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 their 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 the prioritized technologies (that is clearly beyond the scope of the report). This chapter, building upon the NRC report, aims at providing 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 and future directions. The result is a unified explanation 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 (NRC, 2011; NASA, 2011b). 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 objectives and prioritize their 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 (National Research Council, 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 survive long voyages throughout the solar system, get to their chosen destination, work effectively, and return 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 Earth (astrobiology) and on other planetary bodies.
- **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 benefit, alignment with NASA and non-NASA aerospace needs as well as non-aerospace national needs, an assessment of technical risk and reasonableness, sequencing and timing that included requisite technologies, and an assessment of time and effort to achieve the goals. 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 (that is clearly beyond the scope of the report). This chapter, building upon the NRC report, aims at providing 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, in Section V, conclusions are drawn concerning the technical challenges facing the engineering community in each of these areas and what needs to be addressed to meet NASA's 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*

The TA04 roadmap outlines the key capabilities in robotics, autonomy, and sensing needed for expanding the frontier of robotic exploration and improving access to space. Though many significant improvements have been made to robotics and autonomy over the past century, culminating in the recent successful Mars Curiosity mission, the majority of space systems are too expensive, too mission-specific, or of insufficiently low technology readiness level (TRL) for widespread implementation. In addition, many techniques do not yet seem fully mature, as evidenced by the number of glitches and anomalies experienced in shuttle operations (John Goodman, 2007) and recent autonomous demonstration missions, e.g. (Kawano et al., 1999), (NASA, 2006), (Davis and Melanson, 2004), and (Howard et al., 2008). This serves to illustrate the degree of difficulty of autonomous navigation and control in space applications and on a broad scale the significant challenges that must be overcome in aerospace engineering.

NASA has repeatedly identified robotic, autonomous, and sensing systems as enabling technologies over its history, as far back as the Gemini program in the 1960's (Polites, 1998). For spaceflight, many technologies such as real-time autonomous decision-making, opportunistic science, and human-robotic cooperation have not yet been developed and tested. For roving applications, the capability does not yet exist for traversing extreme lunar, martian, or dusty terrains, including the lunar poles, high-grade surfaces, and microgravity environments (Bajracharya et al., 2008). The advancement of robotics will be central to the transition of space missions from 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). If the reach of humanity is ever to expand beyond the confines of the Earth-moon system, it is necessary to develop these critical areas and mature our current understanding of autonomous systems and control. Drawing similar conclusions, the NRC Report identified TA04 "Robotics, Tele-Robotics, and Autonomous Systems" specifically as a high-priority technology area. Much remains to be studied in the subjects of robotic systems and autonomy in order to broaden access to space and expand human 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 (National Research Council, 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 objectives, and of the general technology objectives presented at the beginning of this section, eight high-priority technologies were identified in the TA-04 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 FDIR*.
- **Technology 4.6.2**, *Relative Guidance Algorithms*.
- **Technology 4.6.3**, *Docking and Capture Mechanisms/Interfaces*.

Each of these technologies will lend a hand in 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.

Overall, advancements in these eight areas will enable the US Space Agency to improve and automate its capabilities, expanding its frontier to currently inaccessible environments. 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 technology are discussed in detail in the following sections in order to better arm the technical community to deliver on these advancements and meet the needs of the US Space Program and general public.

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 state trajectory planning, in real-time, for both the translation and rotation of spacecraft. This involves computing desired set translational and rotational states and corresponding control forces and torques as a function 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. This section addresses the technical details and challenges for *relative guidance* of autonomous spacecraft in four space-based application 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 and constraints on the spacecraft state and controls. This can be expressed generically as follows:

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

$$\min_{t_f, u} g_b(x(t_f)) + \int_0^{t_f} g_i(x(t), u(t))dt,$$

subject to the following: for all $t \in [0, t_f]$,

$$\begin{aligned} &\dot{x}(t) = f(t, x(t), u(t)), \\ &u(t) \in \mathcal{U}(t), \\ &x(t) \in \mathcal{X}(t), \end{aligned}$$

where $x \in \mathbb{R}^n$ is the state of the spacecraft, $u \in \mathbb{R}^m$ is the control input, t is time, $f : \mathbb{R}^{n+m+1} \to \mathbb{R}^n$ 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). This requires computation of solutions to a complex optimization problem onboard in real-time, implying that solution algorithms must be:

- **Robust**: Given that feasible solutions exist, an optimal solution is desired.
- **Real-time implementable**: Algorithms must be implemented and executed on real-time processors in a reasonable amount of time.
- **Verifiable**: There must be design metrics that accurately describe the performance and robustness of G&C algorithms, with accompanying methods for verifying these metrics.

Onboard guidance algorithms meeting these challenges must be developed in order to enable a significantly more advanced level of autonomy that is needed for next-generation space missions.

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 most future NASA missions (NASA, 2011b; National Research Council, 2012). In some cases this need is due to the physical constraints of the mission. A very good example is Mars landing, arguably one of the most tightly-constrained control sequences in spaceflight achievable by current technology. Control of the lander spacecraft by remote operation is simply impossible due to a nearly 26 minute two-way signal communication time, a duration far greater than the seven minutes required for the entire atmospheric Entry, Descent, and Landing (EDL) process. This then demands complete autonomy for Mars EDL applications. Similarly, close proximity operations around small bodies, many of which travel beyond the extent of Mars orbit, require autonomous control of spacecraft due to the delays associated with signal transmission to and from Earth. In many other cases, the need for autonomy can be derived from a desire to increase mission frequency, robustness, and reliability. This includes missions within low Earth orbit such as Autonomous Rendezvous and Docking (AR&D) and Autonomous Inspection and Servicing (AIS). As access to space improves and mission frequency grows due to space commercialization, ground-in-the-loop guidance of spacecraft will become prohibitively expensive due to scheduling conflicts and increases in maintenance and labor costs. The chance for human error will increase as well. Automation can prevent such outcomes, enabling greater numbers and types of missions while improving robustness and reducing risk, and hence increasing future commercial and scientific return from space.

C. State of the Art

Current state-of-the-art techniques for *autonomous* spacecraft maneuvering include Apollo guidance, Artificial Potential Functions (APF) (Badawy and McInnes, 2008; Bevilacqua et al., 2011a; McInnes, 1995), Mixed-Integer Linear Program (MILP) formulations (Breger and How, 2008a; Richards et al., 2002), and Model Predictive Control (MPC) (Acikmese et al., 2011; Bevilacqua et al., 2011b; Carson III et al., 2011; Nolet et al., 2005; Park et al., 2011). Such methods, while very valuable in static and uncluttered settings, appear to fall short in scenarios where time-varying constraints (such as debris or other spacecraft), logical modes (e.g. safety modes), and hard real-time guarantees (that translate into tradeoffs between feasible and optimal trajectories) become key features of the problem setup. In these cases, an alternative technique that appears more appropriate is robotic motion planning. A brief discussion of each of these methods is given here.

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) (William S. Widnall, 1968). The techniques used, now considered part of *classical* control, formed one of the earliest successful deployments of spacecraft autonomy. These DAP systems are each briefly described to provide context for more modern control techniques:

- **Reaction-Control System Digital Autopilot**: RCS DAP, responsible for controlling the attitude and attitude rates of the CSM during coasting flight, both with or without the lunar module (LM) stage attached. The DAP employed four clusters, called quads, of four RCS thrusters for pitch, yaw, and roll control, using a phase-plane logic controller with straight 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 resolving DAP 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 CSM during powered flight, both with or without the LM attached. Pitch and yaw were adjusted by actuating the gimbal servos of the main engine, while a separate autopilot called TVC ROLL DAP controlled CSM attitude and rate about the roll axis during powered flight via the RCS 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 CSM (LM attached or otherwise) due to the changes in overall CG 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 risk of thruster failures.
- **Lunar Atmosphere Descent Digital Autopilot**: ENTRY DAP, which assumed control of the command module (CM) after separation from the service module (SM) and handled all CM 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 CM, as well as an additional pair near the tip for pitch-down control. The first phase of operation marked exo-atmospheric mode, using various combinations of rate damping, attitude-hold, and attitude-control depending on the pitch angle value. Phase-plane logic controllers (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 case, 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 vs. 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.

2) Model Predictive Control: Model predictive control is a feedback law based on a repeated solution of an Optimal Control Problem (OCP) using the current state as the initial condition. From the current state, the states at future times are predicted according to a dynamics model. An OCP is formed to minimize a cost functional, which is a function of the actual initial state and the predicted states and controls over the duration of some planning period or *time horizon*. This OCP is solved for a finite-horizon optimal control trajectory that optimizes the predicted state response over the duration of the planning period. Once solved, however, only the initial segment of the optimal control trajectory is actually applied to the system. After implementation of this first control segment, the new current state of the spacecraft is then used as the initial state and the optimization problem and planning periods are updated. This process is repeated until convergence to the goal. This characteristic procedure of renewing the OCP over a repeatedly updated horizon is what gives MPC its other common names: *receding horizon optimal control* or *moving horizon optimal control*. The receding horizon concept allows one to design a feedback controller on the basis of nearly any open-loop optimal control-based approach, improving its robustness and imparting it the ability to handle disturbances and mitigate error growth. Even without prior knowledge of the nature of these disturbances, one can demonstrate under appropriate assumptions that this introduction of feedback will 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 incorporation of previous disturbance information, the capability to withstand time delays, and reconfiguration in the presence of degradations and failure modes (Camacho and Bordons, 2007).

3) Artificial Potential Functions: The artificial potential function method represents the robot environment by various mathematical potential functions distributed over the state space. Attractive potentials are used for goal regions, while repulsive potentials are used for obstacle regions; the environment is then represented by the sum of each individual term. 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 one of the goals. An OCP may also be formed to plan a path that minimizes the path integral along the gradient force field (analogous to work in physical systems). The approach benefits greatly from the ability to adjust in real-time the magnitudes of individual potential functions in reaction to changes in the environment. Some difficulty lies in adjusting each function such that the robot behaves as desired (i.e. ensuring sufficient margin from obstacles, rapid convergence, etc). However, the main drawback is the well-known susceptibility of the approach 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, real-time path modification, and bubble methods, for instance).

4) Spacecraft Motion Planning: Motion planning constitutes a class of algorithms used to generate sequences of decisions, called *plans*, that safely navigate a robot or group of robots from a set of initial states to a set of target states called *goals*. In the general motion planning framework, the term robot is taken to mean an object for which a motion plan is desired, which ranges in application from rovers, to complex pharmaceutical molecules, to Artificial Intelligence (AI) agents, and much more. 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 portion of the configuration space occupied by obstacles, 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 configuration space. Representative examples include cellular decomposition, planning between Voronoi cell centroids, and maximum-clearance roadmaps based on free-space skeletons. Most often, for computational practicality, problems solved using exact approaches require low-dimensionality, polygonally-shaped obstacles, and static environments. Approximate techniques or sampling-based algorithms, on the other hand, forgo explicit construction of the obstacle configuration space and instead formulate motion plans by exploring pathways via sampling. The safety of trajectories is determined by a "black-box" collision detection routine; this allows motion planning formulations to be formed independent of any particular geometric models. 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 rapidly-exploring dense trees, probabilitistic roadmaps, and Ariadne's Clew algorithm (Lavalle, 2006). Though motion planning algorithms exhibit such diversity over a wide array of fields, relatively little application to spacecraft control systems has been seen. Traditionally, motion planning is concerned with finding only feasible plans as opposed to optimal plans; however, there has been growing interest in developing algorithms that offer some form of (often weaker) optimality, which is particularly important for spacecraft.

Autonomous maneuvering using related methods combined with digital logic has been recently experimented on a number of (mainly demonstration) missions, including JAXA's ETS-VII (Kawano et al., 1999; 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). However, anomalies and mishaps happened on the latter three missions, in some cases spelling their end (Kawano et al., 1999; NASA, 2006; 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 MUBLCOM satellite (NASA, 2006). This suggests that presently autonomous spacecraft navigation and maneuvering, even in static and uncluttered environments, is neither a mature nor a safe technology (Breger and How, 2008b; National Research Council, 2012). Much work remains to be done in autonomous spacecraft control.

D. Challenges and Future Directions

This section first presents the main general challenges for autonomous relative guidance; then, the challenges are specialized to two key areas: (1) Planetary Entry, Descent, and Landing (EDL), and (2) Proximity Operations, namely Autonomous Rendezvous and Docking (AR&D), Autonomous Inspection and Servicing (AIS), and close-range operations for primitive bodies.

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

The main technical challenges to meet this ambitious goal are:

- Developing robust, real-time implementable, and verifiable onboard optimization algorithms for the solution of Problem $\mathcal{G}\&\mathcal{C}$;
- Developing design metrics and verification and validation methods for real-time optimization-based guidance and control algorithms;

- Extending guidance techniques to multiple collaborative vehicles;
- 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 convexify Problem $\mathcal{G}\&\mathcal{C}$ for a given application, that is, express it as a convex optimization problem, then one can employ Interior Point Method algorithms (IPMs) to solve the resulting problems to global optimality (Boyd and Vandenberghe, 2004; Nesterov and Nemirovsky, 1994). Further, it is shown that, for a given problem class, IPMs can be customized to increase runtime execution speeds by 2-3 orders of magnitude (Mattingley and Boyd, 2010). This observation clearly motivates using real-time convex optimization to solve these problems whenever possible. In (Açıkmeşe and Ploen, 2007; Blackmore et al., 2010) the authors show that the planetary landing problem can be convexified in a lossless manner. Clearly this is the ideal situation, where converting the problem into a convex problem one does not cause a loss of optimality or introduce erroneous approximations. But in some cases, more than optimality, the important need is just being able to compute feasible solutions obeying all mission constraints, particularly as the complexity of the problem and the difficulty of satisfying constraints and avoiding hazards increase. In those cases, having reasonable approximations of the problem that can be solved via convex optimization techniques can still be a satisfactory solution.

One such approximate technique is sampling-based motion planning. Sampling-based planners discretize the set of all possible spacecraft configurations into a representative set of points called samples, and seek solutions by intelligently attempting to formulate connections within the constraint-satisfying space between these samples and the initial and goal states. This essentially converts the continuous planning problem given by Problem $\mathcal{G}\&\mathcal{C}$ into an approximate, discrete, geometric one that is generally easier to solve. Algorithms that formulate partial plans by building them in small steps are referred to as incremental, sampling-based planners. Important examples of sampling-based algorithms include probabilistic road maps (PRMs) (Kavraki et al., 1996) and rapidly-exploring random trees (RRTs) (Lavalle, 2006; LaValle and Kuffner, 2001). Sampling-based motion planning algorithms under mild conditions have been shown to quickly and uniformly explore the collision-free state space. Many have the additional benefit of *anytime* capability, a property particularly useful for real-time implementations of autonomous control in rapidly-changing environments. "Anytime" computation refers to ability of an algorithm to terminate pre-maturely and return a feasible solution to the problem (if such a solution has been found to exist) without requiring a run to completion (Sertac Karaman et al., 2011). For practical applications of motion planning, this requires rapid finite-time convergence to a feasible solution, so as to guarantee a safe trajectory in the event that further iterations cannot be made. Time-permitting, subsequent iterations can be used to improve the initial trajectory; asymptotically-optimal anytime algorithms can be shown to approach the globally optimal solution over time. Faster, more-accurate approximate methods with similar guarantees will be vital to meeting the challenging spacecraft control objectives of the future.

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 in design time. In the case of complex guidance algorithms, on the other hand, which can also be applied in a receding horizon sense in a feedback mode, such general metrics do not exist. One challenge is developing metrics such that their satisfaction would establish confidence in the solution algorithm. A good example can be given in the context of Mars precision landing. The task of the trajectory designer is to be able to direct the vehicle from any initial state at the end of the parachute phase to the target on the Mars surface with zero velocity. Suppose the expected set of initial conditions at the start of the powered descent phase is $\mathcal{I}_{pd}$. Then for a given spacecraft with fixed control parameters, such as propellant mass fraction, thrust-to-weight ratio, and fuel consumption rate, etc., suppose the set of all initial conditions from which the lander can reach the target is given by $\mathcal{I}_c$. Note that the ability to solve Problem $\mathcal{G}\&\mathcal{C}$ means that one can fully utilize the set $\mathcal{I}_c$ for landing. Then the verification process can simply be to check whether the following set inclusion relationship holds or not:

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

The next question is how to generate $\mathcal{I}_c$ for a given set of design parameters. Clearly one approach is exhaustive search of sample points in the set to construct an approximation for the set. But this approach is very time consuming, and not usable at the design time. Herein lies another challenge: efficient and automated computation of $\mathcal{I}_c$. Again if Problem $\mathcal{G}\&\mathcal{C}$ can be convexified, one can potentially employ systematic methods from convex optimization to efficiently compute this set. Therefore exploitation of the structure of the problem in computations is always a priority to make them robust and tractable.

Approximate techniques for computing the set I_c may be derived from *reachability analysis*, which studies whether a system can transition from an initial condition set to some goal set(s) according to a transition function or dynamical mapping. 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, many efficient algorithms have been adopted for approximating reachability sets, 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, and (3) propagation of conservative over-approximations to the true sets. One interesting approach that may be promising for reachability analysis and safety verification of spacecraft planning proposes the use of Rapidly-Exploring Random Trees (RRTs) to rapidly calculate unsafe state trajectories for safety falsification and to intelligently explore the reachable space by connecting randomized or deterministically-random samples (Bhatia and Frazzoli, 2004).

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, each of which has an unknown and/or uncertain future course. This is often resolved in the literature by forming a heirarchy 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*, which demands full communication of state and intent between all (or at least neighboring) vehicles, or fully dependant control called *centralized control* in which one vehicle or mothership determines the plans for all other vehicles, which demands that information be relayed only to the central agent. A number of methods have been developed to handle multiple spacecraft guidance, including multi-agent game theory (Lavalle, 2006), passive/active relative orbit formulations (e.g. Clohessy-Wiltshire-Hill equations, halo orbits about libration points) and optimal reconfigurations (Scharf et al., 2004), rigid body or quasi-rigid body rotation planning (Blake and Misra, 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 solution in the not-too-distant future. So priority in research must first be to develop robust solution methods for the right problems with appropriate constraints. Then comes the customization of solution algorithms for flight implementation.

And finally the third critical step is establishing a rigorous process for their verification and validation (desirably with flight testing).

The general challenges of this subsection are now specialized to planetary EDL and proximity operations, each of which constitute difficult, mission-critical control maneuvers at the cutting edge of modern research.

2) Challenges for Planetary Entry, Descent, and Landing: The main focus of planetary exploration has been missions to Mars. Clearly lunar missions have been historically important and have enjoyed a recently renewed interest; however, landing missions to other bodies in the solar system will also be of growing prominence as planetary exploration expands over the coming decades. This section begins with a focus on Mars and Moon landing missions and their autonomous G&C challenges.

The main purpose of G&C during the landing phase of planetary missions is to reduce lander speed from orbital or interplanetary velocities to a speed near zero. For Mars EDL, this involves an entry phase (see Figure 1) that cancels most of the planetary relative velocity. Once the lander slows down 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 released and the Powered Descent (PD) phase is initiated. Due to atmospheric uncertainties in winds and density, and due to passive means of deceleration during the parachute phase, the position and velocity relative to the target are dispersed significantly and cannot be predetermined. In the example of Mars landing, the horizontal distance error can be on the order of 8-10 km with a velocity trigger (used during the MSL mission), and 5-6 km with a range trigger for the start of parachute phase (Way, 2011). To achieve precision landing (position error $<$ 1 km at touchdown), an autonomous Powered Descent Guidance (PDG) algorithm is required to redirect the vehicle to the surface target in real-time in order to correct for these errors as much as possible. In manned missions,

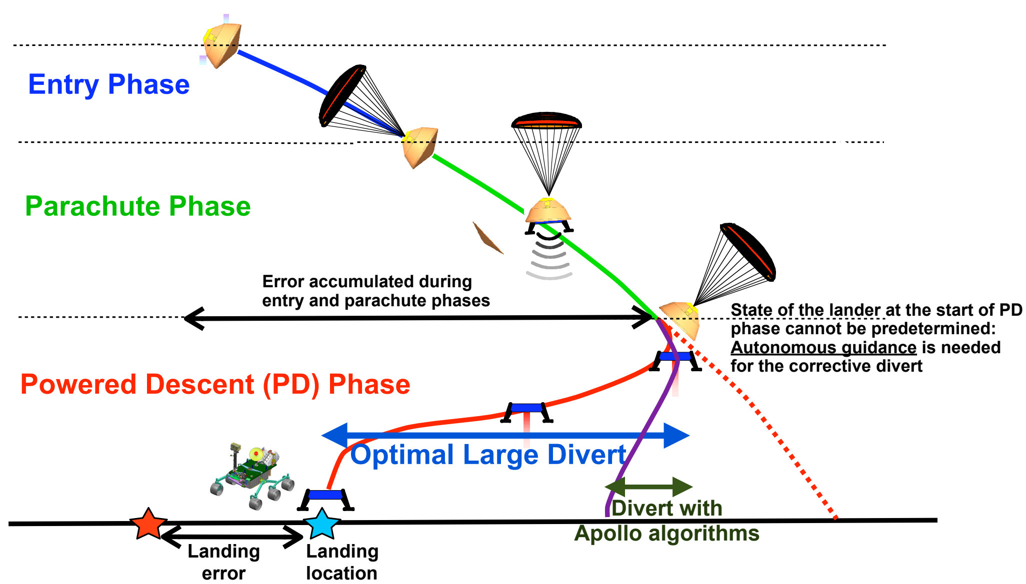


Fig. 1. Optimal Powered Descent Guidance (PDG) will enable planetary precision landing. These algorithms search over all physically possible diverts to find a fuel optimal one, significantly improving divert capability over current state-of-the-art onboard algorithms. *Image courtesy of*

challenges are magnified. Lander masses can vary from approximately 2 metric tons in robotic missions all the way up to 50 metric tons in manned missions, implying that passive means of deceleration would be very difficult to employ, if not impossible. Successful planetary descent of such heavy landers will necessitate the use of active controls starting from very high altitudes and within the supersonic speed range.

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 phase controlled by liquid fuel propulsion for final landing. Complexity arises from the fact that, since a solid rocket is initiated, it must burn out all its fuel to completion. 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 best landing accuracy, i.e. the minimum landing error.

In all planetary or lunar landing missions, the associated autonomous guidance problems for translational motion can be expressed as highly-constrained optimal control problems (Açıkmeşe and Ploen, 2005, 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 formed as,

$$
\begin{aligned}
f(t,x,u) &= A(\omega)\,x + B\left(g(x_1) + u/x_3\right) \\
\mathcal{X}(t) &= \begin{cases} \{x : x = x_o\} & \text{for } t = 0 \\ \{x :\ \gamma \hat{n}^T x_1 \geq \|T x_1\|,\ \|x_2\| \leq \bar{V}\} & \text{for } t \in (0, t_f) \\ \{x : Hx = a\} & \text{for } t = t_f \end{cases} \\
\mathcal{U}(t) &= \{u : \rho_1 \leq \|u\| \leq \rho_2,\ \hat{n}^T u \geq \beta \|u\|\}
\end{aligned}
$$

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 and a nonzero lower bound 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, $\hat{u} \in \mathbb{R}^3$, 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 the initial relative state x_0 a priori, this problem must be solved autonomously in real-time. Some versions of this problem have been addressed via analytical solutions (D'Souza, 1997; Klumpp, 1974; Meditch, 1964; Najson and Mease, 2006; Topcu et al., 2007). In order to fully utilize the possible landing envelope (the initial conditions from which it is physically possible to land), it is observed that the full version of the problem must be solved by explicitly accounting for the constraints (Açıkmeşe and Ploen, 2005, 2007; Blackmore et al., 2010; Steinfeld et al., 2010). However the control constraints can define a non-convex set for $\mathcal{X}(t)$. In (Açıkmeşe and Blackmore, 2011; Açıkmeşe and Ploen, 2007; Blackmore et al., 2010, 2012), it is proven that a novel relaxation of these constraints can be constructed that leads to the lossless covexification of the problem. Hence one can utilize Interior Point Methods (IPM) (Nesterov and Nemirovsky, 1994) of convex optimization to solve the resulting problems to global optimality. The trajectories of lossless convexification based algorithm (Açıkmeşe and Ploen, 2007) have already been successfully flown by NASA JPL in test flights, see (JPL and Masten Space Systems, 2012a,b,c) for the flight videos. In these test flights, successively aggressive trajectories are flown, where the last flight (JPL and Masten Space Systems, 2012c) had the longest possible divert of 750 meters for the particular test vehicle without violating any of the control and state constraints. Before these test flights of the optimized trajectories, the same vehicle had diverts below 100 meters. Therefore these flights not only demonstrated that optimized trajectories are physically realizable but they also showed strong evidence that the 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 collaborative or non-collaborative spacecraft or space objects (primitive celestial bodies), the primary guidance objective is to compute a state trajectory to bring the spacecraft as close as needed (including docking) to the target object safely and with minimal fuel use. In general, this requires that the following constraints be incorporated into the optimal control problem given by Problem $\mathcal{G}\&\mathcal{C}$:

- **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:
$$\hat{n} \cdot (r - r_T) \geq \cos\alpha \|r - r_T\| \tag{1}$$
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 more clearly, 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 could have been expressed as follows,
$$(r - r_T)^T C(q)\hat{n} \geq \cos\alpha \|r - r_T\| \tag{2}$$
where q is the quaternion describing the attitude of the spacecraft, and $C(q)$ is the directional cosine matrix that takes a vector in spacecraft body reference frame to the LVLH frame. Equation 2 clearly shows attitude-translation coupling.
- **Avoiding plume impingement**: Plume impingement can be quite a serious problem, damaging sensitive optical devices, generating force perturbations and large disturbance torques, and disrupting thermal blankets and coatings. To avoid plume impingement, the thrusters pointing at the target vehicle must not fire below a prescribed relative distance, which imposes a loss of control authority. This constraint exists for primitive bodies due to contamination concerns. In sample return missions, for instance, it is not desirable to contaminate the area from which the sample will be obtained. This implies that one can not apply force away from the primitive body as the spacecraft approaches the sampling point, reducing available control authority. Consequently the nominal guidance plan must account for plume impingement in both classes of applications.
The plume impingement constraint can be stated as follows: for $i = 1, \ldots, n_t$
$$u_i = 0 \quad \text{when} \quad (r - r_T)^T C(q)\hat{t}_i \geq \cos\beta_p \|r - r_T\|, \ \|r - r_T\| \leq R_p$$
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
$$u_j \in \{0\} \cup [u_{j,1},\, u_{j,2}] \quad \text{where } u_{j,1} > 0 \text{ and } u_{2,j} > u_{j,1} \text{ are min. and max. thrusts, } \ j = 1, ..., n_t.$$
- **Avoiding collisions**: Collisions are catastrophic to a spacecraft mission, damaging or destroying participating vehicles and often marking 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
  $$F_i(t) = 0, \ \ \forall i = 1, ..., n_t \quad \text{when} \quad t \in \bigcup_{j=1,...,n_s} \mathcal{T}_j, \tag{3}$$
  where $\mathcal{T}_j, \ j = 1, ..., n_s$ form a disjoint set of zero-thrust time intervals.
- **Handling uncertainties**: Thruster firings, aerodynamic drag in low Earth orbits, solar radiation pressure, and camera measurements can introduce uncertainties in the relative state knowledge and control accuracy. As the spacecraft nears its target, these uncertainties can cause violations of the previously mentioned mission constraints. In the mean time, the relative state accuracy typical improves as relative separation decreases. Hence one should embed the capability to handle any expected uncertainty, i.e. one should incorporate strategies to handle "known unknowns".
- **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.

Due to potential coupling between translational and attitude dynamics, one has 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 that would be incurred by relaxing them, and hence new tools will be needed. Embedded logical constraints are likely necessary to enforce mission constraints such as FOV requirements, actuation constraints such as minimum-on times, and decision-making tasks in multi-spacecraft control problems. Efficient techniques will be required for handling collision detection and avoidance strategies, both key bottlenecks in computation and particularly cumbersome on space-grade hardware. One possible solution that appears viable in this context is robotic motion planning, which has been shown to be effective at solving challenging real-time kinodynamic planning problems on real systems. Their most notable application to-date was the 2007 DARPA Urban Challenge, for which several of the winning entrants to the 60-mi autonomous urban driving race used motion planning algorithms to safely navigate their vehicles in real-time, 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., 2009; Kuwata et al., 2009; Leonard and the Talos team, 2008; Montemerlo and the Junior team, 2008; Urmson and the BOSS team, 2008). Robotic motion planning algorithms allow efficient hierarchical collision detection models and have the potential to apply well to numerous mission scenarios due to their independence from geometric modeling. Though not yet flown on spacecraft hardware, the ability of these algorithms to handle differential constraints while providing robustness certificates for such challenging systems as autonomous driving is promising for non-convex kinodynamic planning problems, including spacecraft proximity operations.

III. Extreme Mobility

Among the top technical challenges of technology area TA-04 is *maneuvering* in a wide range of NASA-relevant environmental, gravitational, and surface and subsurface conditions. Two different review boards in the NRC process ranked extreme terrain mobility a high-priority technology for the next five years to address part of this maneuvering challenge: the study panel ranked it 6th and the steering committee ranked it 8th (National Research Council, 2012, Table 3.7, p. 88). This section discusses the technical aspects and challenges associated with extreme terrain mobility.

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 soil types include crater walls and floors, cliffs, sand dunes, gullies, canyons, cold traps, and fissures. 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 to, in and out of extreme terrains, safe traverses to designated targets, loitering at targets for in-situ-measurements, and sample collection and retraction from such extreme terrains. 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 aerial or other airborne mobility, a key feature of extreme terrain access is loitering at targets of interest for in situ measurements. Here, technologies related to aerial mobility are not addressed, which were defined and prioritized as a separate category by the NRC.

B. Need

Some of the most appealing science targets for future exploration missions in our solar system lie in terrains that are inaccessible to state-of-the-art robotic rovers, including NASA's Mars Exploration Rover (Mission, 2011a) and Mars Science Laboratory (Mission, 2011b) vehicles. For example, a recent flyover of Titan by NASA's Cassini spacecraft revealed what scientists believe to be a cryovolcano[1]. Direct sampling of the cryovolcanic ejecta on steep slopes would shed new light on the processes underlying cryovolcanism, as well as provide valuable access to material from Titan's interior. The LCROSS experiment, by impacting the lunar surface and analyzing the ejected debris, found evidence of water ice in the Moon's permanently shadowed Cabeus Crater[2] (Colaprete et al., 2010). The shadowed regions lie at the bottom of a long steep slope. Lunar cold traps, which have never received a photon of light, are believed to have water ice within a few centimeters of the surface. The assessment of water abundance and an ability to extract such valuable resources would be critical for future exploration. Extreme terrain mobility would enable the exploration of locales with high probability of water ice (Michael J. Wargo, 2012), allowing access

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

[2]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

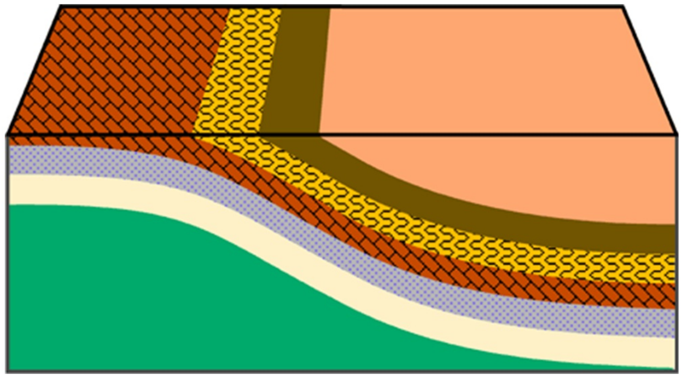


Fig. 2. Comparing horizontal and vertical access to stratigraphic layers. Some deeper layers may not be accessible via horizontal traverses.

to and in-situ analysis of lunar vents (Hawke et al., 2012). During successive flybys, the Mars Global Surveyor detected bright gully deposits on the walls of two separate unnamed craters, indicating geological or hydrological flows on the Red Planet[3]. In-situ samples of these flows would likely lead to new insights into Martian geology. Additionally, methane plumes have been discovered over hazardous terrain regions on Mars, compelling researchers to ask if their source is geological or biological in nature[4].

A new generation of robotic explorers is needed to access these extreme terrains in order to probe, sample, and measure. New inquiries of this sort could yield significant scientific rewards. While the primary motivation and focus here is on planetary exploration, robotic vehicles that can traverse extreme terrain may find applications on Earth as well, such as scientific sampling of active volcanoes and Antarctic slopes or providing support for mining operations. Mobility platforms that would enable access to, obtain in-situ measurements from, and retrieve samples from extreme terrains would play a critical role in the success and diversity of extraterrestrial body exploration. Traversing and loitering on steep exposed substrate slopes reaching up to 90° would enable examination of stratigraphic layers of exposed bedrock (Mars Exploration Program Analysis Group, 2010) and icy bodies. While current practice relies on long traverses across the surface to access these layers (Figure 2), direct access of exposed strata enables close examination of the interface between the strata, has substantially less weathering, and offers more details in the layers compared to what can be obtained through horizontal traverse alone.

Traversing and loitering on granular and mixed media slopes up to the angle of repose enables access to locales such as those where recent hydrological activities have been observed from orbit on Mars (Figure 3). Traversing across and through alluvial fans for in situ examination would further our understanding of the underlying physical processes and composition of the ejected material (Mars Exploration Program Analysis Group, 2010). Detailed topography of the fans (terrain roughness) may not be well known a priori, which requires reliable and versatile mobility platforms for their exploration. Through the course of accessing extreme terrain, hazards such as soft relogith or landslide could occur. An ability to survive such dynamic processes becomes an important means for demonstrating low risk for access.

Recent discovery of lava tubes on the moon and Mars has generated interested in their exploration as they could potentially serve as future temporary habitats for astronauts, providing them with protection from space radiation. The exploration of lava tubes could also have scientific interest for similar reasons.

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

[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.

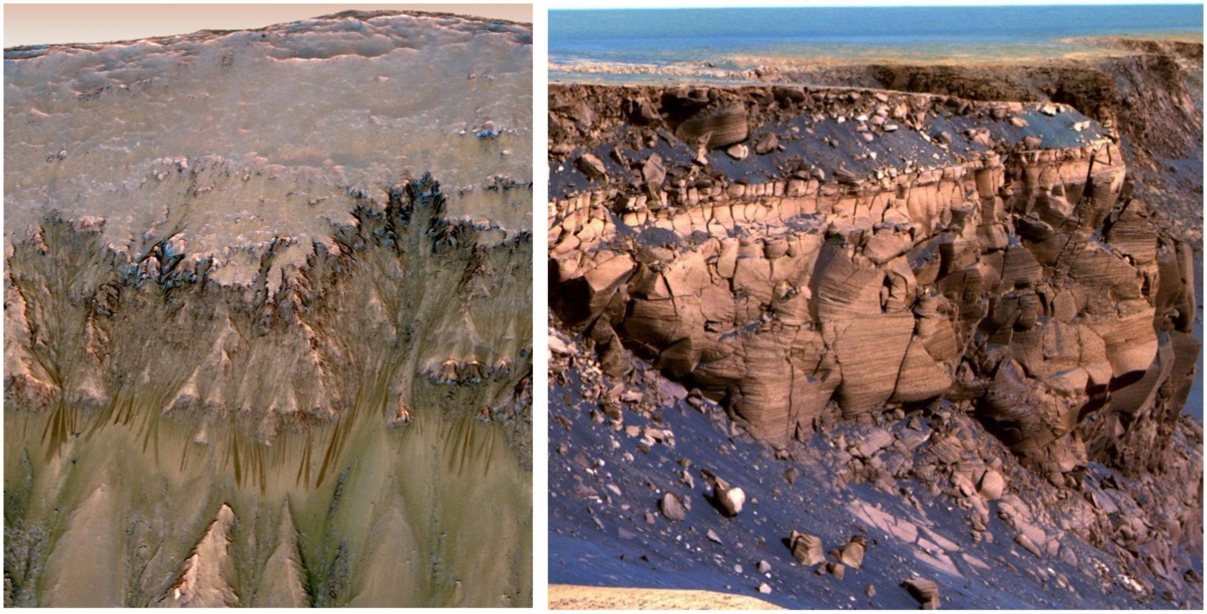


Fig. 3. Examples of extreme terrains on Mars: recurring slope linae believed to be water seeps in Newton crater (left), and false color image of Mars Victoria crater taken by the Opportunity rover showing steep slopes, scattered rocks, bedrock, and tall cliffs (right).

terrain could be operated from cis-Lunar orbit. Future human missions to Mars could tele-operate robotic assets from stations on Phobos, which are significantly easier for astronauts to access and from which they would be enjoy some protection from 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 Mars and lunar science missions that is applicable to any planetary (or lunar) surface exploration mission, human or robotic (National Research Council, 2012).

C. *State of the Art*

Terrestrial robots have made significant progress in recent years toward more extreme terrains, but have primarily focused on human-traversable terrains that would be applicable to military scenarios. For example, Boston Dynamics’ BigDog and LS3 used dynamically stable gaits to negotiate rough terrain and slopes up to 35° in angle under rough and slippery conditions. They have also demonstrated robustness to external force disturbances that could be imparted to throw the platform off-balance.

More extreme terrain requirements as well as mass and power constraints in space robotics have limited 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 were built and fielded. 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 legged ATHLETE robot, designed to handle cargo in support of 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 [5] (Nesnas et al., 2012) have

[5]Axel Videos (2011). URL: https://automation.jpl.nasa.gov/~nesnas/projects/axel/movies/. Retrieved August 20th, 2011.

demonstrated traversal of slopes reaching near vertical and sloped terrain littered with large boulders. Other robots have been proposed to use leg-mounted active anchors in lieu of tethers (Badescu et al., 2005). In either case, the inherent complexity that arises from large numbers of actuators needed by a capable multi-legged rover has greater potential for mission failure, particularly on very steep terrains. Moreover, typical power and mass constraints on space platforms and the extreme thermal environment of cold traps make the engineering of leg actuators, sensors, and electrical harnesses for sustained operation in such an environment challenging with today's technology.

In addition to these legged robots, a number of wheeled robots have also been proposed and several prototypes have been built and fielded. A recurring mechanism configuration used a six-wheeled rocker bogie suspension (e.g. the MER and MSL rovers) or a four-wheeled scissor-like active suspension that can lift each wheel independently off the ground. Such platforms were designed to control/lower the center of mass to provide great 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 also 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 to overcome high-slip on slopes, steeper slopes are likely to require an external force, such as that provided by a tether. A four-wheeled tethered rover was demonstrated with Cliffbot (Pirjanian et al., 2002). This architecture required a minimum of three rovers. Two rovers would traverse the rim of a crater while a third rover, which was 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 this advantage diminishes as the rover descends deeper into the crater. The Cliffbot used the rim rovers to manage the tethers, which, unlike rovers that pay out their own tether, risks higher abrasion as the tether constantly scrapes the rocks. 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-wheel 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. More recent such morphologies included 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 mobility elements that are more likely to fail 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 and flexible mobility and operations on challenging terrain. Its single tether was managed by the same mechanism that controls the caster arm and the instrument orientation. The DuAxel concept included docking and undocking with a central module, enabling both untethered mobility away from landers to the extreme terrains and tethered mobility within a crater. Axel also featured high mobility grouser wheels, with later versions employing an additional degree-of-freedom to decouple pointing from tether management so as to enable instrument suite reorientation while hanging. Recent versions also included improved tether management and tether tension sensing (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° 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. Conventional, flat-topography rover designs must be re-evaluated in the context of high-risk terrain missions.

Figure 2 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. A rocker-bogie class rover such as MER or MSL is not designed for such terrain and would not likely be well-suited to navigate it. Such terrains would be very difficult to traverse, as platforms would face reduced mobility on such steep slopes due to loose soil that can severely diminish traction forces. 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 terrains.

Another hazard associated with traversing steep and rugged terrain is tip-over. 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 center of mass and carefully planning safe routes around obstacles so as to avoid tether entanglement and potential tip-over conditions. Alternatively, one could design a rover capable of operating in a vertical or upside-down configuration, thereby eliminating the dangers of tip-over altogether. Wind, slippery ice, loose rocks, and many other environmental factors can cause tip-over, and since these variables cannot be controlled, tip-over needs to be taken into consideration when designing an extreme terrain rover. More generally, robotic mobility engineering for extreme terrain must combine both novel mechanical design features as well as active planning and control algorithms.

Additionally, sources of energy can be difficult to find in areas of extreme terrain. For example, the Cabeus Crater is located near the Moon's south pole, and thus lies in near-perpetual darkness, 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 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.

Finally, the limited capability of available radiation-tolerant flight qualified processors constrains on-board processing even while avionic and software systems continue to grow in complexity. Currently the performance gap between standard commercial processors and flight processors remains quite large. In the commercial world, the trend is for greater parallelism/multiple cores. Attaining the required levels of robustness and reliability in the face of increasing cost constraints remains an open problem.

In addition to these general challenges, each platform design would offer a range of capabilities and introduce a set of constraints that would need to be addressed and a risk that would need 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: traverse to designated targets in extreme terrains, retro traverse for captured samples, control of tethered 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.

- **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 several kilometers to reach them by ground. Technologies that would enable fast traverse for flight systems become important. State-of-the-art platforms currently navigate the surface by first processing stereo imagery, then generating three-dimensional maps, assessing the rover's traversability, planning its motions, and finally conducting the 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 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 field-programmable gate arrays (FPGAs). This 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, 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.
- **Tethered Mobility and Control**: This brings us to a second technology: tethered mobility. Highly-sloped terrains require strong and robust mechanical support to counteract the effects of gravity. One approach would be to use external means of mechanical support. Research in tethered mobility has included both single and multi-tethered platforms. Anchoring can be another means of providing mechanical support in highly-sloped terrains. Technologies enabling anchoring and de-anchoring across a wide range of terrain types would provide an alternate means of providing mechanical support.
- **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 configuration, which would also require further development. Platforms employing multiple tethers would necessitate coordination and a means to avoid tether entanglement. Extreme terrain excursions that deploy a tethered asset would need technologies for deployment and retraction of the tethered assets. 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.

  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 (such as cameras, inertial measurement units, and other instruments). Miniaturization of avionics sensors and instruments would increase capabilities. Sample acquisition, caching and handling in extreme terrain presents its own unique challenges. Drilling and coring require stabilization of the platform or some form of grappling to impart necessary forces for percussion or coring.
- **Traversability Analysis and Motion Planning**: Control, traversability analysis and path planning for an extreme terrain mobility platform takes on a new meaning, where motion may be more constrained in particular for tethered systems, control may require more sophisticated dynamical models given the gravity field, and knowledge of regolith properties may be more critical.

  Long-duration excursions in extreme terrain would demand more sophisticated motion planning techniques that take into account the effects of gravity and terrain properties, as compared to state-of-the-art motion planners that primarily consider terrain geometry and wheel characteristics to assess traverability. 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 the 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, mobility in extreme terrain is likely to trigger tip-overs. Recovery from tip-overs could be addressed via a mechanical design that operates from all stable states or through an alternate operational strategy.

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.

a) Entry, descent and landing: One such area is landing precision, which is under the Entry, Descent and Landing technology area (TA-09). The key relevant areas in *entry, descent and landing* are: (a) surface access to increase the ability to land at a variety of planetary locales and at a variety of 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, hence mission duration, to those sites. Further advances in 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 leverage its resources 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. Some technologies for extreme terrain mobility could be applicable to the exploration of collapsed lava tubes (caves) and lunar vents. For example, tethered platforms with access to the interior of crater walls could also potentially be used to explore lava tubes.

c) Microgravity mobility: Technologies developed for *microgravity mobility* as discussed in Section IV, such as anchoring, fixturing, tethering, as well as articulated legged, tracked, wheeled and hybrid mechanisms, could additionally apply to extreme terrain mobility applications and vice versa.

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 development and testing of microgravity systems 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

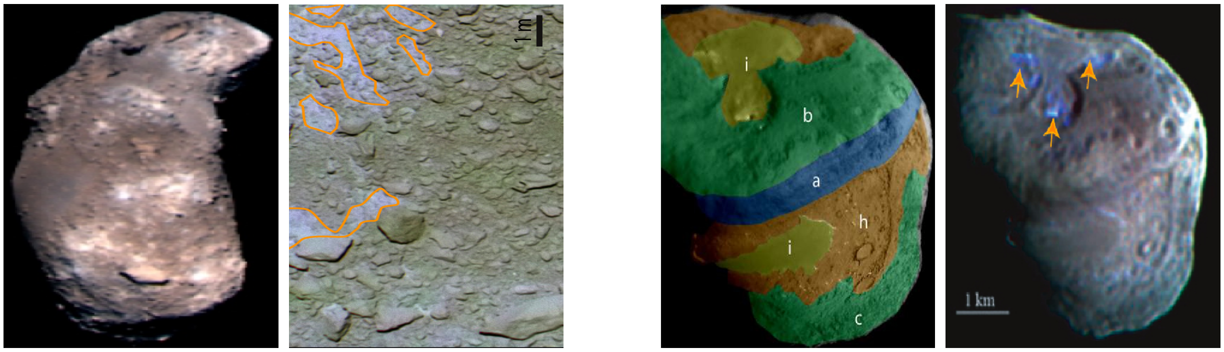
Small body mobility concerns spatial surface coverage on planetary bodies with substantially reduced gravitational fields for the purpose of science and human exploration. This includes mobility on Near-Earth Objects (NEOs), asteroids, comets, irregularly-shaped objects, and planetary moons, including Phobos, Deimos, Enceladus, and Phoebe, for example. 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 could include hoppers, wheeled, legged, hybrid and other novel types of mobility platforms. Hoppers, short for hopping mobility platforms, can employ many types of actuation for mobility, such as propulsive thrusters, spring-loaded mechanisms, and internal actuation that generates reaction forces or changes the center of gravity. Note that impact of hopping robots with the surface is less likely to cause damage in this case 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 autonomy 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 technologies for small body and microgravity mobility as a high-priority for NASA given its destination potential for human spaceflight beyond Earth orbit, an endeavour 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 (Michael J. 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*, 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), 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 4 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 homogenous.

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 (NRC, 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 exploration of small bodies such as near-Earth objects and Mars' moons is also a key component 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 can be obtained from remote platforms (such as space telescopes or orbiting spacecraft), several other measurements 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



(a) Asteroid Itokawa. (b) Comet Tempel 1.

Fig. 4. 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).

et al., 2012). This is also the case for precursor science enabling human exploration, which requires the characterization of surface physics, including regolith mechanical properties, dust dynamics, and electrostatic charging (Michael J. 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 5, 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 are not outgassing and do not 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 of *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 in each location. Second, the comet Tempel 1 presents four distinct geological units; in particular, it exhibits cryoflow features (that are products of geological evolution) near areas that appear to be less evolved and may be more representative of the original material (see Figure 6). 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 heterogeneity 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. This demonstrates a clear motivation for investment in microgravity mobility technology.

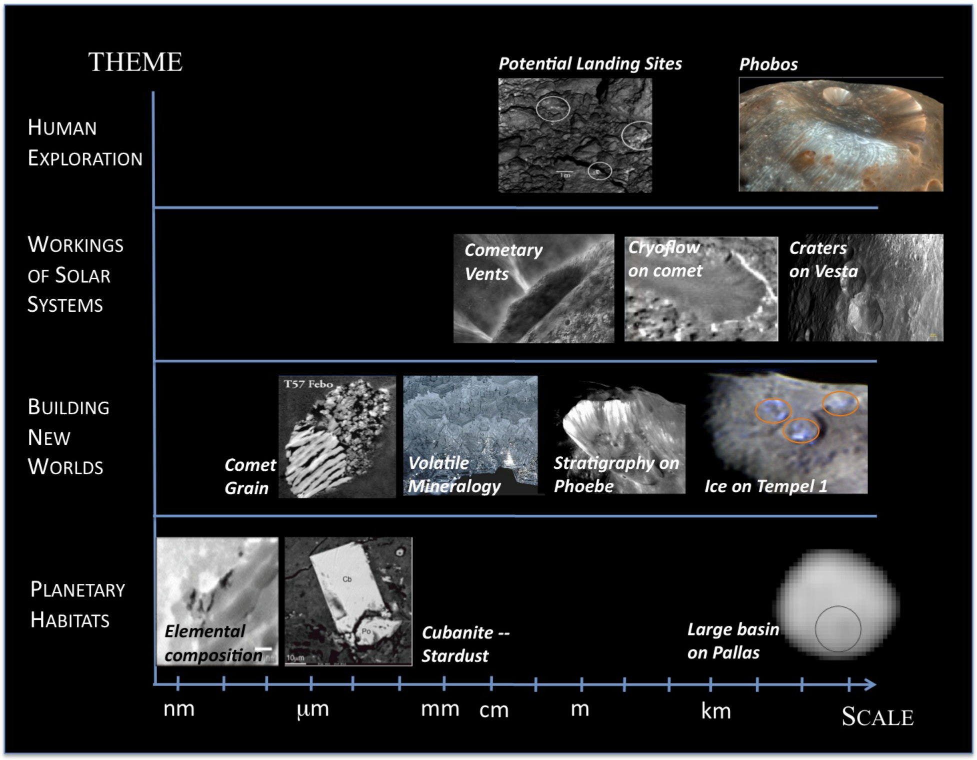


Fig. 5. Illustration of the type of observations to be achieved by space missions in order to successfully address the key science pertaining to the three cross-cutting theme highlighted in Vision and Voyages. Note that in general we lack high resolution observations at the millimeter to meter scale that can be best obtained by in-situ exploration.
Image courtesy of (Castillo-Rogez et al., 2012)

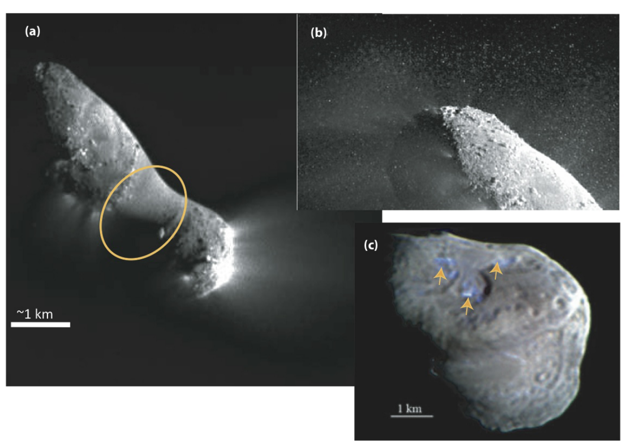


Fig. 6. Illustration of the variety of landscapes found at comets. (a) Picture of Hartley 2 obtained by EPOXI showing a contrast in surface roughness between active and waste areas. (b) This close up shows the variations of physical properties, especially roughness, at all scales. (c) In this close-up 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)

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, and 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, two missions so far have included a robotic hopper as part of their payload: Phobos 2 and Hayabusa. Their designs, as well as most attempts of hopping mobility, made use of two basic principles:

1) The hopper uses a sticking mechanism (thus jumping away from the surface).
2) The hopper moves 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 7). Its actuation was based on a spring-loaded leg mechanisms designed to stick 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). On the other hand, JAXA's Hayabusa mission was planning to carry JPL's Nanorover (see Figure 8), a four-wheeled rover with articulated suspension that was capable of roving and hopping. Due to budgetary reasons, the rover was canceled. Subsequently, JAXA/ISAS developed the MINERVA rover, a 591 gram hopping rover that used a single internal flywheel mounted on a turntable, which allowed to control the direction of each hop. The MINERVA design was considered capable of achieving speeds as high as 0.1 m/s. Unfortunately, the MINERVA rover also failed upon deployment (JAXA, 2000). Both the Nanorover and the MINERVA hopper were solar-powered systems and hence had very limited power (on the order of a couple of Watts) and computation. A handful of other hopping designs have been attempted. NASA-JPL has developed in the past several generations of robotic hoppers actuated by sticking the surface. ESA developed a small hopper rover prototype called MASCOT, actuated by spinning two eccentric masses, that was intended as the payload of the Hayabusa Mk2/Marco Polo mission (Dietze et al., 2010). 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 rely on a combination of wheels and sticking mechanisms), ESA's hopper prototype, RKA's landers for the failed exploration of Phobos, and JAXA's MINERVA lander do not allow for precise traverses to designated targets. To address this problem, a team from Stanford, JPL, and MIT is currently developing an internally actuated rover that encloses three mutually orthogonal flywheels. By spinning the flywheels, the rover gives rise to surface reaction forces that make the rover tumble (for fine mobility) or hop (for large surface coverage) (Allen et al., 2013).

Other types of low gravity surface mobility have also been explored. Mobility via thrusters is the key actuation mechanism for the Comet Hopper (CHopper) mission concept, which has been recently preselected for a NASA Discovery-class mission to comet 46P/Wirtanen (NASA, 2011a). If selected, the mission is baselined to be launched in 2016. CHopper, designed to investigate changes in surface properties with heliocentric distance, would land multiple times (4-5 times) on the surface of the comet, hopping twice each time before coming to a stop.

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 such as drilling or coring on bodies with substantial gravity fields can be quite difficult for a robot in microgravity in these types of environments, unless some form of fixturing or anchoring is used to impart necessary stabilization forces. The use

Fig. 7. The PROP-F Phobos Hopper. *Image courtesy of (Sagdeev and Zakharov, 1989)*

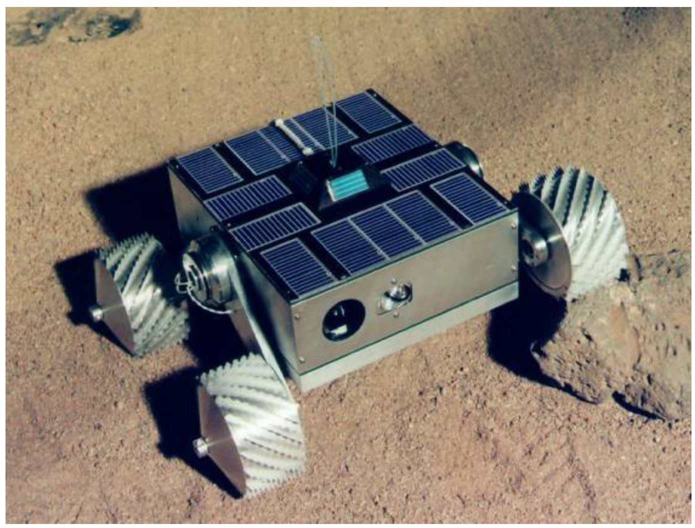


Fig. 8. The Nanoover. *Image courtesy of (Jones and Wilcox, 2000)*

of tethers or other aids could enhance control and improve maneuvering precision, but also have the unfortunate side effect of added mass and complexity.

Technologies relevant for small body mobility include advances in mobility and control techniques that would operate on a range of heterogeneous terrain types. They would also include techniques for localization of surface assets given the discrete nature and pose uncertainty that results from hopping and tumbling operations. As surface assets will likely be deployed by a hosting spacecraft, advances in control strategies exploiting synergistic operations between them and the mothercraft could enhance asset localization, mapping and motion planning, while simultaneously lightening 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, where functions that require wide area information such as perception and planning are assigned to a mothership, and functions that require local information such as obstacle avoidance are assigned to the mobile platforms, would allow end-to-end minimalistic design of mobile assets.

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 would 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 new global, scientifically-meaningful landing sites and facilitate traverse. Possible drawbacks of this architecture include the risk of damaging the orbiter during landing, the constrained number of locations that could be visited due to fuel, and the limited mobility once on the surface (which, combined with the uncertainty in the landing ellipse, implies that the visited locations could be fairly nonspecific). To overcome such limitations, it has been suggested to have a mother spacecraft deploy hopping rovers that would use thrusters for 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 extremely successful for the exploration of Mars. However, environmental conditions caused by gravitational accelerations in the milli-g to micro-g range limit their practicality for small body applications. Because of the very low traction available, 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 serious issues with wheeled vehicles are the complications in maintaining wheel contact with the surface (required for fine mobility and precision navigation to selected targets) and their sensitivity to dust contamination and external conditions that could cause the wheels to become “stuck”. In addition, surface bumps can cause loss of surface contact and result in uncontrolled tumbling, a potentially catastrophic situation for roving in deep space.
- **Legged mobility**: The primary drawbacks of legged systems are that they are mechanically and operationally complex, they require some form of anchoring system, and their performance is highly dependent on soil properties (Chacin et al., 2009; Seeni et al., 2008). However, as surface properties and soil 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 fairly insensitive to the soil characteristics of small body objects. Indeed, unlike other types of actuation, one can recognize that hoppers exploit the low gravity to their advantage, rather than facing it as a constraint. A particularly useful advantage of internal actuation mechanisms on hopper platforms is self-containment of moving parts, which significantly reduces the problem of dust contamination and thermal control. For these reasons, if one is able to include the option of fine mobility, hopping robots with internal actuations 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, 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 and structural materials, planning and guidance algorithms, and telemetry and sensing.

Each of these subcategories and their benefit 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, lifetimes would be limited to a couple of days at most. Future effort 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 area for solar cells and the possibility of the cells being covered with dust from the regolith. However, 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 less risky power alternative, despite the cost and regulatory issues; recent breakthroughs in this 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 the example with 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 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 temperatures allowed for electrical heaters that are consistent with the planned electrical power system. A RTG or RHU would most likely require a heat switch designed to prevent overheating during pre-launch and cruise phase. 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 magnitude 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. telecommunications between mobile rovers and their mothership, which is perhaps 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 have a first period during which the hopper "shakes" 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 when mobile assets are not in communication with the mothership.

d) Localization: Localization is a key challenge, 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. These may be based on use of extended Kalman Filters on fused 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 can 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 usage of vision sensors and cameras, which are able to provide "absolute" position measurements and can also detect the local environment, such as the presence of nearby rocks and craters. Unfortunately, vision may be prohibitively difficult in some cases depending on the geometry of ground assets. Small and compact shapes severely constrain the baseline for stereo vision (hence precluding precise depth estimation), while short geometries return a significant percentage of images captured from a low vantage point. The continuously rotating fields of view experienced by hopper platforms would make the estimation process particularly challenging and computationally expensive in their case.

Multi-asset mission architectures require special attention. Given the low-mass, small-scale construction and the limited computation capabilities of hybrid rovers, localization should rely on novel synergistic mission operations wherein the mothership bears the primary responsibility for determining the position and orientation of each hybrid and the mobile platforms are responsible only for local perception. As this scenario is unprecedented, this would require a substantial technology development. Within this architecture, localization of the hybrids could be done through a combination of sensors onboard the mothership and sensors onboard the hybrid. The hybrids would carry only a minimal suite of navigational sensors to keep the complexity, computation and power of each asset to a minimum. 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 in particular to multi-asset operations. Because of the discontinuous communication contacts with the mothership, each platform would need to operate autonomously, collecting, compressing, and storing data until each uplink opportunity. In cases of low radiation environment, an FPGA, small micro-controller or micro-processor solution would be strong candidates with relatively high density memory. The nature of the scientific payload would naturally allow for a high degree of sequential operation with initial uplink of accelerometer data, followed by in-situ data.

V. Conclusions

This chapter has addressed the engineering aspects and challenges of technology area TA04 “Robotics, Tele-Robotics, and Autonomous Systems,” extending 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 “Relative Guidance Algorithms”, “Extreme Terrain Mobility”, and “Small Body/Microgravity Mobility” in the autonomous systems area, motivating the importance of each technology, highlighting current state-of-the-art methods, and outlining 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 technological advancement lies in the development of algorithms and software that can offer more robust execution, increased mission assurance, augmented system capabilities, and improved spacecraft operations efficiency. Enhanced autonomy in “Relative Guidance Algorithms” discussed in the second section of this chapter is needed to develop robust, real-time implementable, and verifiable onboard optimization algorithms to instances of the guidance and navigation problem, particularly in situations involving delayed communications, time-varying obstacles, elevated mission risk, and tight maneuver tolerances. Important applications discussed in this chapter that exist at 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. This 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. Prospective approaches must be able to handle logical and risk constraints, certify algorithm correctness and convergence rates, and provide guarantees of mission safety. Guidance algorithm maturation will additionally require methods for verification and validation, design of metrics for assessing algorithm performance, techniques for reachability analysis, and handling of difficult non-convex state-control constraints.

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 and rocky, loose soil, or otherwise uncompromising terrain negotiation. 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 and 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 platforms' 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.

Addressing the needs of the US Space Agency will set the stage for technological advancement around the world. The potential for human exploration throughout the solar system, the benefits of scientific and commercial return, and the advancement of knowledge stemming from technological progression in robotics and autonomous systems are tremendous. It is up to the aerospace and robotics communities to meet these engineering challenges, develop these top-priority technologies, and drive the innovations of the coming decade.

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