally apply to extreme-terrain mobility applications and vice versa. Details on microgravity mobility systems will be given in the subsequent section.

IV. Microgravity mobility

The National Research Council recommended small-body/microgravity mobility as a high priority technology for NASA for the next five years. Initially, microgravity mobility was assigned a medium/low score due to the expensive nature of microgravity system development and testing and its limited applicability outside the aerospace community. The panel later elevated the priority of this technology from medium to high because the NASA 2010 Authorization Act (P.L. 111-267) indicated that small body missions (to near-Earth asteroids) should be an objective for NASA human spaceflight beyond Earth orbit. If this goal is pursued as a high NASA priority, it would also likely require precursor robotic missions to small-body surfaces with applicable mobility capability. This section describes the benefit, technical aspects, and challenges facing the robotics community today in achieving microgravity mobility.

A. Scope

Small-body mobility concerns the spatial surface traversal of planetary bodies with substantially reduced gravitational fields for the purpose of science and human exploration. This includes mobility on Near-Earth Objects (NEOs), asteroids, comets, irregularly-shaped objects, and planetary moons, including Phobos, Deimos, Enceladus, and Phoebe, to name a few notable examples. 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 wheeled rovers and anchoring systems. Microgravity mobility includes hopping, wheeled, legged, hybrid and other novel types of mobility platforms. "Hoppers" – a term short for hopping mobility platforms – move via many diverse forms of actuation; examples include propulsive thrusters, spring-loaded mechanisms, and internal actuation, which effects platform motion using internally moving parts that generate reactionary forces or changes in the platform center-of-gravity. Note that any impacts of hopping robots with the surface are unlikely to cause damage due to the very low gravitational acceleration associated with small-body objects. Broadly-speaking, revolutions in these hardware and mechanism designs, as well as improvements in multi-asset mission operations, low power computing, and autonomous control algorithms, will be key to performing mobile missions in microgravitational environments.

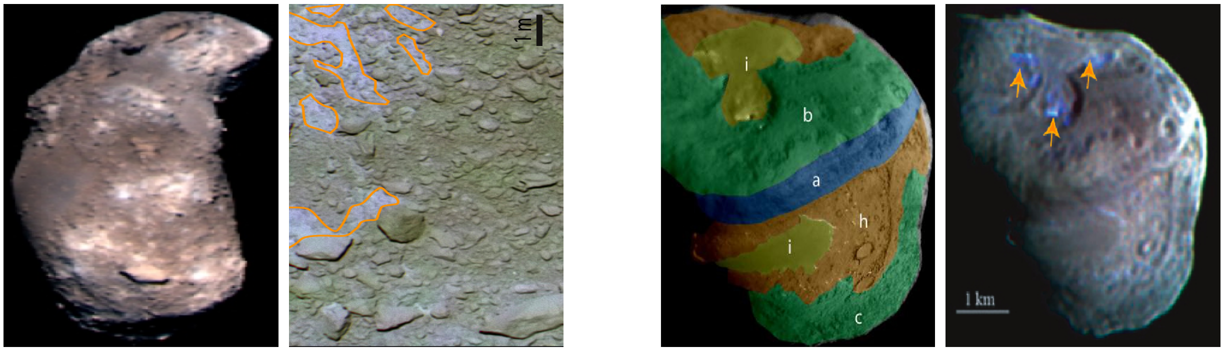
B. Need

Weak gravitational fields (micro-g to milli-g), characteristic of celestial small bodies, hamper the adoption of traditional robotic mobility systems and call for the development of disruptively new technologies for both surface mobility and surface operations. The National Research Council has designated these mobility technologies for small-body and microgravity environments as a high-priority for NASA given their destination potential for human spaceflight beyond Earth orbit, an endeavor likely to require several precursor robotic missions. The relevance of enhancing small-body exploration in the context of future human exploration programs was highlighted in the exploration roadmap published by the Small Bodies Assessment Group (Nuth et al., 2011) and in the objectives of the Strategic Knowledge Gaps for Human Exploration (Wargo, 2012). The need for these technologies is further emphasized by the fact that, to-date, no *mobility* system has ever been successfully deployed over the surface of a small body[8], indicating that little is currently known about robotic operations in microgravity environments.

Surface investigation of small bodies with a low-mass platform for both large-scale coverage and fine-scale maneuvers (i.e. from kilometers to meters), as enabled by microgravity mobility, would be monumental to the advancement of space missions. Data obtained from recent missions to small bodies show that surface properties on most small bodies evolve over scales ranging from hundreds of meters to as little as a few meters (Figure 5 highlights the diversity in surface properties at a variety of scales for two representative objects); this is in contrast to the long-held idea that the surfaces of small bodies are, in general, both chemically and physically homogeneous.

The benefit of microgravity mobility to expected scientific return can be seen explicitly in the recent decadal survey report for planetary science, which prioritized three main cross-cutting themes for planetary exploration: (1) the characterization of the early solar system history, (2) the search for planetary habitats, and (3) an improved understanding about the nature of planetary processes (Committee on the Planetary Science Decadal Survey, 2011). A growing number of ground and space observations have recently shed new light on the astrobiological relevance of small bodies, indicating that the exploration of a selected subset of small solar system bodies would collectively address all three themes (Castillo-Rogez and Lunine, 2012; Castillo-Rogez et al., 2012). The explorations of small bodies such as Near-Earth

[8]Small-body soft landings of spacecraft orbiters and *static* landers have, however, been achieved; the first was NASA's NEAR Shoemaker on asteroid Eros in 2001 (Dunham et al., 2002), followed by two touchdowns of JAXA's Hayabusa on asteroid Itokawa in 2005 (Yano et al., 2006). ESA's Rosetta mission (Ulamec and Biele, 2009) achieved the first successful deployment of a static lander, named *Philae*, over the surface of comet 67P/Churyumov-Gerasimenko on November 12th, 2014 (ESA, 2014).



(a) Asteroid Itokawa.

(b) Comet Tempel 1.

Fig. 5. Illustration of the diversity of landscapes and of physical and chemical properties encountered at small bodies. Figure (a): asteroid Itokawa (observed by *Hayabusa*) exhibits lateral variations in albedo at the regional scale due to the combination of space weathering and surface dynamics (left); high-resolution imaging of Itokawa reveals bright patches of "fresh" material excavated in discrete places with spatial extent of the order of 1 meter, distributed with a spatial wavelength of a few meters (right). Figure (b): observations of comet Tempel 1 by *Deep Impact* also indicates regional variations in geological properties (left), with presence of volatiles in a few discrete places (indicated by arrows, right).

Objects and the moons of Mars are also key components of the flexible path for human exploration. In general, origins science and the search for habitats revolve around characterizing planetary material chemistry (elemental, isotopic, mineralogical, noble gas, organics, etc.). While some measurements could be obtained from remote platforms (such as space telescopes or orbiting spacecraft), most require direct contact with (or close proximity to) the surface, called *in situ measurement*, for an *extended* period of time at *multiple* locations (Castillo-Rogez et al., 2012). This is also the case for the precursor science that enables human exploration, which first and foremost would require the detailed characterization of surface physics, including regolith mechanical properties, dust dynamics, and electrostatic charging (Wargo, 2012). Though in situ exploration of small bodies is currently in its "technological infancy," it is poised to become a major science enabler in the near future, as the following several paragraphs serve to illustrate.

Astronomical observations (such as seen in Figure 6, made by ground-based and space observatories), though particularly suited to characterizing the orbital properties of large populations of objects, are insufficient for constraining the origins of single objects, as resonances can dramatically alter their orbital properties. As a result, in situ exploration plays a pivotal role in determining the density distributions and dynamical properties of small bodies, while allowing more accurate characterization of volatile composition and isotopic ratios. Though isotopic ratios could be determined in some cases through mass spectrometry of outgassing material, most small bodies neither out-gas nor present enough exospheric density to allow such measurements. Hence for a large class of small bodies, the measurement of isotopic ratios requires in situ exploration. With appropriate instrumentation packages, this capability would enable physical and chemical characterization of surface properties relevant to both human and science exploration.

For a given science objective, in situ exploration at *designated* and *multiple locations* should be an integral component of future missions, and techniques for such operations will need to be developed. Two motivating scientific examples are presented here. First, the comet Hartley 2 exhibits two starkly different terrains: very granular areas with vents and smooth areas that have been interpreted as wasting areas. Full characterization of the comet's surface would require sampling at each location. Second, the comet Tempel 1 presents four distinct geological units; in particular, it exhibits cryoflow features (products of its geological evolution) near areas that appear to be less evolved and may be more representative of the original material (see Figure 7). Spatially-extended exploration of Tempel 1 would be key to capturing information on the accretional environment of that object as well as on signatures of its long-term evolutionary processes.

In summary, in situ information enabled by surface mobility about the chemical and physical hetero-

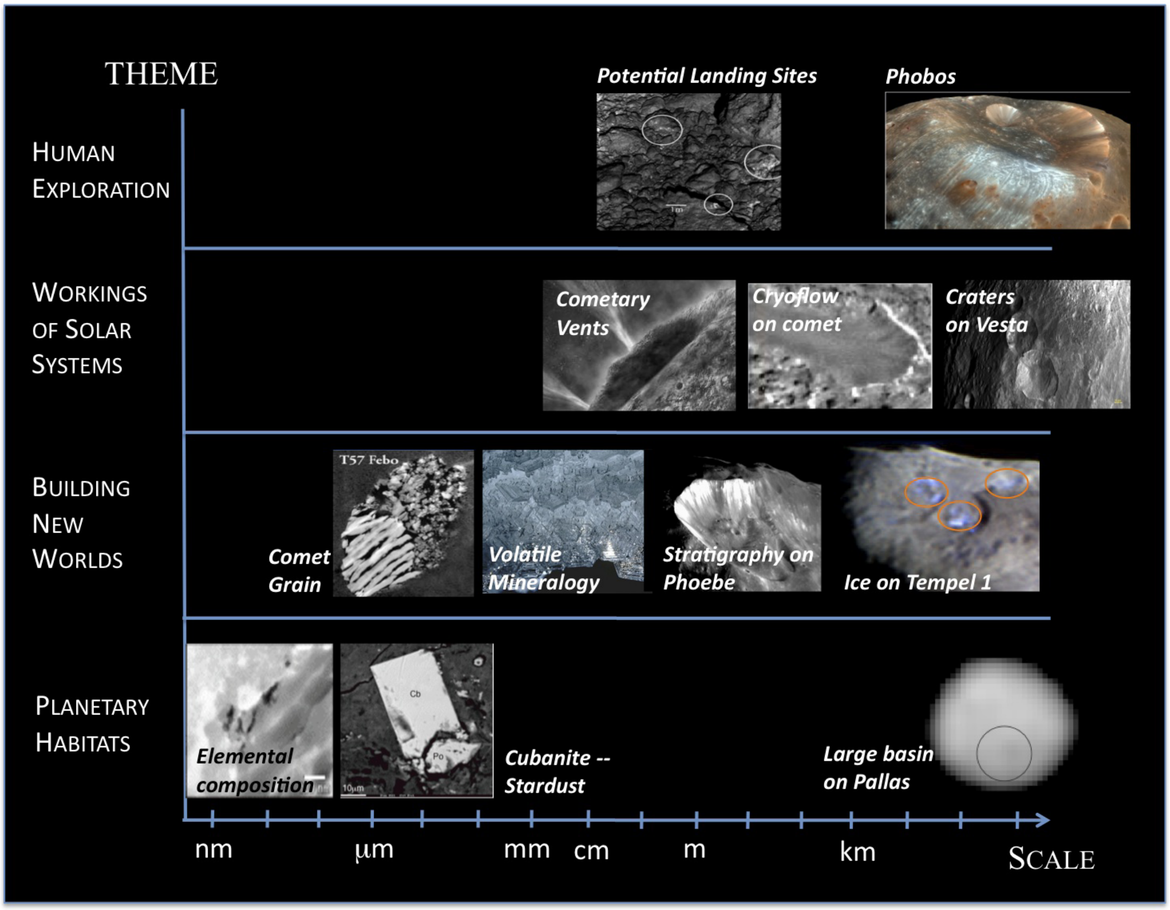


Fig. 6. Illustration of the type of observations to be achieved by space missions in order to successfully address the key science pertaining to the three cross-cutting themes highlighted in Vision and Voyages. Note that in general we lack high resolution observations at the millimeter to meter scale that can be best obtained by in situ exploration.
Image courtesy of (Castillo-Rogez et al., 2012)

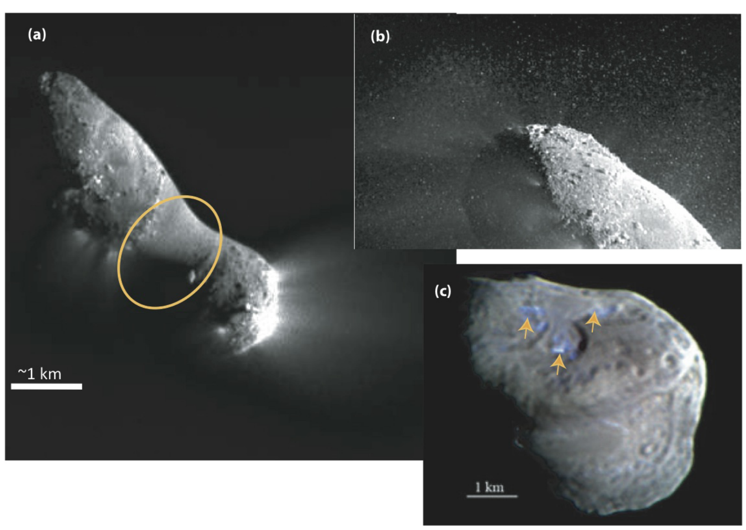


Fig. 7. Illustration of the variety of landscapes found at comets. (a) Picture of Hartley 2 obtained by EPOXI showing a contrast in surface roughness between active and waste areas. (b) This close up shows the variations of physical properties, especially roughness, at all scales. (c) In this close-up picture of Tempel 1 observed by Deep Impact lateral variations in chemistry (ice and dust) occurs on short spatial scales.
Image courtesy of (Castillo-Rogez et al., 2012)

geneity of small bodies has the potential to lead to a much improved understanding about their origins, evolution, and astrobiological relevance, yielding important ramifications for science and an expanded human presence in our solar system.

C. State of the Art

While there have been several attempts at small-body surface mobility, as of this writing no such system has successfully explored the surface of a small body. Traditional forms of robotic mobility, such as wheels and legs, present bevies of new challenges when operated in microgravity. As a result, a number of innovative designs have been attempted using unconventional means of locomotion; for instance, NASA, RKA, ESA, and JAXA have all attempted various forms of hopping strategies for traversing small bodies. In fact, three missions so far have included a robotic hopper as part of their payload: Phobos 2, Hayabusa, and Hayabusa 2. Their designs, as well as most attempts of hopping mobility, made use of two basic principles:

1) Hopping using a sticking mechanism (thus jumping away from the surface).
2) Hopping by moving an internal mass.

Phobos 2 was a Soviet RKA mission launched in 1988, aimed at studying Mars and its moons Phobos and Deimos. The plan was to deploy in close proximity to the surface of Phobos a 41-kg robotic hopper called PROP-F (see Figure 8). Its actuation was based on a spring-loaded leg mechanism designed to adhere to the moon'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 (Sagdeev and Zakharov, 1989). Several years thereafter, the JAXA Hayabusa mission planned to carry JPL's Nanorover (see Figure 9), a four-wheeled rover with articulated suspension that was capable of roving and hopping. Unfortunately, the rover was canceled due to budgetary concerns. Subsequently, JAXA/ISAS developed the MINERVA rover, a 591 gram hopping rover that employed for locomotion a single internal flywheel mounted on a turntable, which imparted control over the direction of each hop. The MINERVA design was rated to surface traversal speeds as high as 0.1 m/s. Unfortunately, the MINERVA rover also failed upon deployment (JAXA, 2000). Both Nanorover and MINERVA were solar-powered systems and hence constrained to very limited power (on the order of a couple of Watts) and computation. Since then, a handful of other hopping designs have been attempted. NASA-JPL has prototyped several generations of robotic hoppers actuated by surface adhesion. ESA developed a small hopper rover, called MASCOT, actuated by spinning two eccentric masses. MASCOT is currently a part of the Hayabusa 2 spacecraft payload (Dietze et al., 2010; Tsuda et al., 2013).

All of these platforms were designed for exploring extended areas; however, both of NASA's hopper prototypes (Fiorini and Burdick, 2003; Jones and Wilcox, 2000) (that relied on a combination of wheels and sticking mechanisms), ESA's hopper prototype, RKA's unsuccessful landers for the exploration of Phobos, and JAXA's MINERVA lander did not allow for precision traverses to designated targets. Controlled mobility and precise positioning of instruments on the surfaces of small bodies are still active areas of current research. Researchers continue to examine several approaches to small-body mobility that include legged platforms with anchoring for traction (Parness et al., 2013; Wilcox, 2011), as well as other forms of small-body legged mobility that allow drilling and surface sample collection (Helmick et al., 2014). In addition, a team from Stanford, JPL, and MIT is currently developing an internally actuated rover that encloses three mutually-orthogonal flywheels. Through controlled spinning of its internal flywheels, the rover can give rise to surface reaction forces that instigate rover tumbling (for fine mobility) or hopping (for large surface coverage) in a controllable direction (see Figure 10) (Allen et al., 2013).

Other types of low gravity surface mobility have also been explored. Thrusters are the key actuation mechanism for the Comet Hopper (CHopper) mission concept, one of the three preselections for the NASA 2016 Discovery-class mission to comet 46P/Wirtanen (Clark et al., 2008). The CHopper mission was designed to investigate changes in surface properties with heliocentric distance and land multiple times (4-5 times) on the surface of the comet, hopping twice each time before coming to a stop; however, it did not make the final selection.

Fig. 8. The PROP-F Phobos Hopper. *Image courtesy of (Sagdeev and Zakharov, 1989)*

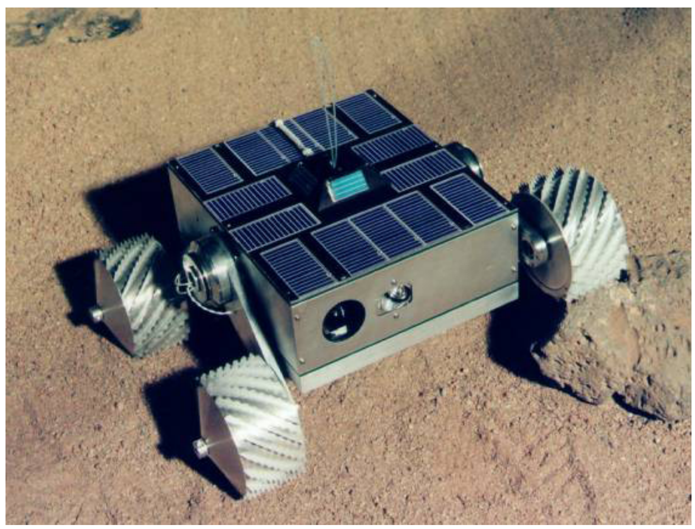


Fig. 9. The Nanorover. *Image courtesy of (Jones and Wilcox, 2000)*

D. Challenges and Future Directions

Microgravity environments pose many challenges not only for mobility and manipulation at the surface of small bodies, but also for control, localization and navigation. 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 to ones with rocky and protruded regions. What may seem like simple operations on bodies with substantial gravity fields, such as drilling or coring, can be quite difficult for a robot in microgravity, unless some form of fixturing or anchoring is used to impart necessary stabilization forces. The use of tethers or other aids could enhance control and improve maneuvering precision, but they also yield the unfortunate side-effects of added mass and complexity.

Technologies relevant for small body mobility include advanced mobility and control techniques that would operate on a range of heterogeneous terrain types. They would also include specialized techniques for localization of surface assets, which are likely to require support from an orbiter given the number of

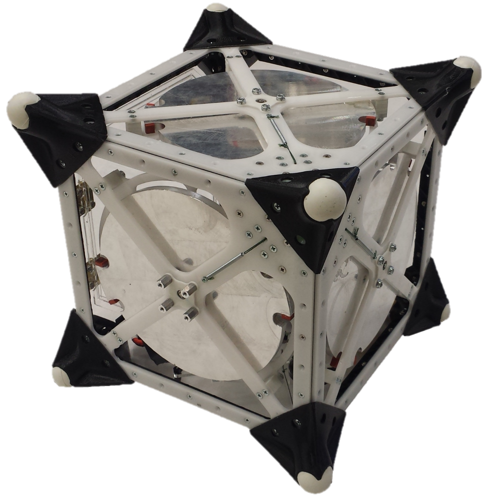


Fig. 10. A flywheel-actuated hopper designed for precise maneuverability. *Image courtesy of Stanford University*

significant line-of-sight occlusions that result from the large topographic changes characteristic of many small bodies. Localization is particularly complex for hopping and tumbling systems due to the discrete, impulsive changes in pose that result from actuation. The orbiter, hosting spacecraft, or "mothership," is also likely to be used for asset surface deployment; as a result, advances in control strategies exploiting synergistic operations between them and the mothership could also enhance asset mapping and motion planning, while simultaneously alleviating their computational load. To date, most of the proposed architectures involving in situ mobile platforms rely on *decoupled* mission operations, in the sense that the mothership is essentially used as a communication relay (a sort of "bent pipe"). This either requires sophisticated capabilities on-board the mobile assets for perception, localization and surface navigation, or leads to platforms with limited maneuverability (when such onboard capabilities are not implemented). *Coupled*, hierarchical approaches, on the other hand, would allow end-to-end minimalistic design of mobile assets by redistributing their computational tasks. Here the functions that require wide-area information, such as perception and planning, are assigned to the mothership, while functions that rely solely on local information, such as obstacle avoidance, are assigned to the mobile platforms.

To facilitate the discussion of microgravity systems, classification of mobility platforms is divided into four groups according to their primary actuation mechanism.

- **Thruster Mobility**: Thruster actuation for small body exploration involves the use of thrusters for control of far operations, with occasional visitations by de-orbit onto the surface of the object. Once finished on the surface, sorties conclude when the spacecraft lifts off and resumes far operations. The premise is that landed operations allow an extended period of time for scientific data collection, while return to orbit can benefit the selection of and traversal to new scientifically-meaningful landing sites. Possible drawbacks of this architecture include the risk of damage to the lander during landing operations, the constrained number of visit locations due to a fixed fuel budget, and the limited surface mobility (which, combined with landing ellipse uncertainties, could limit the platform's ability to target specific sites of interest). Furthermore, for science missions, contamination of the landing site from thruster exhaust could potentially interfere with scientific measurements unless the lander had an alternate means of mobility or of reaching pristine terrain. To overcome these limitations, it has been suggested to use a thruster-actuated mother spacecraft that deploys hopping rovers for surface mobility (Cunio et al., 2011). The main drawbacks of this approach are its mechanical and operational complexity, and the fact that hovering at very low gravities can be extremely challenging.
- **Wheeled Mobility**: Wheeled vehicles have been quite successful on bodies with substantial gravity

like the Moon and Mars, demonstrating as many as tens of kilometers in driving distance. However, gravitational accelerations in the milli-g to micro-g range limit their practicality for small body applications. Because of very low traction, wheeled vehicles are constrained to extremely low speeds of less than 1.5 mm/s (Jones and Wilcox, 2000), a major issue that prevents fast mobility in microgravity. Other concerns with wheeled vehicles are the complications in maintaining wheel surface contact (required for fine mobility and precision navigation to selected targets) and wheel mechanism sensitivity to dust contamination and external conditions that could cause the wheels to become "stuck." Furthermore, surface bumps that cause loss of contact can result in uncontrolled tumbling, a potentially catastrophic situation for roving in deep space.

- **Legged Mobility**: Legged mobility systems face many challenges in microgravitational environments. The primary drawbacks of legged systems are their mechanical and operational complexity, the need for some form of anchoring system, and a strong dependence of performance on regolith properties (Chacin et al., 2009; Seeni et al., 2008). Unfortunately, as surface characteristics and regolith physics are largely unknown before launch, designing legs with good grasping properties is challenging. On the positive side, legged systems would provide very precise mobility.
- **Hopping Mobility**: Hopping rovers, or "hoppers," are perhaps the most promising technology for future missions to microgravitational environments. Their key advantage is that, with a fairly simple actuation mechanism, they are capable of large surface coverage with relatively little control effort. Moreover, they are less sensitive to the regolith properties of small body objects. Indeed, unlike other types of actuation, hopper designs seek to exploit the low gravity to their advantage, rather than facing it as a constraint. A particularly useful bonus of internal actuation mechanisms on hopper platforms is self-containment of moving parts, which significantly reduces the problem of dust contamination and thermal control. One of the potential drawbacks to hopping mobility, however, is precision maneuvering for targeted instrument placement and sampling hard surfaces. In spite of this, if one is able to devise control strategies for fine mobility, hopping robots with internal actuation could represent a good trade-off between performance and complexity (see also an analogous conclusion in (Scheeres, 2004)).

Unlike typical rover developments targeted for larger bodies, development of microgravity technologies calls for specialized test beds (see Figure 11), which are expensive and have operational constraints. As a result, a necessary task for microgravity technologies would be the development of high-fidelity simulations and cross-validation with results from experimental test beds and environments. High-fidelity physics-based simulations of the regolith and its interaction with the platforms, such as granular media microgravity simulations, would play a significant role in enhancing our understanding of small-body mobility.

Several subsidiary technologies would also be relevant to microgravity mobility. Robotic mobility advancements are strongly correlated with a number of fields, particularly power and energy regulation, thermal control, structural material development, planning and guidance algorithms, and telemetry and sensing. Each of these subcategories and their benefits to microgravity mobility is described below.

a) Power Supply: Mobility platforms, like all space-based applications, are tightly constrained by available power. This is particularly apt for operations in microgravity. For example, the average power consumption for a Phobos-like environment is on the order of 15 Watts. For mobility systems functioning primarily off of batteries, with no recharging capability and assuming current state-of-the-art technology, lifetimes would be limited to a couple of days at the most. Future efforts should explore life-expanding power subsystem approaches, most likely including hybrid systems of multiple power sources. To increase microgravity assets' lifetimes beyond 48 hours, it may be necessary to consider a combination of solar panels and secondary batteries. The critical concerns for this system would be the available solar cell area and the possibility of solar cell regolith dust build-up. Contact with the surface or the use of thrusters that stir up dust may make solar cell/secondary battery choices unacceptably risky. Given the uncertainty of the dust environment, it may be that *miniaturized* Radioisotope Thermoelectric Generators (RTGs) would provide a lower-risk power alternative, despite the cost and regulatory issues; recent breakthroughs in this

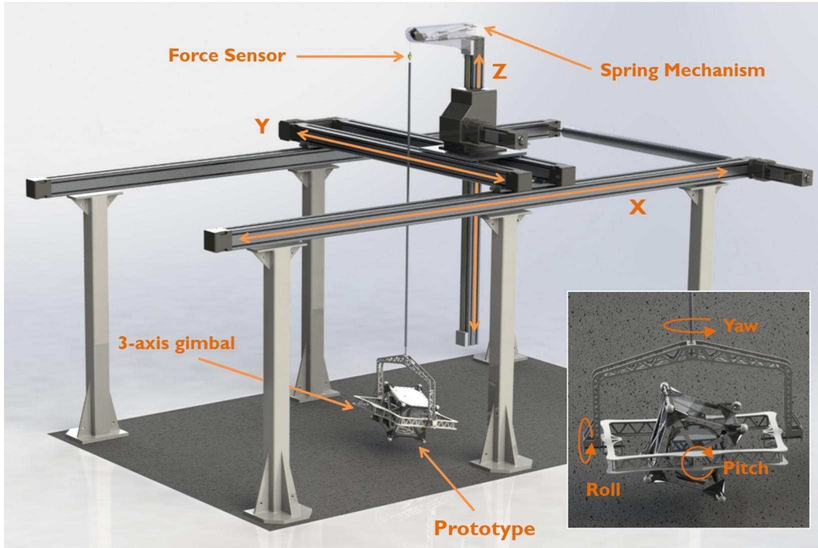


Fig. 11. A six degree-of-freedom gravity offload test bed for testing mobility platforms in emulated microgravity. *Image courtesy of Stanford University*

field might make this option viable. Another alternative technology that appears promising are advanced regenerative fuel cell systems.

b) Thermal Control: Thermal requirements differ widely depending on the environment being explored. Continuing with the example of Phobos, the moon's rapid movement (7.66 hour orbital period) helps to average out the hot and cold exposure experienced on its surface. First-order estimates show a thermal time constant on the order of the orbital period, with an average temperature slightly above freezing (Castillo-Rogez et al., 2012). Hence, at least for Phobos and other short-period small bodies, passive thermal protection with additional coatings and multi-layer insulation could be acceptable. On the other hand, for the case of slowly-rotating NEOs, Radioisotope Heater Units (RHUs) may be required if worst-case temperatures fall below minimum values allowed for electrical heaters consistent with the planned electrical power system. An RTG or RHU would most likely require a heat switch designed to prevent overheating during the pre-launch and cruise phases. During surface operations, mobile assets would also need to be isolated against heat exchange with the ground.

c) Shielding Against Electrostatic Effects: Electrostatic effects arising from solar wind and plasma build-up in Debye sheaths on the dusty surfaces of celestial objects have the potential to wreak havoc on the electrical components of space vehicles. However, if the electrostatic field has a potential less than 100 V (as appears typical for most small bodies), electrostatic charging should not represent a significant problem for deployed rovers' operations, e.g. during telecommunications between mobile rovers and their mothership, arguably the most sensitive subsystem to static. For hoppers in continuous tumbles, any net accumulated charge should rapidly reach an equilibrium with the surface. The only phase that could represent a risk to such designs is the night-day transition; a possible solution would be to turn off all telecommunications and allocate an initial phase for the hopper to "shake" itself by tumbling. Other potential mitigation strategies for static electricity include: (1) encapsulating hoppers or thruster-actuated mobile assets in a wire cage that would prevent communications equipment from touching the ground, or (2) automatic off-switches that activate when mobile assets are not in communication with the mothership.

d) Localization and Navigation: Localization and navigation are key challenges, particularly for unmapped environments such as small bodies, which have not yet been fully characterized. During local navigation across the terrain, existing localization approaches for rolling or walking robots may apply, such as the use of extended Kalman Filters to fuse celestial sensor data and optical-flow measurements (Baumgartner et al., 1998). Through dynamic sensors such as MEMS inertial measurement units, accelerometers, gyroscopes, and contact sensors, mobility platforms could also reconstruct their trajectory and hence determine their current position. One or more sun sensors or star trackers could be incorporated for attitude determination; thruster-actuated mobility platforms may be able to employ horizon sensors as well during far operations. However, dynamic sensing approaches may be subject to large position errors due to sensor drift. This motivates the use of imaging sensors, which can map the local environment to assess terrain hazards and identify nearby rocks and features to help with localization. Depending on the geometrical constraints of mobile assets, vision may not be feasible or ideal. Small and compact platforms would capture images from low vantage points, resulting in large occlusions and significant geometric variations. They also constrain the baseline for stereo vision (thus limiting depth perception). For hopping platforms, the continuously rotating fields of view would make mapping and localization particularly challenging and would call for new, less resource-intensive algorithms.

Multi-asset mission architectures, which employ a hosting spacecraft or mothership together with minimalistic mobile rovers, demand special attention. Given the low-mass, small-scale construction and the limited computational capabilities of such rovers, localization should rely on novel synergistic mission operations wherein the mothership and its daughter assets share the responsibility for localization and mapping. As this scenario is unprecedented, this presents some unique opportunities for technology development in the area of hierarchical synergistic operations. Within this architecture, localization of the rovers could be achieved through fusion of sensors onboard both the mothership and its daughter assets, with the mothership bearing the primary responsibility for rover's localization. To keep the complexity, computation and power of the mobility assets to a minimum, the rovers should be responsible only for local perception and carry a minimal suite of navigational sensors. The major hurdle associated with this architecture is its sensitivity to reliable telecommunication.

e) On-Board Handling and Telemetry: Due to the largely uncertain environment on small-body objects, successful attempts at communication for control commands are likely to be sporadic and discontinuous. This poses a significant challenge, particularly for multi-asset operations. Irregular line-of-sight with the mothership would force each mobile platform to operate autonomously, collecting, compressing, and storing data in between available uplink opportunities. In low radiation environments, an FPGA, small micro-controller or micro-processor solution would be a favorable choice with relatively high-density memory. The nature of the scientific payload would naturally allow for a high degree of sequential operation with the initial uplink of accelerometer data, followed by in situ data.

V. Conclusions

This chapter has addressed some of the engineering aspects and challenges associated with technology area TA04 "Robotics, Tele-Robotics, and Autonomous Systems," expanding the discussion of the 2011 NRC Report on top technology priorities for NASA's Office of the Chief Technologist to a more detailed, technical scope. Specifically, this chapter has discussed the "Relative Guidance Algorithms," "Extreme-Terrain Mobility," and "Small-Body/Microgravity Mobility" technologies within the autonomous systems area, motivating the importance of each, highlighting current state-of-the-art methods, and outlining the major technical hurdles facing the aerospace engineering and robotics communities.

Spacecraft guidance and control has attained a sufficient level of maturity that the majority of remaining technological advancement lies in on-board guidance capability and performance. Robust, real-time implementable, and verifiable optimization algorithms for "Relative Guidance," as discussed in the second section of this chapter, are necessary to address situations involving delayed communications, time-varying obstacles, elevated mission risk, and tight maneuver tolerances. Important applications on the forefront of today's capability include planetary entry, descent, and landing, autonomous rendezvous and docking, autonomous inspection and servicing, and proximity operations about small bodies. Enhanced autonomy in these difficult applications will require the extension of modern state-of-the-art techniques, including Mixed-Integer Linear Programming, Model Predictive Control, Artificial Potential Functions, and motion planning algorithms, as well as the invention of novel approaches. As described in the chapter, prospective approaches will need to be able to deal with logical modes, handle complex state-control constraints, and provide certificates of algorithm correctness and convergence rates, all while providing hard guarantees of mission safety.

In addition to spacecraft, future science and human exploration missions will heavily rely on autonomous control of mobile systems operating on and in proximity of extreme, hazardous landscapes of extraterrestrial bodies, including deep craters, canyons, fissures, gullies and cryovolcanoes. The discussion in the third section of this chapter on “Extreme Terrain Mobility” prompts for further technology advancements toward the development of affordable and versatile mobility platforms that would enable access to otherwise inaccessible areas, capable of safely traversing to multiple and designated targets, loitering for in situ measurements, and harvesting samples from extreme terrains. Conventional, flat-topography rover designs must be re-evaluated in the context of such high-risk missions in order to avoid the dangers of tip-over, loose regolith, and other uncompromising terrain hazards. The advancements described in this chapter revolved around novel traverse technologies, tethered mobility and control (including anchoring and fixturing deployment and management), avionics and terrain equipment, traversability analysis, motion planning techniques, and lastly high-fidelity terrain modeling and mobility simulation. Motion planning algorithms and control laws must be developed so that both fine mobility and instrument pointing can be reliably achieved over extreme terrains with narrower targets on motion accuracy.

The subject of mobility was extended further in the final section of the chapter to the specialized case of microgravity. Weak gravitational fields are characteristic of celestial small bodies, whose unique environments call for dramatically different modes of operation. “Small Body/Microgravity Mobility” constitutes mobile operations on Near-Earth Objects (NEOs), asteroids, comets, irregularly-shaped objects, and planetary moons, enabling the access to and study of entirely new and highly-prized scientific sites, including Phobos, Deimos, Enceladus, and Phoebe. Microgravity introduces a number of new and difficult challenges. Simple operations such as drilling or coring can be quite difficult unless some form of fixturing or anchoring is used to impart necessary stabilization forces. Rovers relying on traditional mobility concepts (such as wheels and legs) originally developed for high-gravity environments cannot be used without significant modifications. On the other hand, low gravity enables entirely new types of mobility, namely thruster-actuated locomotion and hopping by surface impact and/or internal actuation mechanisms. Concurrent technological maturation of key subsystems is needed to enable these extreme applications of engineering. Research must be done to identify power supply options to increase mobility platform lifetimes, further develop communication and localization strategies, improve thermal control and electrostatic shielding, and enable on-board handling and telemetry. Finally, trades between monolithic and multi-asset mission architectures will be needed to determine the most appropriate balance of computational load for localization, mapping and motion planning between mobile assets and potential host spacecraft; this paradigm-shifting approach for synergistic mission operations directly exploits small bodies’ low gravity in the design process, rather than facing it as a constraint, a key design perspective that will need to be adopted in order to enable small-body missions.

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