Spacecraft/Rover Hybrids for the Exploration of Small Solar System Bodies

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Abstract—**In this paper we present a mission architecture for the systematic and affordable in-situ exploration of small Solar System bodies (such as asteroids, comets, and Martian moons). At a general level, a mother spacecraft would deploy on the surface of a small body one, or several, spacecraft/rover hybrids, which are small ($< 5\,\mathrm{kg}$, $\approx 15\,\mathrm{Watts}$), multi-faceted robots enclosing three mutually orthogonal flywheels and surrounded by external spikes (in particular, there is no external propulsion). By accelerating/decelerating the flywheels and by exploiting the low gravity environment, the hybrids would be capable of performing both long excursions (by hopping) and short traverses to specific locations (through a sequence of controlled "tumbles"). Their control would rely on synergistic operations with the mother spacecraft (where most of hybrids perception and localization functionalities would be hosted), which would make the platforms minimalistic and in turn the entire mission architecture affordable. Specifically, in the first part of the paper we present preliminary models and laboratory experiments for the hybrids, first-order estimates for critical subsystems, and a preliminary study for synergistic mission operations. In the second part, we tailor our mission architecture to the exploration of Mars' moon Phobos. The mission aims at exploring Phobos' Stickney crater, whose spectral similarities with C-type asteroids and variety of terrain properties make it a particularly interesting exploration target to address both high-priority science for the Martian system and strategic knowledge gaps for the future human exploration of Mars.**

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978-1-4577-0557-1/12/$26.00 ©2013 IEEE.

1. INTRODUCTION

In-situ exploration of small bodies at multiple designated locations is an important need in the scientific community [1], [2]; on the other hand, current mission architectures for the in-situ, multi-point exploration of small Solar System bodies tend to be high-cost and/or unable to ensure targeted sampling. On the one hand, monolithic architectures, which entail landing a spacecraft multiple times (as in the Comet Hopper mission architecture, pre-selected by NASA for a Discovery-class mission [3]), only allow for limited *discrete* and *random* sampling (versus spatially dense and targeted sampling, which requires surface mobility and is key for understanding, e.g., the nature of the interface between two spectral units), might lead to surface contamination (due to firing thrusters), and might involve high risks during each surface sortie, which translate into high-cost risk mitigation strategies. On the other hand, multi-asset architectures, which entail the deployment of mobile platforms, have to *overcome* the lack of gravity. Specifically, in low gravity environments wheeled vehicles are bound to extremely low speeds (less than 1.5mm/s [4]) due to low traction, and surface bumps can cause loss of surface contact and uncontrolled tumbling. Alternatively, legged systems are mechanically complex and highly dependent on soil properties [5], [6], which are largely unknown. NASA, RKA, ESA, and JAXA have all recognized the advantages of hopping on small bodies. However, both of NASA's hopper prototypes [4], [7] (that rely on a combination of wheels and sticking mechanisms), ESA's hopper prototype (that hops by spinning two eccentric masses [8]), RKA's landers for the failed exploration of Phobos (that hop by sticking the surface [9]), and JAXA's MINERVA lander (that hops by rotating a single flywheel mounted on a turntable and did not succeed during its deployment [10]) do not allow for precise traverses to designated targets. Furthermore, their surface operations (in terms of perception and planning) are essentially independent of the mothership (used as a communication "bent pipe"), which makes such platforms fully-fledged spacecraft in their own right.

This paper describes a novel mission architecture for the *systematic* and *affordable* in-situ exploration of small Solar System bodies. Specifically, a mother spacecraft would deploy over the surface of a small body one, or several, spacecraft/rover hybrids, which are small, multi-faceted enclosed robots with internal actuation (critically *enabled* by

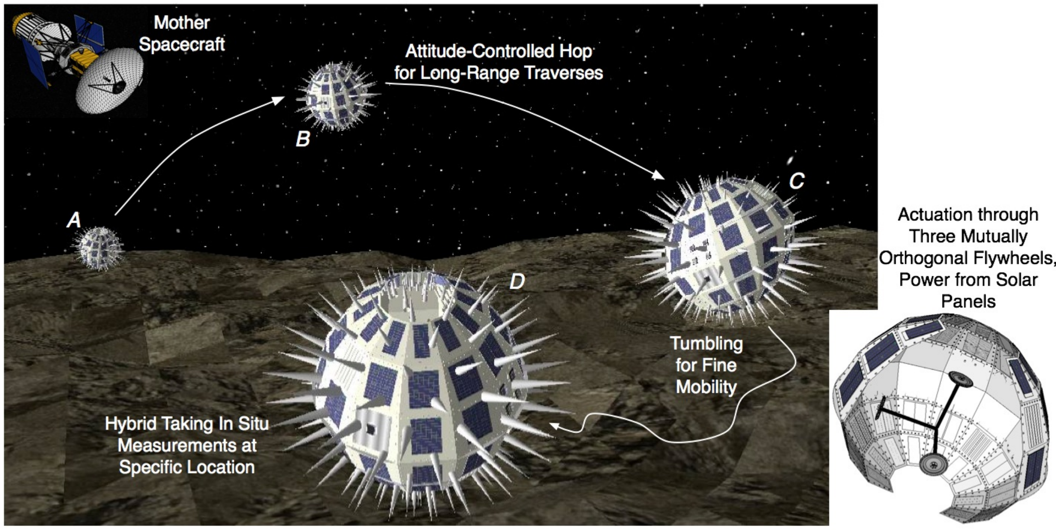


Figure 1. The mission architecture: one mother spacecraft would deploy on the surface of a small body one (or more) spacecraft/rover hybrids (from dm- to m-scale). Once deployed, the hybrids would perform attitude-controlled hops for long-range traverses (on the order of 10 m per hop, steps A to B to C in the figure) and would tumble to reach specific locations (steps C to D in the figure). Each hybrid is sealed in one enclosure and internally actuated through three mutually orthogonal flywheels (see bottom-right figure). Synergistic mission operations would ensure precise planning and control of the hybrids, while keeping their end-to-end design minimalistic.

microgravity) and external spikes. They would be capable of 1) long excursions (by hopping), 2) short traverses to *specific* locations (through a sequence of controlled tumbles), and 3) high-altitude, attitude-controlled ballistic flight (akin to spacecraft flight). Their control would rely on *synergistic operations* with the mother spacecraft (where most of hybrids' perception and localization functionalities would be hosted), which would make the platforms *minimalistic* and, in turn, the entire mission architecture affordable, see Figure 1. The key novelty of this mission architecture lies in the minimalism *and* maneuverability of the mobility platforms, and on the synergies between the mothership and the in-situ assets (both for mission operations and for the responsibility of primary science).

This paper is structured as follows. In Section 2 we summarize the design and the main mobility properties of the hybrids; we also discuss the development of a prototype and initial experimental results on a physical test stand emulating a low gravity environment (this section summarizes the results in [11] and makes this paper self-contained). In Section 3 we provide first order estimates of critical subsystems such as power, communication, thermal, science payload, etc. In Section 4 we discuss a four-phase mission operation concept, and in Section 5 we present a traceability matrix and a preliminary mission analysis for a Phobos mission scenario. Finally, in Section 6, we draw our conclusions.

2. SPACECRAFT/ROVER HYBRID: MOBILITY CONCEPT

A spacecraft/rover hybrid is a small ($\approx$ 0.4 m geometrical diameter, $\approx$ 5 kg even though the design is scalable) multi-faceted geometric solid that encloses three mutually orthogonal flywheels and is surrounded by external spikes or specialized contact surfaces (see Figure 1). Specifically, there is *no* external propulsion. The combination of the flywheels with the enclosure- and spike-geometry enables controlled tumbles, hops, and high-altitude ballistic flight. The target motion accuracy is on the order of $20\% - 30\%$.

The basic principle behind a flywheel is the conservation of angular momentum, which ensures that angular momentum can be swapped between the platform and the flywheels. Specifically, a flywheel consists of a spinning mass with a substantial amount of inertia. Due to the presence of the flywheels, the total angular momentum of the platform is given by (vectors and matrices are represented in boldface):

$$\mathbf{H} = \mathbf{I}_{\text{platform}}\, \boldsymbol{\omega}_{\text{platform}} + \sum_{\mathbf{i=1}}^{\mathbf{3}} \mathbf{I}_{\text{flywheel},\mathbf{i}}\, \boldsymbol{\omega}_{\text{flywheel},\mathbf{i}}, \qquad (1)$$

where $\mathbf{I}$ denotes the inertia matrix and $\boldsymbol{\omega}$ denotes the angular velocity vector. Since, in absence of *external* torques, the total angular momentum stays constant, by controlling the *internal* torque between the flywheels and the platform one can control both magnitude and direction of the angular rotation of the platform. In turn, this angular rotation can give rise to (controllable) surface reaction forces at contact points, which lead to either tumbling (i.e., pivoting around a tip) or hopping (when the reaction forces are large enough). The JAXA's MINERVA *hopper* included a related actuation mechanism (specifically, a *single* flywheel mounted on a turntable), which, however, did not allow for precise traverses to designated targets. Unfortunately, MINERVA did not succeed during its deployment [10].

We developed a variety of models and prototypes to study this mobility concept and related control and motion planning algorithms. In this section we only provide a brief summary to make the paper self-contained; more details can be found in [11].

Mobility

Figure 2 shows the minimum torques for tumbling and hopping on a Phobos-like environment (i.e. g in the $0.001\ \mathrm{m/s^2}$ range) as a function of spikes' length, as well as the scaling of the required torques as a function of gravity. Assuming that the flywheel is powered by a "conventional" DC motor, one can conclude that for a gravity level similar to the one on Phobos the power consumption is about $2-5$ Watts. The corresponding linear velocity for tumbling is about $0.05\ \mathrm{m/s}$ (Phobos's escape velocity is about $11\ \mathrm{m/s}$). Our models show that the required torques depend quadratically on the length of the spikes, hence there is an important tradeoff between the capability of negotiating obstacles (that would require long spikes) and the amount of actuation (that prefers short spikes). Also, the actuation level depends quadratically on the desired angular speed.

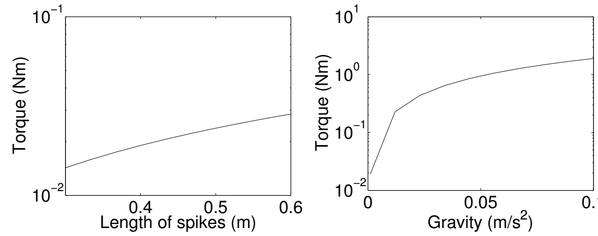
A key feasibility aspect for such mobility concept is flywheel's speed saturation. There are a number of strategies to mitigate this problem. The first strategy is to operate without consideration of saturation; for a Phobos-like environment (i.e. g in the $0.001\,\mathrm{m/s^2}$ range), assuming that the maximum rpm for the flywheel motor is 10,000, the maximum travel distance before saturation is about $150\ \mathrm{m}$. The second strategy relies on careful acceleration and deceleration of the flywheel such that forward motion is produced without a net increase in flywheel speed. The first strategy is reasonable for very low gravity and/or moderate coverage requirements ($\approx 100\,\mathrm{m}$ for Phobos-like conditions). The second is most effective, but requires sophisticated sensing and control. Third strategy: after a certain number of tumbles/hops, the flywheel is slowly despun in such a way that the platform does not tip over. This strategy is simple but substantially decreases the hybrid's average speed. Fourth strategy (in some sense dual of the third strategy): the flywheel is slowly accelerated (such that the platform does not tip over) and then decelerated in a very short time interval (by using brakes). In this way the hybrid starts a hop/tumble with a flywheel angular velocity of zero. This strategy is further developed below.

Planning and control

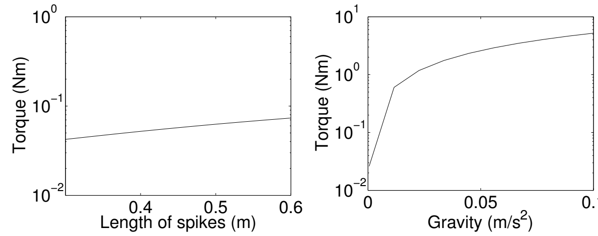
The main difficulties to control the hybrids stem from the gyroscopic coupling of the rotational degrees of freedom due to flywheel motion, and the unpredictable nature of hopping/bouncing due to the hybrid's non-spherical shape.

Our approach consists of a simple 3-mode hybrid control algorithm, whereby the flywheels are slowly accelerated to achieve a desired total angular velocity (referred to as "objective net angular velocity"), and then impulsively braked to generate the torque needed to produce hopping/tumbling. Specifically, the key idea behind the proposed motion planning algorithm is that the net angular velocities of the flywheels prior to braking should form a vector that is mutually orthogonal to both the heading and local gravity vectors. In this way, the torque from braking the flywheels causes the hybrid to tumble or hop in the general direction of the next waypoint. Deviations from the intended hopping direction, caused by a non-spherical geometry (e.g. edges, spikes), are compensated for by applying this approach to a sequence of hops/tumbles. Accordingly, the direction of the objective net flywheel angular velocity prior to braking is

$$\hat{\omega}_{\text{objective}} = \frac{\vec{h}\times\vec{g}}{\left|\vec{h}\times\vec{g}\right|}, \tag{2}$$



(a)Torques for *tumbling* motion. Left figure: torque vs. spikes' length (gravity $g = 0.001\,\mathrm{m/s^2}$). Right figure: torque vs. gravity (spikes' length $l = 0.4\,\mathrm{m}$).



(b)Torques for *hopping* motion. Left figure: torque vs. spikes' length (gravity $g = 0.001\,\mathrm{m/s^2}$). Right figure: torque vs. gravity (spikes' length $l = 0.4\,\mathrm{m}$).

Figure 2. Minimum torques for tumbling and hopping motion (the y-axis is in logarithmic scale). System's parameters: platform's mass equal to $2.9\,\mathrm{kg}$, flywheel's mass equal to $0.1\,\mathrm{kg}$ (hence the total mass is $3\,\mathrm{kg}$), radius of platform equal to $0.2\,\mathrm{m}$, and 4 spikes (hence $\alpha = \pi/4$). Longer spikes facilitate tumbling over large rocks but require higher torques.

where $\hat{\omega}_{\text{objective}}$ is the unit vector of the objective net angular velocity of flywheels, $\vec{g}$ is the local gravity vector, and $\vec{h}$ is the heading vector to the next waypoint (see Figure 3).

Successful execution of this algorithm for four arbitrary waypoints is displayed and discussed in Figure 4. The motion accuracy is on the order of 10%, which *compares well* with the requirement of $20\% - 30\%$ that is typical for a Phobos-like target (see Section 5). Our simulation results assume a smooth surface; future work should address the case of rocky terrains and non-uniform gravity levels.

Prototype and design considerations

A first generation of spacecraft/rover hybrids was developed to validate the results of the computer simulations. The prototype and CAD models for the structure and the flywheels are given in Figure 5. The design includes one internal motor/flywheel combination aligned with the unconstrained rotational degree of freedom on the passive gravity off-load test stand we developed.

Specifically, the test stand consists of a gravity off-load system with pulleys and a counterweight. Two off-load cables are used to prevent rotation about the vertical axis due to gyroscopic precession. This test stand introduces pendulum dynamics that quickly dominate all motion, yet it can still provide valuable information about the initial conditions of a hop or tumble. Two configurations were used, a $2\,\mathrm{m}$ test stand and a $5\,\mathrm{m}$ test stand. Experiments were run by programming a pre-defined acceleration (therefore torque) profile into the Arduino microcontroller that runs the flywheel's DC motor. The experimental torque profiles were then used in a 3D simulation environment to control a model of the prototype. The goal of these tests was to compare the torque levels

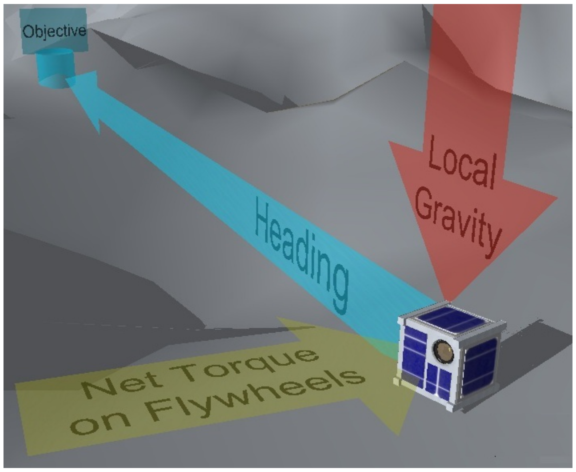


Figure 3. The net angular velocities of the flywheels prior to braking ($\hat{\omega}_{\text{objective}}$) should form a vector that is roughly anti-parallel to the net torque on the flywheels during braking (yellow arrow in above figure). This set of vectors is defined to be mutually orthogonal to both the heading and local gravity vectors according to equation (2).

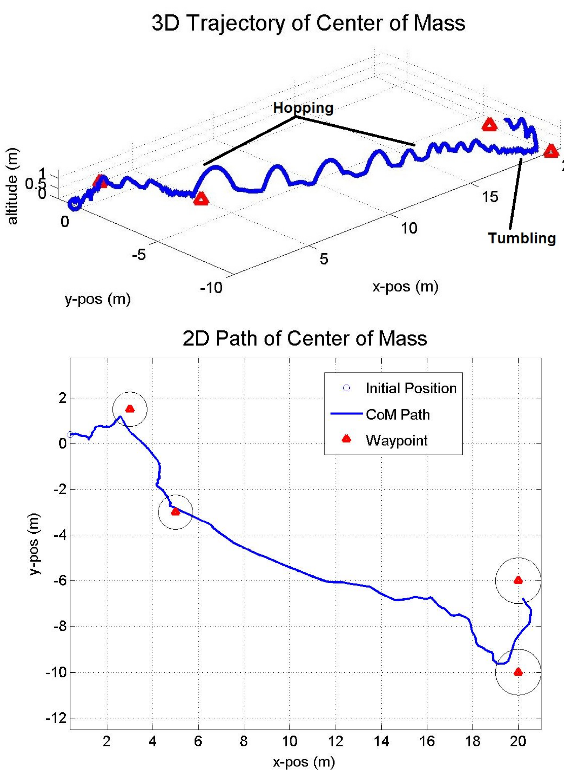


Figure 4. Demonstration of *controlled* mobility (as opposed to random hopping motion): the plots represent the application of the motion planning and control algorithm under Phobos-like conditions (i.e., gravity levels on the order of $\mathrm{mm/s^2}$). Waypoints were selected to demonstrate short and long traverses and directional changes. The hybrid averages a velocity of $\approx 1.6\,\mathrm{cm/s}$ over the 1770 seconds it takes to visit the four waypoints. The motion accuracy is on the order of 10%.

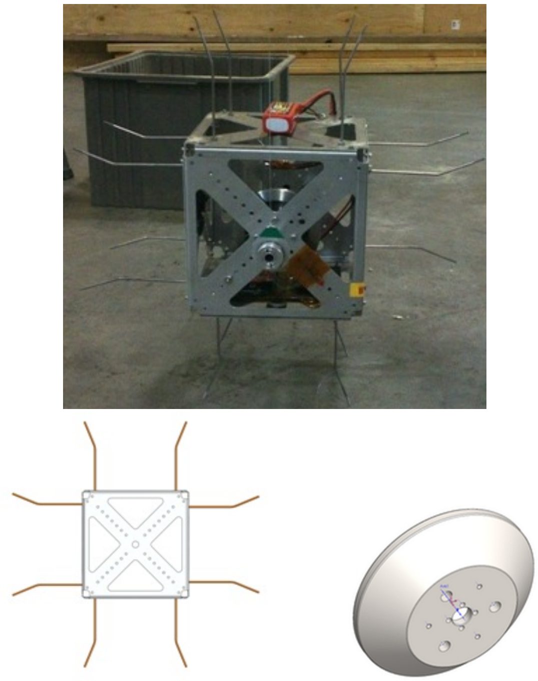


Figure 5. Prototype and CAD models (not to scale). The prototype, without the flywheel, has a mass of $1.39\,\mathrm{kg}$ and a moment of inertia about the axis of rotation of $\approx 0.054\,\mathrm{kg\,m^2}$. The flywheel is $0.57\,\mathrm{kg}$ and $8.07 \times 10^{-4}\,\mathrm{kg\,m^2}$.

at which hopping/tumbling are initiated both during the experiments and in simulation (some disagreement is expected due to modeling approximations and the pendulum dynamics introduced by the pulley mechanism of the test stand). Specifically, if behaviors did not match (e.g. experiment demonstrated tumbling but the simulation did not), then the torque profile would be amplified or attenuated until similar behavior was observed. The key result is that an average torque amplification of only 6% is required for the simulation to emulate the experiments (more details about the prototype and the experiments can be found in [11]).

We also developed a 3 DOF test stand that relies on a frictionless table and does not require any pulley system (and, hence, does not introduce any exogenous dynamics). In general, experimental results on this test stand were in agreement with the results from the pulley system test stand, the analytical models, and the numerical simulations. More details can be found in [11].

3. Spacecraft/rover hybrid: subsystems

In this section we provide first-order estimates for some of the critical subsystems of the hybrids, including power supply, communication, thermal, localization, and science payload.

Power supply

As discussed before, each actuator would draw about $2-5\,\mathrm{Watts}$. We also estimated a power consumption of $\approx 3\,\mathrm{Watts}$ for the onboard computer, of $\approx 8\,\mathrm{Watts}$ for communication, and of $\approx 5\,\mathrm{Watts}$ for scientific instruments. According to the operational modes that we identified (see Section 4), the average power consumption is on the order of

15 Watts. Considering the simplest possible strategy, which involves the usage of primary batteries with no recharging capability, the lifetime of the hybrid would be limited to a couple of days at most. As is discussed in Section 4, operating the hybrids would involve completely new procedures and would involve an extended learning curve. This makes the lifetime limitation imposed by using primary batteries inadvisable, unless several hybrids are deployed sequentially or there is already some legacy for their operations. To increase hybrids' lifetime beyond 48 hours, one could consider a combination of solar panels and secondary batteries. Solar panels would be placed on the exterior of the hybrid, in the spaces between the spikes. 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. Given that only the tips of the spikes would make contact with the surface, and there are no thrusters to stir up dust, the solar cell/secondary battery choice may represent an acceptable risk. However, 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 option would be advanced regenerative fuel cell systems.

Thermal control

Thermal requirements differ depending on the environment being explored. We have carried out a preliminary thermal analysis for a hybrid resting in proximity to the Stickney crater on Phobos, assuming 15 Watts of power generated inside the hybrid. Phobos's rapid movement (7.66 hour orbit) helps average out the hot and cold parts of the orbit. Our first-order estimates show a thermal time constant on the order of the orbital period, with an average temperature slightly above freezing. Hence, at least for Phobos, passive thermal protection, with coatings and multi-layer insulation, could be acceptable.

Shielding against electrostatic effects

We determined that if the electrostatic field is less than 100 V (as appears typical for small bodies), electrostatic charging should not represent a significant problem for hybrids' operations (e.g., telecom). Indeed, since the hybrid would be continuously tumbling, its overall charge should rapidly reach an equilibrium with the surface. The only phase that could represent a risk is the night-day transition; a possible solution would be to turn off all telecom and have a first period during which the hybrid "shakes" itself by tumbling.

Communication

We have considered various communication schemes for the hybrid. We have assessed that it is not practical for the hybrid to carry a directional antenna for direct communication with Earth. Therefore, the hybrid would use the mothership as a relay both for data and commands. We have considered various antenna schemes for the hybrid and identified the opportunity to take advantage of the hybrid's spikes by using two opposing spikes as the elements of a dipole antenna. Accordingly, the current design involves two opposing spikes of the hybrid as the elements of a dipole antenna. Because the hybrid may come to rest in arbitrary orientations, one needs to ensure against having the mothership ending up in the direction of a low node in the dipole antenna pattern. A possibility would be to use three orthogonal pairs of spikes to create three orthogonal dipoles. Sensors, either on the mothership or on the hybrid, could measure RF signal strength and route all power to the most favorable dipole. Another possibility would be the use of polarization sensing by the mothership as a tool for determining the hybrid's azimuthal orientation. Any antenna on the mothership capable of high data rate communication with Earth would be able to communicate with a several watt dipole on the hybrid. Using the same antenna for Earth and hybrid communications would, however, require periodic reorientation of the mothership attitude and would significantly increase the time required to get data from the hybrid to the Earth and to get commands to the hybrid.

Localization

Through dynamic sensors (such as accelerometers, gyros, and contact sensors) the hybrids can reconstruct their trajectory and hence determine their current position; however, this approach leads to large position errors due to sensors' drifts. This motivates the usage of vision sensors, which are able to provide "absolute" position measurements. However, the small and compact shape of the hybrids severely constrains the baseline for stereo vision (hence precluding precise depth estimation), a significant percentage of images would be captured from a low vantage point, and the continuously rotating field of view would make the estimation process particularly challenging and computationally expensive. The conclusion is that, given the low mass, low volume, and the limited computation capabilities of the hybrids, one should consider *synergistic mission operations*, wherein the mothership bears the primary responsibility for determining the position and orientation of the hybrid, and the mobile platform is only responsible for local perception. Within this architecture, localization of the hybrids would 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 the hybrid to a minimum. The navigational sensors would include a MEMS inertial measurement unit, one or more wide-angle cameras (e.g., to detect the *local* environment, such as the presence of nearby rocks and craters), a means to sense contact on the spikes, and possibly one or more sun-sensors (for rough attitude determination). The major hurdle associated with this architecture is its sensitivity to reliable telecommunication.

On board handling and telemetry

Because of the discontinuous communication contacts with the mothership, each hybrid 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. Given the general simplicity of the hybrid compared to most other interplanetary spacecraft, we do not anticipate the computer system posing any particular difficulties.

Science payload

One of the challenges associated with small mobility platforms is that they can only carry "nano"-instruments. However, miniaturized instrumentation has been blooming during the past decade. A review of the literature revealed that many miniaturized ($< 1\,\mathrm{kg}$) instruments have been flown and already achieved TRL 6 and higher (e.g., tunable laser spectrometer; heat flow probe on Deep Space 2; X-ray spectroscopy on Beagle 2; cameras on multiple missions), see Table 1. Analytical measurement techniques (essential for origins science) have lower TRL but are the focus of current investment by NASA, in its instrument definition programs. A detailed study of the science payload for a reference mission to Phobos is presented in Section 5.

4. MISSION OPERATIONS

In this section we present a preliminary study for mission operations, *under the assumption that the mothership is already in proximity to the target body*. A more detailed study in the constex of a reference mission to Phobos is presented in Section 5. At a high level, the plan for mission operations involves four main phases:

1) Initial reconnaissance of object: The operational objective of this mission phase is to select an area on the object where the hybrid can initially be placed.

2) Deployment of hybrid: The mothership releases the hybrid so as to place it on the surface of the object as near as possible to the selected site. There are two possible scenarios: in-situ deployment with a touch-and-go maneuver or deployment from a distance. While the first scenario is arguably the safest for the hybrids, it involves significant risks (e.g., JAXA's Hayabusa failed this maneuver [10]) and requires sophisticated guidance for the mothership, which translates into a high-cost dedicated mission. In the second scenario, there are three significant risks: the hybrid might crash on the surface, might bounce off the object and become "lost in space", or might penetrate deep enough into the surface so as to become "stuck". We have studied this scenario in detail for a reference mission to Phobos and determined that $3\ \mathrm{m/s}$ is approximately the touchdown speed from the Halo orbit at Mars-Phobos L1 (while this may seem fast, note that is the equivalent of dropping an object from a height of ≈ 50 cm on the Earth), with a settling time on the order of a few hours. Hence, for the proposed mission to Phobos (discussed in Section 5), release from a distance could be a feasible option. In general, release from a distance is the preferable option, provided that *safe* deployment strategies can be developed.

3) Initial "free roaming": The hybrid is commanded to perform several episodes of unguided motion, with increasing durations. The unguided motions are analyzed back on Earth to determine how well the hybrid's behavior compares to preflight simulations.

4) Command and execute guided trajectories: Since the hybrid will be visible to the mothership only during daylight and some measurements would benefit from the low-noise night environment, the hybrid would move during the day and would acquire measurements during the night. One of the most critical problems is surface operations for the hybrids. After a trade-off study (see also the previous discussion about localization), we determined that: a) autonomous operations for the hybrids would require a robotic platform that is a spacecraft in its own right (hence, no longer minimalistic), b) similar performance can be obtained at a potentially reduced cost through synergistic mission operations, where the hybrid relies on the mothership for localization and for part of the trajectory planning process. This assumes, however, a reliable, high-bandwidth telecommunication channel. Next section discusses in more details guidance, navigation, and control within a synergistic mission operations scenario.

Guidance and navigation with synergistic mission operations

In a synergistic approach, the Navigation, Guidance, and Control functions are embedded within the mothership as follows.

Navigation—The goal is to determine the position of the hybrid on the surface of the body and to ascertain its orientation. As far as *orientation* is concerned, sensitive accelerometers would enable the hybrid to determine on its own its orientation with respect to the local vertical. The more difficult task is to determine its azimuthal orientation about the local vertical. This is a function where the mothership would have to play a critical role. The most obvious technique is optical. This requires a camera on the mothership obtaining a high-resolution image of the hybrid resting on the surface, a larger-scale context image of the surface, and some markings on the hybrid that would allow optical correlation of the orientation of the hybrid with respect to the surface. Differentiating azimuthal segments of the hybrid to allow optical identification would be a challenge, made more difficult by potential dust contamination. Blinking lights could provide a solution. Another technique would be for the mothership to measure the direction of linear polarization from one of the hybrid's dipole antennas, from which it could determine the hybrid's azimuthal orientation. Finally, the mothership could command a motion about a specific hybrid body axis. The mothership would visually record the actual motion, from which Mission Control could figure out how the hybrid had been oriented.

Determining the *position* of the hybrids would make use of sensors both on the hybrid and the mothership. A feature-based temporal matching technique, known as visual odometry, has been used for estimating the pose on Mars rovers [12]. While, as discussed before, such techniques cannot be readily applied to the hybrids, the idea of matching visual features to estimate pose can be *adapted* to this unique platform (indeed, some preliminary work to adapt visual odometry to hopping platforms is already available [13], [14], [15]). In our case, using onboard stereo imaging would likely not fit within the envisioned mass and volume of the hybrids. However, a less accurate approach that relies on *monocular* vision would be sufficient for the hybrids. Since the hybrid's onboard computation would be limited, the hybrid can be restricted to executing canned sequences that acquire the necessary information and send it to the mothership. To generate three-dimensional information, one can envision the hybrid acquiring an image in the direction of travel and then slowly tumbling in the lateral direction counting contacts with the ground to establish an approximate baseline. The two images and approximate baseline would be uploaded to the mother craft to process the data. The mother craft would identify tie-point features between two or more temporal frames separated by the approximate baseline(s) to establish a camera model. Using this model, it would compute a low-resolution dense three-dimensional map, on which the position of the hybrid can be located. Future work should develop the algorithms to implement such strategy, and should perform a validation on a hardware testbed.

Guidance & Control—Narrow field-of-view imaging sensors on the mothership operating at several kilometers from the small body surface would provide contextual images for operating the hybrids. These images would be used in conjunction with hybrids' navigation data to perform the motion planning process discussed in Section 2.

Table 1. Science instruments that could be fitted within a hybrid.

Instruments	Mass (Kg)	Size (cm^3)	Power (Watts)	TRL
Accelerometer (8 sensors)	0.07	2.4	0.8 to 1.2	TRL 6-8
Descent Camera	0.160	9	0.160	TRL7+
Heat Flow Probe	0.300	20	0.025	TRL 7
Magnetometer	0.07	200	0.15	TRL 5
Mass Spectrometer	0.75	1000	3-6	TRL 4/5
Seismometer	0.3	200	0.1	TRL 4-5
Engineering Tiltmeter	0.010	25	0.1	TRL 6-8
Water/Volatile Detector	0.750	1000	3	TRL 4-8
X-ray Spectrometer	0.260	160	4	TRL7
Dielectric/Permittivity Sensor	< 0.1	TBD	0.5	TRL 7
Microphone	0.004	2.6	TBD	TRL 8
Radio Beacon	0.400	TBD	4	Huygens
ThermoGravimeter	0.400	25	0.5-2	A-Rosetta

5. Reference mission to Phobos

In this section we present a preliminary mission analysis for a Phobos mission scenario; the results in this section builds upon the previous authors' work in [16]. A single-string electric propulsion mothership would deploy from a distance one, or more, hybrids on the surface of Phobos in proximity to the Stickney crater (see Figure 6). Such platforms would carry a X-ray spectrometer, a radiation monitor, a thermocouple, and a microscope, and would operate for about 48 hours over a surface of about $1 - 5\,\mathrm{Km}^2$. The mothership would be equipped with a gamma ray and neutron detector, a high-resolution stereo camera, a radio science subsystem, and a dust analyzer, and would station keep at the Mars-Phobos L1 point, see Figure 6. Using orbital observations, mission planners would upload traverse sequences to the hybrids via the mothership (see Figure 7). Major science objectives would be to characterize regolith composition, evaluate regolith maturity, constrain mechanical properties, constrain dust dynamics, achieve both topography and gravity mapping, study surface dynamics and the electrostatic environment, and characterize the distribution of water. In the next sections we give more details about the different parts of the mission.

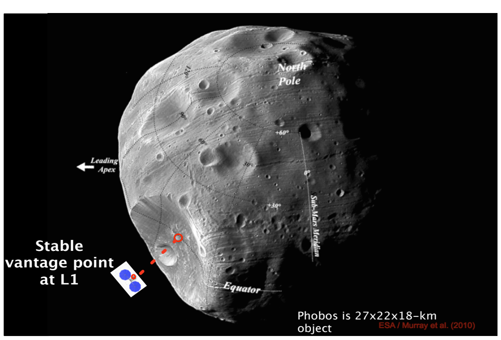


Figure 6. Mission architecture: the mothership (Phobos Surveyor, see Figure 9) would deploy on the surface of Phobos one or more hybrids and would station keep at the Mars-Phobos L1 point.

Science objectives and hybrid's design

The characterization of Phobos' surface chemistry and physics would be key to constrain Mars' origin (Phobos' surface is believed to contain Martian material [17] and especially Mars' meteorites [18]) and to address strategic

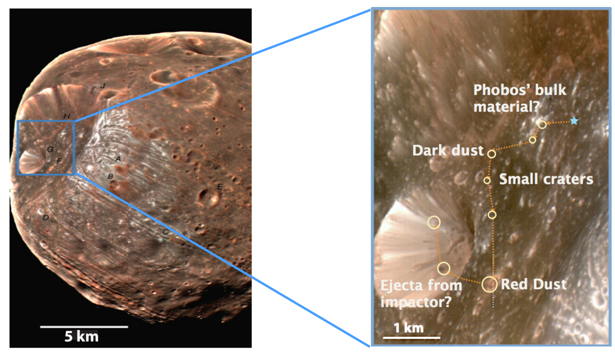


Figure 7. Notional illustration of the trajectory that a hybrid should execute in order to sample both the chemical and the physical diversity on Phobos (close to the Stickney crater). The motion accuracy, given the scale of the landmarks to be visited, should be on the order of $20\% - 30\%$, which compares well with the capabilities of a hybrid.

knowledge gaps required to prepare for human exploration (e.g., Phobos offers a unique vantage point of Mars, from which climate monitoring and telerobotic operations may be conducted [19], [20]). While Phobos has been the target of multiple remote sensing instruments as part of five different missions (Viking, Phobos 2, Pathfinder, Mars Express, Mars Reconnaissance Orbiter), its surface composition is mostly unconstrained, with large uncertainties regarding, e.g., the presence of volatiles on the surface or below the surface. Phobos' red material covers approximately 90% of its surface and is likely of Martian/Deimos origin [21], [22], while surface material that is representative of Phobos' bulk interior appears to be highly localized and within challenging areas such as narrow excavated regions within the Stickney crater [23]. Hence, mission architectures involving static landers (such as Phobos-Grunt, an attempted Russian sample return mission to Phobos) carry a *significant risk* of returning information that is not representative of bulk properties (a key concern for Phobos-Grunt). Sources of lateral variations in surface properties come from weathering (exogenic processing), mass wasting, impacting, ejecta, and dust accretion. These create variations on scales ranging from a few tens of meters to a few hundreds of meters (Figure 8), which call for the usage of *in-situ* mobility platforms for proper characterization.

The observation requirements driving our mission study address some of the key science priorities established in the planetary science decadal survey report [1]. Specifically, the key science questions are as follows:

- What is the composition of Phobos' materials?
  1. Is there water and organics on Phobos?
  2. Is the "blue" spectral unit water-rich?
  3. Are putative phyllosilicates associated with organics?
- What is the origin of Phobos materials?
  1. Does Phobos or part of Phobos come from Mars?
  2. Is Phobos a captured asteroid?
  3. What is the origin of ejecta in Stickney area? (impactor?)
  4. What is the flux of material in Mars system?
- What is the structure of Phobos soil?
  1. What is the degree of maturation of the regolith?
  2. What is the nature of the interaction soil-robot?
  3. What is the nature of the surface dust dynamics?
  4. What is the degree of mobility of the soil?
  5. What is the amplitude of dust charging and levitation?

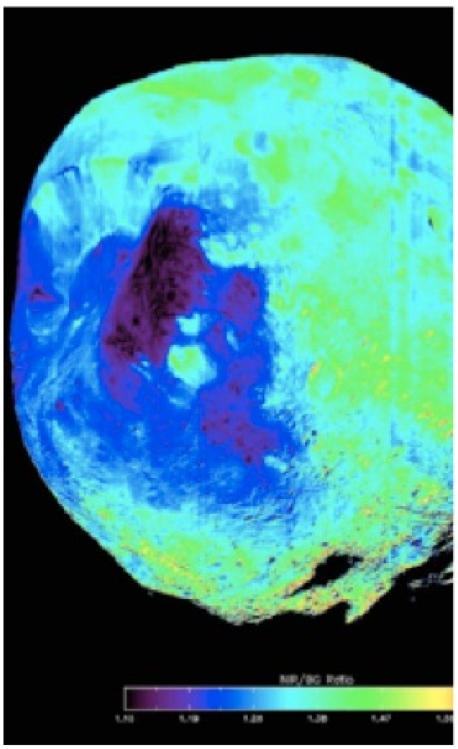


Figure 8. Spectral properties of Phobos' surface as observed by Phobos 2.

Our high-level mission study led to the science traceability matrix presented in Table 2 (that considers miniaturized instruments with TRL 6 or higher) and to a desired path for the hybrid that is represented in Figure 7 and is aimed at sampling both physical and chemical diversity. (In Table 2, XRS = X-ray spectrometer, GR&ND = Gamma Ray and Neutron Detector, HRSC = High-Resolution Stereo Camera, RSS = Radio Science Subsystem; also, "Decadal" stands for science highlighted in the decadal survey, while "Precursor" stands for science in support of precursor missions.) Certain measurements are best achieved by the mothership (e.g., global reconnaissance, gravity, topography) while others can be performed only in-situ (e.g., soil properties). In other words, the mothership would provide broad area coverage, while the hybrid would zoom in on specific areas and conducts in-situ measurements. Hence, the responsibility for primary science would be shared between the mothership and the hybrid. The science objectives shown in Table 2 would be achieved with a hybrid having a motion accuracy of 20%-30%, which compares well with the capabilities of a hybrid.

Table 3 shows the baseline design for the hybrid (in the table, WAC = Wide Angle Camera, and OBDH= On-Board Data Handling); the total mass would be about $5\,\mathrm{kg}$ and the average power requirement would be approximately equal to $15\,\mathrm{Watts}$. The enclosure would have, approximately, a $0.25\,\mathrm{m}$ radius.

Mothership

The mothership would be the Phobos Surveyor spacecraft (Figure 9), which would provide a low-cost, high reliability approach for a mission to Phobos [16]. Phobos Surveyor can be constructed from currently available, well-characterized commercial components and is capable of carrying up to $30\,\mathrm{kg}$ of payload into orbit about Mars. Phobos Surveyor would utilize a flight-proven commercial Solar Electric Propulsion (SEP) system; EP systems developed for commercial GEO communication satellites would be perfectly sized for the electrical power and life requirements for a Phobos precursor mission. Two deployable solar arrays would provide sufficient power to operate the EP system at full power while in orbit at Mars. During the Mars Orbit phase (see below), the spacecraft would enter into a 50 min eclipse, relying on a secondary battery to provide power. Due to the low gravity of Phobos, a cold gas RCS thruster could be used to provide enough thruster to safely land the spacecraft (in case of an in-situ deployment of the hybrid). Direct to Earth communication would be achieved using a standard X-band uplink/downlink for science, command and telemetry.

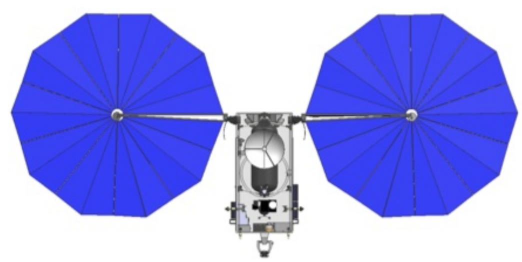


Figure 9. Sketch of Phobos Surveyor. This spacecraft is designed solely out of commercially available off-the-shelf parts [16].

Mission design and operations

Launch and early operations: Mars rideshares provide the most efficient opportunity for the Phobos Surveyor mission, requiring the least transfer propellant. As a SEP mission, the optimal launch time for Phobos Surveyor occurs before the optimal time for a ballistic mission. If unable to utilize a Mars opportunity for rideshare, the Moon becomes the means by which the spacecraft departs to Mars. To leverage the Moon, the mission would require specific targeting allowing for multiple flybys and ultimately Earth departure.

Mars transfer: Figure 10 shows the trajectory from Earth departure to Mars rendezvous. With an Earth departure of $2\,\mathrm{km/s}$, the SEP trajectory does not require thrusting until half way through the transfer, and from that point the trajectory requires constant thrusting to Mars rendezvous.

Table 2. Traceability matrix for a reference mission to Phobos.

Theme	Objectives	Observable	Role	Instrument
Decadal: Origins **Precursor: Soil mechanics/risk**	Obtain regolith composition	Elemental	Mothership	GR&ND
		Mineralogical	**Hybrid**	XRS
	Evaluate regolith maturity	Microstructure	**Hybrid**	Microscope
	Constrain mechanical properties	Angle of repose	**Hybrid**	Camera
		Response to impulse	**Hybrid**	Accelerometers
		Crater morphology	Mothership	HRSC
	Constrain dust dynamics	Measure dust flux	Mothership	Dust analyzer
Decadal: Processes **Precursor: Risk**	Topography mapping	Photoclinometry	Mothership	HRSC
	Gravity mapping	Doppler tracking	Mothership	RSS
		Acceleration	**Hybrid**	Accelerometers
	Assess surface dynamics & electrostatic environment	Dust interaction with spikes	**Hybrid**	Camera
Decadal: Habitability **Precursor: ISRU**	Distribution of water	Neutron detection	Mothership	GR&ND
		Mineralogical	**Hybrid**	XRS

Table 3. Baseline design for the hybrid for a reference mission to Phobos.

	Instrument	Mass (g)	Power (Watts)
Science Package	Radiation monitor	30	0.1
	XRS	300	4
	Thermocouple	50	1
	Microscope	300	0.1
Operational and science support	Accelerometer/Tiltmeter	66	0.002
	Descent camera (WAC/PanCAM)	100	0.1
Subsystems	Transceiver	230	8
	Avionics (including OBDH)	250	3
	Thermal	200	0
	Antenna	200	0
	Motors and flywheels	400 (total)	3 (each)
Structural	Solar panels	300	
	Battery	222	
	Structure	1000	
	RHU (optional)	400	
		Total ≈ 4 kg	**Average**: ≈ 12 Watts
		plus 25% margin	plus 25% margin
		Total ≈ 5 kg	**Average**: ≈ 15 Watts

Mars orbit phase: The proposed thruster for the Phobos Surveyor mission would be life-limited by propellant throughput. As a result, the spacecraft would be unable to spiral down to Phobos. Consequently, the trajectory would use periapsis thrust arcs, shown in Figure 11, to efficiently reach the Phobos orbit. Within such mission scenario, the transfer time between Mars arrival and Phobos orbit rendezvous would be one year.

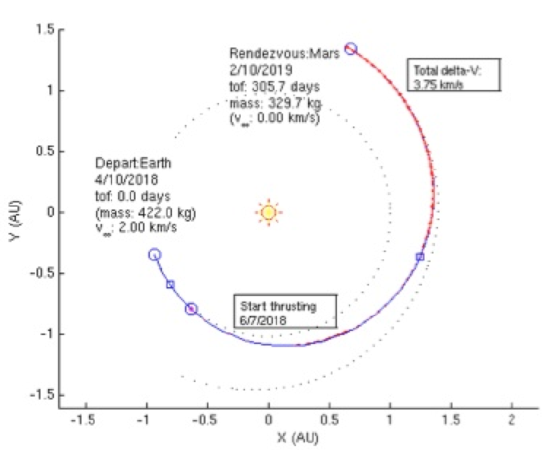


Figure 10. Trajectory from Earth departure to Mars rendezvous [16].

Phobos operations: For close proximity operations, the spacecraft would require autonomous control, similar to JPL's proven AutoNav system used for *DeepImpact*. Requiring more thrust than available from the SEP thruster, the final descent (if needed for the deployment of the hybrid) would utilize the cold gas RCS thrusters. Once the rovers have been delivered, the mothership would remain on a stable station keeping position at the Lagrangian point above Stickney crater. The GN&C system would utilize a high precision IMU and star tracker measurements to provide attitude feedback to the reaction control system. Torque provided by the reaction wheels would be used to maintain stability and orient the spacecraft for Earth communication. Finally, using orbital observations, mission planners would upload traverse sequences to the hybrids via the mothership.

6. Conclusion

In this paper we presented a novel mission architecture for the systematic and affordable in-situ exploration of small Solar System bodies. Such a mission architecture stems from a paradigm-shifting approach whereby small bodies' low gravity is directly exploited in the design process, rather than being faced as a constraint. Feasibility and maturation aspects current under study can be grouped into three main categories:

- **Planning and control for fine mobility**: Improve motion planning algorithms and control laws so that both fine mobility and instrument pointing can be *reliably* achieved over

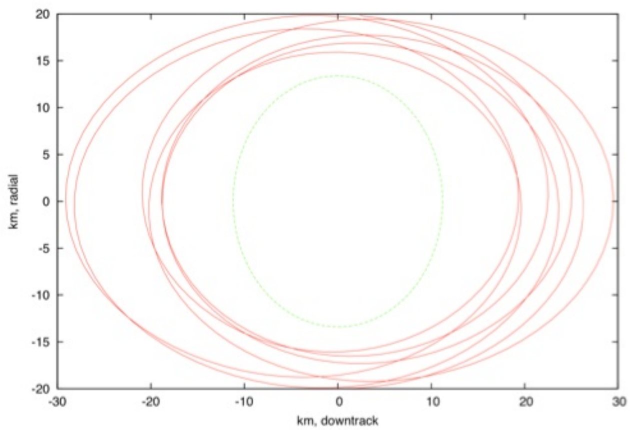


Figure 11. Periapsis thrust arcs to achieve Phobos orbit [16].

loose, dusty, and rocky terrains, with a target motion accuracy on the order of $20 - 30\%$.

• **Maturation of key subsystems**: Identify power supply options to increase hybrids' lifetime beyond 48 hours, and further develop communication and localization strategies compatible with the concept of synergistic mission operations.

• **Affordability of mission architecture**: Quantify the impact of synergistic mission operations within the context of a large mission, with the goal of determining the class of objects for which the hybrids represent a compelling mobility option.

ACKNOWLEDGMENTS

The research described in this paper was partially carried out at the Jet Propulsion Laboratory (JPL), California Institute of Technology, and was partially supported by NASA under the Innovative Advanced Concepts program, and by JPL under the R&TD and CAP programs. The authors wish to acknowledge insightful discussions with Dr. Cinzia Zuffada (JPL), Dr. Tom Cwik (JPL), and Dr. Jonas Zmuidzinas (JPL). Government sponsorship acknowledged.

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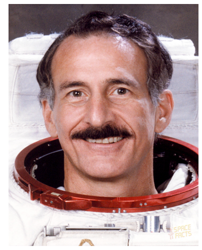

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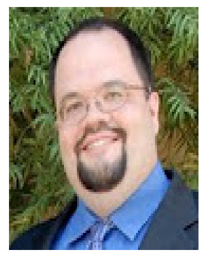

Nathan Strange *has been at JPL for 11 years and is currently a Systems Engineer in JPL's Lunar and Planetary Mission Concepts Group where he works primarily in mission formulation. He is the Mission Design lead for the JPL Innovation Foundry's Architecture Team (the "A-Team"), and has in the past also been the Mission Design lead on JPL's Team-X as well as several JPL and NASA-led mission concept studies. Nathan also has 6 years of flight operations experience on the navigation team for the Cassini-Huygens mission to Saturn where he was the lead trajectory designer for the first Cassini Extended Mission and also the Huygens mission recovery.*