SSC16-XI-08

An Asteroid Lander/Rover for Asteroid Surface Gravity Surveying

Kieran A. Carroll
Gedex Systems Inc.
407 Matheson Blvd. East, Mississauga, Ontario, Canada, L4Z 2H2; +1-289-374-3347
kieran.carroll@gedex.com

Henry Spencer
SP Systems
hspencer@utias-sfl.net

Robert E. Zee
Space Flight Laboratory, University of Toronto Institute for Aerospace Studies
rzee@utias-sfl.net

ABSTRACT

Microsat and nanosat developers have mastered the challenges involved in developing low-cost, high-performance satellite missions in low Earth orbit. Here we describe a proposed small-microsat-scale (~20 kg) planetary exploration mission based on the same design approach used in those LEO missions. The “GRavimetric Asteroid Surface Probe” (GRASP) spacecraft is being designed by Gedex and SFL, to carry out fundamental science and exploration activities on the surface of a small asteroid. It will carry a novel, extremely-high-accuracy space gravimeter instrument (VEGA, the VEctor Gravimeter for Asteroids) being developed by Gedex. Emplaced on an asteroid’s surface, VEGA will make measurements of the local gravity field strength (with nano-G accuracy) and direction (with arc-minute accuracy). A single such measurement will enable an asteroid’s mass to be determined, even for a very small asteroid. Measurements at multiple locations will enable inferences to be made about the asteroid’s internal density distribution, and hence its internal structure and composition. While much of the equipment used in LEO nanosats and microsats is suitable for use in GRASP, the mission’s asteroid landing and roving objectives, and the asteroid orbit and surface environment, lead to several design features not generally seen in LEO missions. Here we review GRASP’s mission objectives, highlighting the challenges which drive the design. We discuss the main mission and system level requirements which GRASP will meet, and describe the overall GRASP design.

OVERVIEW

In this paper, we describe a small spacecraft designed to make geophysical measurements on the surface of an asteroid, with the objective of helping determine the asteroid’s internal structure. Gedex and the Space Flight Laboratory (SFL) are developing the “GRavimetric Asteroid Surface Probe” (GRASP) spacecraft (Figure 1) to be a low-cost means for conducting important fundamental asteroid science, as well as for exploring for possible natural resource deposits in asteroids. To that end, GRASP’s design is based on the “Microspace” approach that SFL has used on many successful, very low-cost and high-capability nanosats and microsats in low Earth orbit (LEO).

GRASP’s main geophysical instrument is a gravimeter, which must make its measurements while stationary on the target asteroid’s surface; doing this at multiple, widely-spaced surface locations (“stations”) is highly desirable. Thus to achieve its mission objectives GRASP must incorporate functionality not needed for a free-floating satellite — the ability to navigate, land and move about an asteroid’s surface — which leads to

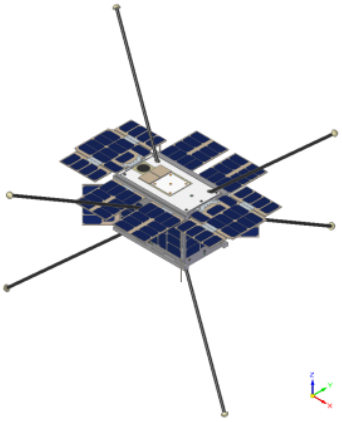

Figure 1: GRASP Asteroid Lander/Rover

design features not seen in "traditional" microsats and nanosats. In addition, the environment to which GRASP will be exposed near and on its asteroid target is very different in several important ways from that of LEO, notably:

Orbit: Target asteroids are typically in elliptical orbits around the Sun, and so spacecraft distance to the Sun can have a wide range. GRASP is designed to operate at Solar distances from 0.8 AU to 2.0 AU. This results in a large variation in the amount of power that can be generated over time, as well as in the thermal load on the spacecraft from the Sun.

Surface: GRASP must operate on the surface of an asteroid, which (obviously) free-floating satellites in LEO needn't. For the targeted small asteroids, surface gravity levels are very low, on the order of 10 μg — far smaller than the surface gravity levels for previous planetary rover missions. The mechanical properties of asteroid surfaces; despite being important to the performance of some surface-mobility concepts, are almost completely unknown. Their thermal properties may sometimes be similar to those of lunar regolith, heating up rapidly to very high temperatures during daytime, and cooling down rapidly to very low temperatures during night-time.

Typical design solutions for LEO micro/nanosats need considerable adaptation to accommodate these differences. Here we show how we have adapted SFL's microsat/nanosat design practices to address these challenges. We focus on describing the logic that drove the GRASP design process, primarily in terms of requirements at the Mission and System level that are unusual in the microsat/nanosat context. The resulting design, of a highly capable and robust spacecraft, a small microsat that fits within a 12U cubesat specification, is also described.

BACKGROUND

Deep Space Microsats/Nanosats

Historically, the factor which separates microsats (and, later, nanosats including cubesats) from "big" space missions, is cost. Funding available for the early microsats was so low, that those missions simply could not afford to purchase a dedicated launch to orbit, and so they were flown as secondary payloads, hitch-hiking to space on a launch vehicle whose cost was mostly (sometimes completely) paid for by a much more well-funded primary payload. While various current attempts to develop very-low-cost small launch vehicles may eventually lead to micro/nanosats being able to afford to purchase dedicated launches to orbit, the current practical definition of microsats (and nanosats, cubesats, etc.) is centred around the fact that they reach space as secondary payloads.

By that definition, the first microsat was the OSCAR-1 amateur radio satellite[1], launched on 12 Dec. 1961, not long after the beginning of the Space Age. Since then, hundreds of microsats and nanosats have flown as secondary payloads to LEO (15 of those being SFL missions), with some flying to even higher Earth orbits. However, until recently secondary payload launch opportunities have rarely been available to orbits beyond Earth orbit. Hence, to date, there have been only a few microsats or nanosats flown to deep space.

There are several reasons why this *has been* the case in the past. One is that for many years, missions to deep space were few and far between, so that there were just very few such launch opportunities. Another is that it is difficult to communicate with small, low-power spacecraft at interplanetary distances, and only recently has suitable radio equipment started to become available[2] to allow nanosats/microsats to communicate directly to Earth over such distances. Similarly, deep-space missions usually require significant propulsion capability, and technologies for achieving large ΔV were not available for microsats and nanosats in years past; they are starting to become available now.

The pace of deep space mission launches by space agencies has been increasing in recent years, a trend that appears set to continue. The technology base for microsats and nanosats has also been steadily increasing, as has the number of organizations with experience in developing such low-cost spacecraft. As a result, there are now several organizations world-wide actively planning secondary-payload missions[9] to destinations beyond Earth orbit including Lunar orbit[24] and Mars[11] and asteroid[15] flybys.

Asteroid Exploration Geoscience

To date, deep space exploration has been the exclusive domain of national space agencies, who have now funded missions to all of the planets of the Solar system, as well as to a growing number of moons and "minor planets" — asteroids and comets. There have been 16 dedicated missions to comets and asteroids (Giotto, Vega 1 and 2, Suisei, Sakigake, Clementine, NEAR Shoemaker, CONTOUR, Deep Impact, Deep Space 1, Hayabusa, Rosetta, Dawn, Hayabusa 2, PROCYON, with OSIRIS-REx soon to launch), plus several attempted missions to the asteroid-like moons of Mars (Phobos 1 &2, Phobos-Grunt), plus numerous other deep space missions to other target destinations, which have included incidental asteroid and/or comet flybys.

Figure 2: NASA's Asteroid Redirect Robotic Mission (ARRM)

Figure 3: ESA's Asteroid Impact Mission (AIM)

Early asteroid missions were flybys, with later missions proceeding to rendezvousing, then landing, then sample collection and return. The purpose of all those missions to date has been scientific exploration. All of these missions have carried instruments capable of observing the outer surface of the target body, such as imagers, spectrometers and radiation detectors. In geoscience terms, these are used for determining geomorphology and surface geochemistry. These have told us a great deal about the bodies that have been visited, but leave other important questions unanswered. One category of such questions has to do with the composition and structure of the interiors of asteroids and comets; answering these questions will help answer deeper questions about the evolution of the Solar system. To the extent to which the interiors of these bodies are not completely reflected in their surface composition, techniques which can "see" below the surface can help address such questions. These techniques will also be valuable in any future asteroid resource-prospecting endeavours, in places where bulk composition varies significantly from proximate surface composition.

Geophysics is the branch of geoscience that uses instruments that are sensitive to subsurface properties, and analyzes data from those instruments to make inferences about subsurface composition and structure. Geophysical measurement techniques include gravimetry, magnetometry, seismometry, heat flow and interaction with electromagnetic waves. A few asteroid missions to date have carried geophysical instruments, with several missions carrying magnetometers, and the Rosetta mission carrying an EM instrument (a deep-penetrating tomographic radar). In addition, radio tracking of spacecraft near these bodies has enabled precision determination of the masses of some of them, and in the case of the larger bodies, low-resolution models of their gravity fields.

Other types of geophysics measurements muse be made on the surface, and so can only be carried out on asteroid lander missions. While there have been no asteroid lander missions flown to date (aside from NEAR Shoemaker's end-of-mission setting down on asteroid 433 Eros), several are now being seriously planned. For example, NASA is planning the Asteroid Redirect Robotic Mission[14] (ARRM) for launch in 2020 (Figure 2), and ESA is planning the Asteroid Impact Mission[16] (AIM) for launch in 2020 (Figure 3) as part of the joint ESA/NASA Asteroid Impact Deflection Assessment (AIDA) mission.

GRASP is intended to conduct surface gravimetry on smaller asteroids — smaller asteroids being much more numerous than the larger ones, they are much more frequently available as mission targets. Gravimetric measurements made on the surface of an asteroid can determine its mass, potentially more accurately than via radio tracking techniques[2]. It can also be used to produce a much higher-resolution model of an asteroid's internal density distribution, than could be determined via radio tracking methods[5]. To do this, GRASP will carry a space gravimeter being developed by Gedex, the VEctor Gravimeter/Accelerometer (VEGA) instrument (Figure 4). VEGA is a very compact (10x10x15 cm), low-mass (1.5 kg) instrument capable of making vector gravity measurements on small asteroids with a vector magnitude accuracy approaching 1 nano-*g*, and a vector direction accuracy better than 1 arc-minute.

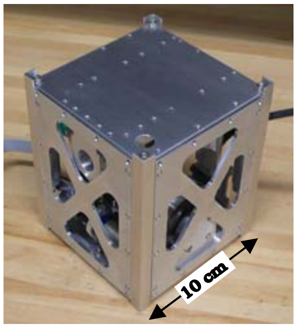

Figure 4: VEGA Gravimeter Mechanical Breadboard

Micro/Nanosats for Asteroid Exploration

Several past and current comet and asteroid missions involved small, low-cost secondary payloads:

- Hayabusa (JAXA, launched in 2003) rendezvoused with the asteroid 25143 Itokawa in 2005, collecting a surface material sample and returning it to Earth in 2010. It carried the nanosat-sized (0.6 kg) MINERVA lander/rover[23]. Unfortunately, due to an operations error, MINERVA was deployed in a direction which caused it to miss landing on Hayabusa. Because it has no propulsion capability, it was unable to recover from this, and it floated away from Hayabusa into an independent Solar orbit.
- Rosetta (ESA, launched in 2004) rendezvoused with the comet 67P/Churyumov–Gerasimenko in 2014, after which it carried out many months of remote sensing of the comet, which is planned to conclude in September 2016. It also carried the large-microsat-sized (100 kg) lander Philae[2,3] (developed by DLR) Unlike MINERVA, Philae succeeded in touching down, indeed very close to the targeted landing site. While Philae was designed to anchor itself to the surface upon landing, it failed to do so, and bounced a considerable distance in the comet's low gravity, eventually coming to rest in a location in which it was mostly shadowed from the Sun. With no on-board propulsion capability, it was unable to move from that location. Unable to recharge its batteries, it was able to operate for several days — while this was much shorter than the planned 1-6 weeks of operations, it nonetheless accomplished many of its mission goals, making important scientific contributions.
- Hayabusa-2 (JAXA, launched 2014) aims to rendezvous with asteroid 162173 Ryugu in 2018, collect surface sample material, and return that to Earth in 2019. It carries the small-microsat-sized (11 kg) MASCOT[21] (DLR), which will be dropped by its mothership onto the asteroid surface, to make scientific measurements. It is equipped with a tumbling-mobility mechanism, which will allow ground controllers to adjust its location on the surface prior to deploying its solar array. Hayabusa-2 will also deploy a shaped-charge-propelled penetrator projectile (SCI), and a deployable camera (DCAM3) to watch the penetrator's impact; both of these are nanosat-sized.
- PROCYON[9] (JAXA) is a microsat-sized (70 kg) spacecraft that was launched in 2014 as a secondary payload along with Hayabusa-2. It was intended to perform a flyby of asteroid 2000 DP107 in 2016, a plan that was abandoned after its ion propulsion system failed.

PROCYON is a stand-alone deep-space microsat, carried as a secondary payload in the usual microsat way on the same launch vehicle which launched Hayabusa-2, and designed to carry out its own major propulsive manoeuvring and communicate directly with ground control stations on Earth. In contrast, both MINERVA and Philae were carried as "daughter" payloads by their primary mission "motherships", and thus were "tertiary payloads" with respect to their launch vehicles. In both cases the primary spacecraft carried them to their target asteroid/comet. On reaching the target bodies each was released by their mothership, which then provided communications relay services to and from Earth. This design strategy enabled major simplifications in the design, and reductions in size and mass, of these small spacecraft. GRASP's design makes use of the same strategy.

One significant lesson to draw from these past and current missions is that it is indeed feasible for an asteroid-rendezvous spacecraft to carry a small lander as a secondary payload, and to support it via providing communications relaying to and from Earth after it is released. In this architecture, the mothership "does the heavy lifting" with respect to two subsystems — propulsion and communications — that are usually particularly large and massive on planetary missions; it also side-steps the difficult problem of deploying and operating a high-gain tracking antenna (a necessity for reasonable-bandwidth communications to Earth at such distances) on the surface of a rotating asteroid. This allows the daughter-craft to be similar in design to standard LEO micro/nanosats, needing only modest propulsion and low-gain communications capabilities.

Another important lesson is that the landing process is risky — of the two attempts to date to land a secondary payload on an asteroid's surface, one failed to land at all, and the other encountered problems which significantly reduced its useful lifetime on the asteroid surface. As discussed further below, this risk is substantially mitigated the GRASP design, which carries a propulsion system and associated equipment, synergistically mitigating another serious issue related to surface mobility.

While all of the asteroid and comet mission mentioned above have been carried out by national space agencies, this may soon change. Two US companies (Deep Space Industries and Planetary Resources Inc.) have stated their intentions to carry out asteroid exploration missions on a privately-funded basis in the near future, with the ultimate objective of mining asteroid resources in order to bring refined products back to Earth orbit for sale. They are both currently building and flying nanosats in LEO as precursor missions, and have both indicated that their early asteroid missions will be microsat-sized. GRASP is designed to be capable of being carried as a daughter payload on even quite-small asteroid prospecting microsat motherships, with a view to supporting future asteroid natural-resource prospecting activities.

GRASP MISSION OBJECTIVES

GRASP's general objective is to make gravimetric measurements on the surface of a target asteroid, allowing inferences to be made about the mass distribution within that body. Additional objectives include collecting additional useful and important data, particularly high-resolution visible-light imaging data, both for immediate mission needs (characterizing the asteroid's size, shape, morphology and spin state), and also for public consumption.

Asteroids come in a wide range of orbits, sizes and other properties, and no single design of lander/rover is suitable for the full range of these. GRASP is targeted towards a particular class of asteroids: small, Near-Earth Asteroids (NEAs). These are the asteroids most easily reached from Earth, in terms of ΔV, and easiest to communicate with from Earth in terms of communications range, hence are mission targets of increasing popularity. Smaller asteroids (< 1 km diameter) are far more numerous than larger ones (> 10 km diameter), making it far easier to find a small asteroid in an easy-to-reach orbit than for a large one. Because of the proximity of their orbits to Earth and their number, small NEAs make up a large portion of the risk of catastrophic asteroid impacts with Earth, and visiting such asteroids to characterize them is now a major mission driver. And, in the years to come, small NEAs are the most attractive targets for asteroid mining, due to the large number of targets, and proximity to Earth orbit (minimizing the cost of returning refined resources back to Earth).

Several near-term candidate asteroid rendezvous missions have been identified as potential opportunities for carrying a GRASP to an asteroid, and specific investigations have been conceived that contribute towards achieving each of those mission's objectives.

Determining the Mass of a Small Asteroid

While numerous space missions have successfully determined the mass of asteroids by the radio tracking method, this technique's accuracy diminishes for smaller bodies — the gravitational effect of the asteroid on a spacecraft flying-by or orbiting it is smaller, and so the signal to noise ratio of the radio tracking Doppler signal is lower, and in addition confounding non-gravitational accelerations (such as from solar radiation pressure) become relatively more important.

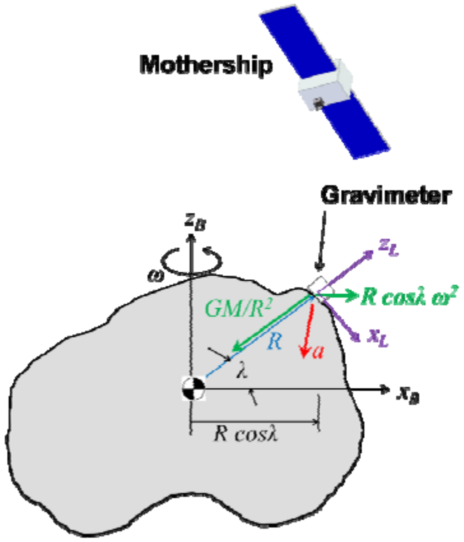

Figure 5: Weighing an Asteroid Gravimetrically

An alternative means for determining an asteroid's mass is to *place an accurate gravimeter on its surface*, and measure its surface gravity[4]. If by some means (e.g., auxiliary measurements from a mothership) the location of the gravimeter-carrying lander on the asteroid's surface can be determined, along with the asteroid's rotation pole direction and rotation rate, then one can combine these to solve for the asteroid's mass (assuming constant bulk density). The relationship between the variables involved is shown schematically in Figure 5.

ESA's AIM mission could benefit from this capability, as knowing the target asteroid's mass accurately contributes to AIM achieving its primary mission objectives. With the VEGA instrument, the mass of AIM's target asteroid could plausibly be determined to within 1% by a single surface gravity measurement, likely better than by any competing technique.

This technique can, in principle, be accomplished by making a single gravity measurement on the asteroid's surface. That could be done using a "stripped-down" version of GRASP, without the propulsion, attitude control and navigation equipment, making for a truly minimum-cost daughter-craft. (Indeed, the GRASP design team has developed a preliminary design for just such a 3U cubesat sized GRASP derivative.) However, such a lander would have to be deployed extremely carefully by its mothership, as well as be lucky, in order to avoid Philae's fate of bouncing into a location with no sunlight in which it would quickly freeze, or too much sunlight in which it would rapidly overheat. At that size, there would be little volume or mass available to include provisions to survive such conditions for very long. Such a mission might only have enough time to make a single measurement, which is what is needed; however, if there are any glitches in its operations, there may not be sufficient time to debug them before the spacecraft becomes too hot or too cold to survive. Such a non-robust design is somewhat antithetical to the principles of the Microspace approach.

Also, while a gravity measurement at a single surface location is sufficient to determine the asteroid's mass if the asteroid's bulk density is homogeneous, variations in internal density can cause a local gravity "high" or "low," which would reduce the accuracy of this method, possibly substantially. The next investigation provides a way to constrain that error source.

Determining an Asteroid's Internal Density Distribution

That first investigation can be generalized, to an *asteroid surface gravimetry survey*, in which the gravimeter is carried on a roving-capable lander, and measurements are made at multiple stations distributed around the surface of the asteroid. Figure 6 illustrates a concept for a plan for such a survey for the 535 x 294 x 209 m asteroid 25143 Itokawa, with each red dot representing a gravimetry measurement station.

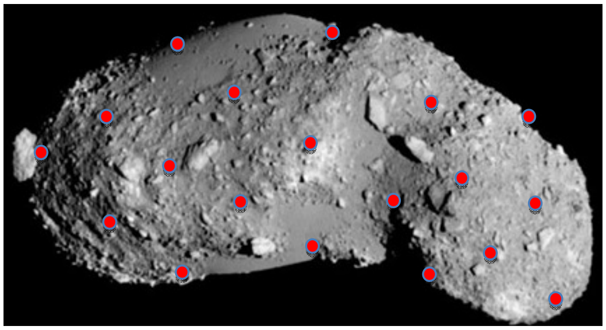

Figure 6: Asteroid Global Gravimetry Survey

Performing such a survey drives a requirement for GRASP to be able to rove around the asteroid surface in a controlled way. A particular challenge that this raises relates to the fact that, like the Earth, asteroids rotate with respect to the Sun, and so any particular location on their surface will experience day and night, and also seasons; GRASP thus needs to be able to cope with prolonged periods of darkness and low temperature during night-time.

This type of survey is similar in some respects to the type of gravimetry survey that is carried out routinely by geophysicists here on Earth. In terrestrial surveys, measurement stations are typically arrayed in a grid on a rectangular plot of land, and maps of gravity magnitude versus latitude and longitude show "highs" and "lows" which a geophysicist can interpret to infer subsurface geological structures. The data can also be interpreted numerically using inversion techniques, to infer subsurface density maps.

This latter technique can be extended to the asteroid gravimetry surveying case; by making measurements all around the asteroid, inversion will produce a 3D model of the asteroid's internal density distribution. That in turn will (as a by-product) estimate the asteroid's mass, significantly more accurately than from a single measurement station (by correcting for internal density variations).

The benefits of such a survey go considerably beyond such a more-accurate mass determination. As with terrestrial gravimetry surveys, the internal density distribution can be used to infer the internal "geology" of the asteroid — its composition and structure. This information on an asteroid's interior, which otherwise is obtainable only via much more expensive means (e.g., a roving lander equipped with a deep drill), can help answer important asteroid science questions. For example, a key question in asteroid science is the amount of "porosity" in asteroids — the amount of an asteroid's volume that consists of "vacuum-filled" voids — and its distribution between "macro-porosity" (a smaller number of large voids) and "micro-porosity" (a larger number of very small voids). Macroporosity could produce large enough "gravity lows" to be detectable, and determining this would help constrain various models of asteroid formation and structural evolution.

In addition to such science benefits, knowledge of internal density distributions could be as useful to explorers for asteroid natural resources, as they are to explorers for natural resources on Earth (the main customers for terrestrial gravimetry surveys). For example, if deposits of water ice (the currently most economically attractive resource thought to be found on asteroids) are distributed heterogeneously within an asteroid, then they could produce detectable gravitational signatures at the surface, due to ice having a lower bulk density than rock. This type of survey could help explorers find deposits of "high-grade ore," which would obviously be more economical to extract than lower-grade "dirt."

Determining the Mass of a Boulder on an Asteroid's Surface

A third investigation enabled by asteroid surface gravimetry falls into the category of geodesy rather than geophysics: the use of vector gravimetry at multiple locations on the surface, in conjunction with surveying-grade imagery and astronomical observations, to estimate the mass of a boulder on the asteroid's surface. This follows a technique pioneered by Maskelyne[15] in 1775, in which he used surveying techniques to determine the shape of the Scottish mountain Schiehallion, then made a series of measurements using a plumb-bob and zenith telescope, to determine the deflection of the vertical at locations close to and far from the mountain; by doing so he was able to determine the mountain's density, and hence its mass (relative to that of the Earth, which was determined for the first time in via this experiment).

The same could be done using a roving asteroid lander equipped with a VEGA instrument, which (like a plumb bob) can determine the local direction of the vertical. It would also have to carry a suitable stellar telescope; a star tracker would suffice. Measurements could be made close to and far away from a boulder whose mas was desired, as illustrated conceptually in Figure 7. While in principle a pair of measurements could suffice to determine the boulder's mass, in practice better accuracy will result from making multiple measurements at various distances and directions from the boulder (following Maskelyne's technique).

This investigation is particularly aimed at NASA's proposed ARRM mission, whose objective is to collect a large boulder from an asteroid's surface, to bring back to high Lunar orbit for later examination by astronauts. Knowing the mass, and hence density, of a candidate boulder before attempting to pick it up could reduce the risk of trying to collect a structurally incompetent boulder, which could fragment during or after collection — unexpectedly low density could indicate a large internal void fraction, for example. Conversely, this could allow ARRM to avoid collecting any unusually high-density boulders, whose mass may be too large for ARRM's available propellant supply to bring back to Earth. In addition, the technique could also be of interest in some other asteroid exploration missions, to investigate properties of exposed boulders, looking for evidence of inhomogeneous density (e.g., it would be interesting to apply this technique to the 6m "black boulder" on Itokawa[11], comparing its density to the asteroid's bulk density, to test the conjecture that it is of exotic origin).

This investigation requires basically the same capabilities as the previous one, plus the ability to collect auxiliary information with which to relate VEGA's gravity vector direction measurement to an asteroid-fixed reference frame. We assume that ARRM will collect enough imagery and other data to allow a complete asteroid shape model to be formulated as well.

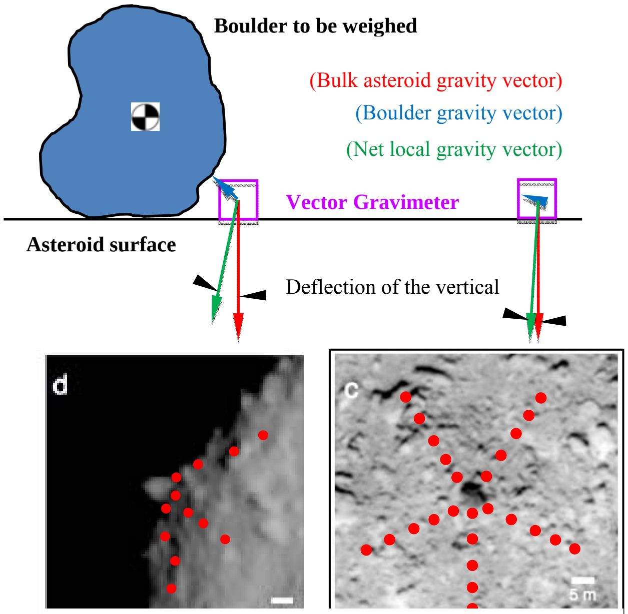

Figure 7: Weighing a Boulder Gravimetrically

Hopping Between Binary Asteroids

One final capability is potentially very useful to ESA's proposed AIM mission. AIM plans to rendezvous with the binary asteroid 65803 Didymos, then observe the small (150 m diameter) secondary (Didymos-B) as it orbits around its larger (800 m diameter) primary (Didymos-A) at an orbital radius of only 1100 m — before, during and after the NASA DART spacecraft impacts Didymos-B at high speed. AIM plans to drop at least one lander (DLR's MASCOT-2) onto the surface of Didymos-B (potentially GRASP as well). GRASP could carry out at least two of the above investigations, making an initial mass determination from a first gravity measurement, then an improved one over time as it carries out a global gravity survey. That could provide valuable information on the mass and internal structure of Didymos-B, which would help AIM achieve its broader mission objectives.

After that, GRASP could "hop" across from Didymos-B to Didymos-A, and perform similar measurements there — the ΔV required to accomplish that is very small (< 10 cm/s). This could significantly augment the scientific knowledge collected during the mission, and the science conclusions that could be drawn from the mission, by addressing the question of how Didymos-B formed, and testing the details of various models of mass-shedding from the fast-rotating Didymos-A.

MISSION REQUIREMENTS

The above Mission Objectives are about "what are we trying to accomplish?" and "why do we want to do that?" The Mission Requirements listed here reflect decisions about "how" those will be accomplished (in terms of how the system will be operated), along with "where" GRASP may go, along with "when" the mission events would happen.

Note that these are not simply flowed-down from the mission objective; rather, following the Microspace[*] approach, they are the result of numerous top-down and bottom-up iterations of the GRASP design, aimed at a set of mission requirements that are both worth-while to achieve, and achievable at a low cost using micro/nanosat methods. (As these are requirements, we use the conventional term "shall," which here encompasses the present as well as the future tense.)

Target Asteroid Class Requirements

Here we add details to the "small NEAs" mission constraint discussed above.

Orbit Range: GRASP shall meet its requirements for missions to asteroids whose orbits range in distance from the Sun between 0.8 and 2.0 A.U. The close-in distance is limited by thermal effects; a spacecraft on an asteroid surface can get very hot when in sunlight, and that gets worse the closer to the Sun it gets. The outer limit is driven by the ability to generate enough power, given that GRASP will have to survive long asteroid nights. The GRASP system design meets this requirement, and with some operational restrictions, it can perform restricted operations at Solar distances somewhat outside that envelope.

Asteroid size and density: GRASP shall meet its requirements when operated on asteroids whose sizes are between 100 and 1000 m, with bulk density between 1000 to 3500 kg/m^3. Larger or smaller than this would reduce the performance of the mobility system, and the accuracy of landing location.

Asteroid rotation period: GRASP shall meet its requirements when operated on asteroids with rotation periods as long as 14 hours, in locations with day:night ratios as low as 30:70. The lower this ratio, the larger the amount of photovoltaic cells must be carried, and the larger the battery needed to last the night.

Asteroid Albedo: GRASP shall meet its requirements when operated on asteroids whose albedo is within the range 0.02 to 0.35. Asteroid albedos range quite widely, so it is advantageous for GRASP to tolerate a wide range. This has strong implications for the worst-case-hot thermal design.

Other Mission Requirements

Microspace Approach: GRASP's design shall follow SFL's version of the Microspace approach, in order to achieve a high capability, highly robust mission at a cost affordable by Canada's space exploration program.

Payload: GRASP shall carry at least a VEGA instrument to make gravity measurements on the surface of a target asteroid.

Surface Mobility: GRASP shall be capable of moving about the surface of the asteroid, to take gravity measurements at multiple locations. The decision on the means by which this is to be done has been promoted to the level of a mission requirement, as discussed below.

Learn Lessons from MINERVA and Philae: GRASP shall be capable of recovering from the mishaps that caused the MINERVA mission to fail, and the Philae mission to terminate prematurely.

Localization: Between them, GRASP and its mothership shall determine the location of GRASP on the asteroid's surface, at each measurement station, with an accuracy of ~ 1 m (TBC).

Productivity: For asteroids as large as 1000 m in size, GRASP shall be able to make measurements at up to 100 stations distributed evenly over the asteroid, and to measure the mass of 5 boulders within 21 days of landing, each boulder involving 15 measurements at stations within 10 m of the boulder. These have implications on the sizing of the propellant carried for hopping, and the amount of time taken making each measurement, and performing the operations needed to move from one station to the next.

Mission Performance: GRASP shall be able to determine an asteroid's mass to within 10% with a single surface gravity measurement, and be able to determine each boulder's mass to within 10%. These mostly drive the accuracy with which auxiliary measurements (of asteroid size, shape and rotation state, and location of each measurement station) are made by GRASP and its mothership.

Size: GRASP shall fit within a 12U cubesat volume and mass specification, in particular that from PSC[17]: 23x24x37cm, 24 kg. This requirement is levied to

---

[*] Rick Fleeter introduced the term Microspace[9] to describe the approach used by microsat builders in the ca. 2000 era. SFL has built its micro/nanosat development approach on that foundation, and has evolved it since then over the course of many micro/nanosat missions.

maximize the compatibility of GRASP with various potential primary missions. While there is not yet any widely acknowledged 12U cubesat specification, CalPoly's recent 6U spec[7] indicates willingness on the part of the community to adopt a few custom specifications developed by PSC and others.

Surface Mobility Approach Requirements

While a huge amount of experience exists regarding mobile robotics here on Earth, and much experience has been gained with Mars rovers, as yet nobody has any experience operating a mobile robot on the surface of any other planetary body, asteroids included. Extrapolating from experience with terrestrial and Mars mobile robots, we expect that mechanical interactions with surface material will impact the performance of most mobility system designs, and that a low gravity level can cause mobility problems. For small asteroids, as yet we know very little about surface material mechanical properties, and gravity levels will be very low. This creates a potential "mission-killer" issue, which we have chosen to deal with at the level of the mission requirements, by specifying a surface mobility approach here. Before stating that, we first discuss various design alternatives in light of that issue.

The target asteroids for GRASP are small enough that their surface gravity magnitude will be very low, much lower than 1 milli-*g*, and typically in the range 10-50 μg. Traditional techniques for roving on a planetary surface, using wheeled "tractive locomotion," is not expected to be useable in this environment[21]. In recognition of this, researchers have conceived of several possible alternate concepts for surface mobility in a very low-gravity environment, including:

- Richter[21] described a technique of locomotion about a small asteroid using ballistic flight, whereby a rocket propulsion system is used to make small thrust manoeuvres to initiate short ballistic hops.
- The Nanorover[23] that JPL proposed as a payload on JAXA's Hayabusa mission was to make use of wheels on a pair of axles that were able to be drawn rapidly together, allowing the rover to hop about the asteroid's surface. It could also use this arrangement to self-right itself, if it landed on its back. (The Nanorover project was cancelled before flight.)
- Several groups have proposed another means of hopping about small asteroids, by rotating either a reaction wheel or an eccentric mass within the rover, creating a torque that would cause the rover to tumble; with suitable surface traction, this tumble could result in either translational motion while staying in contact with the surface, or hopping motion with a translational component. MINERVA carries a flywheel which was intended to accomplish this by producing a torque[23]. MASCOT makes use of a rotatable, motor-operated eccentric arm, which will produce both a torque and a force. Pavone[20] is currently doing research on the use of 3 orthogonal reaction wheel actuators for tumbling, in combination with multiple symmetric legs.
- Hokamoto and Ochi described a mobility method in which a rover would be equipped with a number of radially extendable and retractable legs[11]. Chacin and Tunstel described a multi-limbed ambulatory locomotion system for an asteroid rover[6].

One of the core principles of the Microspace approach as practiced by SFL, is to have "no Death Modes" — which is to say, design a spacecraft's hardware so that any software or operational errors can't result in situations in which system hardware becomes damaged. This approach to making a robust hardware design is a crucial enabler to the goal of achieving very low costs in Microspace-engineered space systems. In designing GRASP, one challenge has been to extend this principle to cope with the significant differences in environment between LEO and proximity to an asteroid. For example, it is simply not possible to *completely* preclude hardware damage as a result of software or operator error, when there is an asteroid nearby into which your spacecraft can collide.

That being said, design choices still affect mission and system robustness, and the choice of mobility method is a prime example of one such. Any mobility method which relies on creating traction with the asteroid surface, must be designed using assumptions about the mechanical properties and behaviour of the material covering the asteroid surface. It may seem reasonable to assume that asteroid surfaces may be covered with material something like Lunar regolith (about which we know much, thanks to the Apollo missions), due to surface bombardment by meteoroids over a very long period of time. However, it is also reasonable to speculate that the low surface gravity of asteroids could result in very different surface material properties than on the Moon (due to much of the ejecta from high-velocity impacts escaping the asteroid, rather than falling back). For example, the area of Itokawa where Hayabusa briefly touched down is quite different from the lunar surface.

The fact is, we know very little about the mechanical properties of asteroid surfaces, and have little basis for making predictions about how any particular traction-based mobility system would behave. Various bad outcomes for such systems can be imagined, such as a wheeled rover spinning its wheels (the eventual fate of NASA's Spirit rover on Mars), or a tumbling rover simply spinning in place, or digging itself into a hole. A design team could spend a great deal of effort trying to model such behaviour and quantify such risks, while never developing much confidence in the risk magnitude estimate; the "risk of risk" would then continue to hang over the mission, and continually tempt all involved into risk-aversion behaviours, likely consuming much time and money. Adapting the "no Death Modes" principle to GRASP with this issue in mind thus leads us to the following mission requirement:

Assumptions Regarding Surface Properties: The approach used by GRASP to achieve surface mobility shall depend as little as possible on assumptions about surface properties

Accordingly, we have chosen to adopt a mobility method that does not rely on traction at all — the ballistic hopping technique. This is as indifferent as possible to the details of the asteroid's surface mechanical properties, assuming only a surface into which the lander/rover won't sink or get stuck (as would be required by *any* lander/rover design, in order to succeed). Apart from that, its operation is dependent only on the laws of ballistic motion, and on correctly functioning propulsion, navigation and attitude control systems — the achievement of which is now standard fare for microsats.

Primary Surface Mobility Approach: GRASP shall use propulsive hopping as its primary approach to surface mobility, in such a way that all mission objectives can be accomplished using that approach.

This decision has significant consequences — it results in GRASP carrying a propulsion system, which adds mass and volume. It also creates the need for a suitable navigation and attitude control system, which add further mass and volume. But, it leads to a high certainty of GRASP being able to accomplish its asteroid-roving function, regardless of asteroid surface properties. And, serendipitously, the equipment needed for that also provides the means for making GRASP robust against the mission-terminating failures experienced by the two asteroid landers flown to date, MINERVA and Philae (as discussed below).

This is not to say that the other techniques for asteroid roving *won't* work, just that *we don't yet know enough about asteroid surfaces* to know if they will work with high reliability. If one or more of those other techniques can be shown to work, that would be highly valuable knowledge for designers of other future asteroid lander/rover missions. As it happens, GRASP's design — which for other reasons incorporates a set of reaction wheels and symmetrically-disposed legs — is capable of implementing Pavone's[20] tumbling mobility technique. Accordingly, we introduce a mission-level requirement, for GRASP to conduct experiments to learn more about how well this technique works in an asteroid environment.

Alternate Surface Mobility Method Experiment: GRASP shall conduct surface mobility experiments using Pavone's tumbling mobility technique[20].

If this technique proves to work well, it could go on to be used as an alternate operational mobility approach, which could result in reductions in GRASP propellant consumption, and potentially increase the mission's life and/or range.

MISSION DESIGN

The principle design choices at the Mission level for GRASP are:

- GRASP will launch as a "tertiary" payload, attached to a host spacecraft (mothership) which rendezvouses with the target asteroid, whereupon GRASP will be released in such a way that (barring mishaps) it will land at a selected point on the asteroid's surface, with an impact velocity low enough (typically < 5 cm/s) that it will not bounce off of and escape the asteroid.
- GRASP's ground controllers will send commands to it, and receive data back from it, relayed via its mothership.
- GRASP will attempt to control its impact speed by performing a propulsive manoeuvre immediately prior to impact, in order to minimize the amount of uncontrolled bouncing that happens after impact. That being said, GRASP will be designed to survive impact should that manoeuvre not happen, and GRASP operations shall be planned to recover from bouncing to anywhere on the asteroid's surface, include into a permanently shadowed region.
- If GRASP is released on a trajectory that does not intersect the asteroid, or bounces off the asteroid with greater than escape speed, or propulsively escapes from the asteroid, its position and velocity relative to the asteroid will be determined, out to a distance of at least 50 km, and the propulsion system will be used to first bring it to a halt relative to the asteroid, then manoeuvre it back to the asteroid's surface, as shown in Figure 8. This will be done via commands from the ground, not autonomously.
- Once GRASP has come to rest at some point on the surface, ground controllers will determine if that

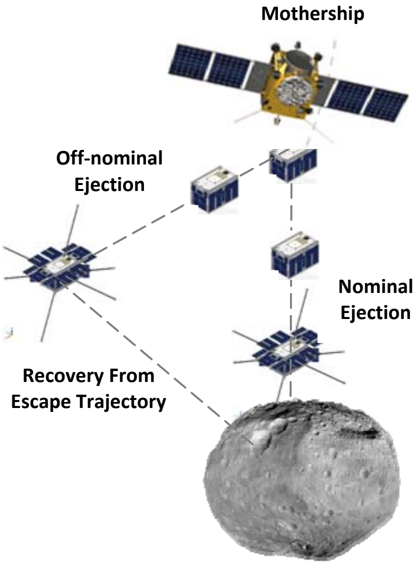

Figure 8: GRASP Descent Trajectories

location is suitable for a gravimetry survey station. If so, they will command it to make a gravimetry measurement. If not, they will command it to move to another selected location. This will be done repeatedly until all desired gravimetry stations have been visited and measurements made.

- If GRASP comes to rest in a location in which there is inadequate sunlight (over the course of one asteroid day) to keep GRASP average-power-positive indefinitely, then ground controllers will command GRASP to move to a sunnier location. Similarly, if GRASP comes to rest in a location that is *too* sunny, such that GRASP is unable to maintain its temperature below its maximum allowable operating temperature, then ground controllers will command GRASP to move to a less-sunny location. If there is inadequate time to determine GRASP's location on the surface or to plan a controlled hop to a more desirable location on the surface before GRASP overheats or runs out of power, controllers may command GRASP to hop to a near-escape trajectory, following which power and temperature will be stabilized, and a return to the surface will be commanded. In this way, GRASP's propulsion capability provides the means to approach the "no death modes" capability that SFL's LEO satellites all have, in the face of the rigours of the asteroid surface environment.
- GRASP will collect imagery at each station on the surface, and send it to ground controllers. Significant compression is expected to be necessary to meet downlink bandwidth constraints; for many images thumbnails only may be sent, with full versions of only a few of those then requested for follow-up download. These will be used to aid in determining position on the surface, particularly when doing boulder-weighing operations.
- GRASP will also be able to collect imagery when off the surface of the asteroid. This will be used by ground controllers to help determine GRASP's position and velocity with respect to the asteroid, during recovery operations should GRASP accidentally escape from the asteroid.
- GRASP will use propulsive hopping as its baseline means of locomotion on the surface. For long hops this will involve first thrusting a short distance (on the order of 10 m) upwards, then slewing GRASP's attitude to point a single thruster in the desired azimuth direction, at an angle 45° from the vertical (to achieve an optimal ballistic trajectory with minimal use of propellant), then firing that thruster to achieve the desired ballistic trajectory towards the next surface station. On the way to that point, GRASP will slew to the appropriate orientation to zero its motion with respect to the surface (again at a 45° from the vertical, but on the opposite azimuth). It will then fall approximately vertically to the surface, either passively or with a small final vertical burn. This is illustrated in Figure 9. Short hops may use a simplified version of this. The terms "vertical" and azimuth" here will be interpreted appropriately in terms of the asteroid's actual shape, which may be significantly non-spherical.

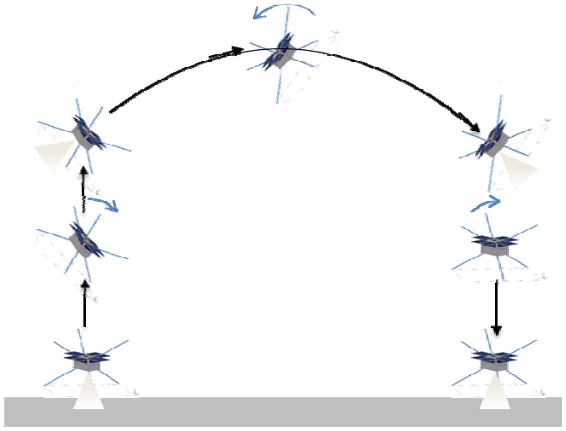

Figure 9: GRASP Long-Hop Manoeuvre

- Although GRASP is designed to tolerate landing in any of 8 stable orientations (Figure 10), it has a "preferred up" direction (e.g., only one face has a star tracker). GRASP shall attempt to land in the desired orientation at the end of each landing or hopping manoeuvre. If it bounces on landing to a different orientation, ground controllers will be able to command it to hop upwards a short

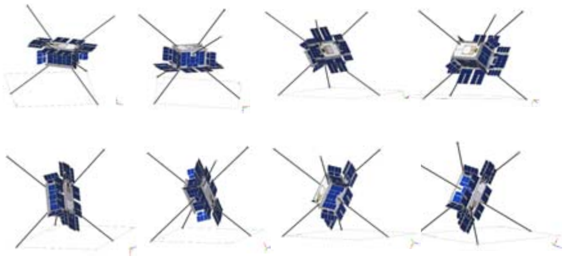

Figure 10: GRASP Stable Surface Poses

distance, slew to the correct orientation, and then land in that orientation (repeating this "pirouette" as necessary). GRASP is designed to survive and operate for a considerable period of time (on the order of one day) in any orientation in most locations on the surface, in order to give controllers plenty of time to sort this out.

- GRASP contains all of the equipment needed to conduct Pavone-style tumbling mobility — mainly, a set of reaction wheels and symmetrically disposed legs. An early activity, once on the surface and commissioned, will be to attempt tumbling motion, both simple motion (keeping two "feet" on the ground, hinging about the line defined by those feet), and also "tumble-hopping" in which larger reaction wheel torques are used to rotate GRASP fast enough that it hops off the surface in the desired direction. If that mode of motion is found to work successfully, it may then be used routinely in some circumstances instead of propulsive hopping; e.g., this would be a useful alternative to the pirouette manoeuvre, to orient the preferred face upwards. This could also be very useful in mobility operations in the vicinity of a boulder being weighed. Doing this could save significant propellant, potentially extending the number of stations that could be visited.

MISSION ANALYSIS

Here we summarize some of the results of mission analysis that has been done for GRASP to this point.

Environment

Here we focus on the principal ways in which the environment that GRASP faces will be different from that typically faced by micro/nanosats in LEO. GRASP will need to be able to operate both in ballistic flight in the vicinity of the asteroid (which is in many ways similar to being in orbit around the Earth), but also, of course, on the surface of the asteroid (which presents many factors very different from being in Earth orbit).

Insolation: The amount of Sunlight incident on GRASP (while it is in sunlight) on or near the asteroid will range from a high of 156% to a low of 25% of the average amount of insolation in sunlight in Earth orbit, due to varying distance from the Sun. This will have a proportionate effect on the amount of electricity able to be generated by photovoltaic cells, and the amount of heat from the Sun absorbed by GRASP. Such a wide range of values (a factor of 6.25) makes for very challenging power and thermal subsystem designs.

Gravity: Surface gravity on the class of asteroids targeted is expected to range from 1.5 to 50 μg, depending on asteroid size and density. That is low enough to confound the usual idea of "landing on a surface" — especially at the low end of that range, GRASP will "settle against" the surface of the asteroid. It is high enough to result in a relatively large amount of ΔV needed to carry out a global asteroid survey, for the largest asteroids in the target class (see below for details), although the amount needed for the smaller asteroids in the class can be much lower. If in free space, gravity will be low enough that entering an orbit around the asteroid will be difficult, and for the smaller asteroids essentially meaningless.

Escape Velocity: The escape velocity from the target asteroids will similarly depend on size and density, ranging from about 2 to about 70 cm/s. This has implications for the conditions of release from the mothership (height and downward speed), as well as for the strength required for the legs. Landing on the smallest, lowest-density of this class of asteroids, without bouncing off to escape, would be very challenging.

Surface Mechanical Properties: As discussed above, very little is known about the properties of the surfaces of small asteroids. What information we have comes from thermal IR photometry of numerous asteroids from a great distance, imagery of a very few asteroids close-up (principally Itokawa), and measurements from Philae's landing accelerometer (which landed on a comet, not an asteroid). A property that could be crucial to any lander on such bodies is the coefficient of restitution, which will control how much an incoming lander will bounce — too much of a bounce, combined with too high a landing speed, could result in bouncing to escape. Philae observed a fairly hard surface on its comet target. Recent lab experiments at SUPAERO[17] give very preliminary indications that landing at speeds of a few cm/s into granular material at low gravity (milli-g) may result in a low coefficient of restitution.

Dust: A fraction of the material on the surface of the asteroid may consists of fines, which may contaminate the surfaces of GRASP's photovoltaic cells, optical instruments and thermal control surfaces. Practically nothing is known about the nature of such dust. One may speculate endlessly about how much of it there may be, its size distribution, whether it might e hovering electrostatically, whether it might stick to GRASP electrostatically, etc. One thing that is fairly certain is that any such dust that is present, will likely be displaced by the operation of thrusters pointing towards the asteroid surface; landings and take-offs from the asteroid may well raise dust.

Thermal: When in Solar orbit near the asteroid, the thermal situation for GRASP will be challenging (due to the wide range of insolation values) but fairly straightforward. Near the asteroid, GRASP will see an additional heat load from the asteroid surface. That will reach its maximum when on the asteroid surface in sunlight. There is some information available about how hot asteroid surfaces get in the Sunlight, how cold they get in the shade, and how quickly they transition when going from day to night. Here we assume that the asteroid surface thermal properties are like those of Lunar regolith, with very low thermal conductivity, and hence very rapid heating when exposed to Sunlight, and cooling when exposed to shade. At 0.8 AU we assume that the asteroid surface could reach temperatures as high as 450 K. The worst-case-hot condition for GRASP will occur when it is in Sunlight, sitting within a crater deep enough that its walls surround GRASP, leaving significantly less than a hemisphere (perhaps as little as π sr) of view-factor to deep space. The worst-case-cold asteroid surface temperature will occur at night-time, starting very shortly after nightfall; it is expected to be below 100 K.

Propulsion Capabilities Needed

GRASP will use its propulsion system to brake on landing on the asteroid, to hop from station to station, and potentially to recover from the contingency of being accidentally placed on an escape trajectory. The required propulsion system capabilities are strongly driven by the mass and size of the asteroid, and hence the strength of the surface gravity field. The propulsion system is sized to meet requirements for the largest (1 km diameter) and densest (3500 kg/m^3) target asteroid. This results in the following required propulsion capabilities:

- ΔV: 170 m/s (including 100% margin). This is based on 100x hops of 100 m distance each, plus 5x15 hops of 2 m each for boulder surveying. ΔV for recovering from an escape trajectory is not included here; we assume that should that happen, a degraded mission with fewer survey stations will be acceptable. Note that this is greatly over-sized for the smaller, lower-density asteroid targets.
- Thrust magnitude: 100 mN. This is based on a surface gravity of $4.9 \times 10^{-4}\ m/s^2$ and a GRASP mass of 20 kg, assuming a thrust-to-weight ratio of 10 to achieve tolerably low gravity losses.

SYSTEM REQUIREMENTS

Here we summarize (in no particular order) the more significant requirements on the GRASP system, emphasizing those that are unusual with respect to LEO micro/nanosats.

Mothership Interface

GRASP will be carried by the mothership to the target asteroid, to be released there; a requirement levied by GRASP upon the mothership is that the mothership shall release GRASP at an altitude (as low as 50 m) and speed such that GRASP's velocity upon surface impact is less than 50% of surface escape velocity. For thermal control reasons, we assume that GRASP will be carried within a cavity in the mothership's body, in close thermal contact with its internals. GRASP's carrier shall be equipped with means to shield the "top" of GRASP before it is ejected, and to block the aperture left after GRASP is ejected, to avoid a radiative "hole" in the mothership's bus.

We assume that GRASP will be carried within a carrier based on an existing cubesat deployer. This shall be able to eject GRASP at a precisely chosen speed (~ 5 cm/s, TBC) that is much slower than that used in standard cubesat deployers (typically ~ 1 m/s).

Some GRASP system equipment will remain behind on the mothership. This includes communications relay equipment, and navigation equipment to aid in determining the location of the GRASP spacecraft should it end up on an escape trajectory. Both of these shall function for mothership/GRASP ranges of at least 50 km. The GRASP lander shall include an optical beacon, and the GRASP equipment on the mothership a camera capable of detecting that beacon at a distance of 100 km, with a plane-of-sky accuracy of 3 arc-minutes. That camera shall be able to detect that beacon when GRASP is on the asteroid surface, in full sunlight.

Communications

GRASP shall communicate with its ground controllers via comms relay equipment on the Mothership; this mothership-mounted equipment shall be part of the overall GRASP system. It shall include a transmitter, capable of sending data to GRASP at a rate of rate of 4000 bps. It shall include a receiver, and GRASP shall be capable of sending data to that at a rate of 3500 bps. These data rates shall be achieved at a range of 100 km; transmission in both directions shall be possible at lower data rates out to a range of 1000 km (TBC). Both links shall be able to operate simultaneously.

GRASP shall include a radio ranging function with an absolute accuracy of better than 10 m over a time-scale of 10 s. This is part of the navigation equipment to be used in recovering GRASP from an escape trajectory.

Payloads

GRASP's primary payload is the VEGA instrument, to be used as a gravimeter on the asteroid's surface. GRASP may carry other geophysical payloads, such as a magnetometer, and a transceiver for a bistatic deep-penetrating radar (such as the one carried by Philae, and the one planned for MASCOT-2). GRASP shall also carry imagers, which will be used for various functions. These include:

- Taking images of the asteroid during descent from the mothership, and during hops across the surface, to provide georeferencing information.
- Taking images while on the surface, for science and publicity purposes.
- Taking images of the asteroid if on an escape trajectory, to be used for navigation purposes. For this purpose, cameras shall have 4π *sr* coverage.

Propulsion

GRASP includes a propulsion subsystem, whose main requirements are described above. It will have rather more propulsive capacity (on the order of 100 m/s) than most propulsion-equipped micro/nanosats to date. It shall be arranged to be able to thrust in all directions, in order to be able to hop from any landed orientation. It shall be able to exert torques in all directions, to be able to desaturate reaction wheels without having to change orientation. The propellant shall not be grossly hazardous, and shall not employ very high pressure, to minimize mothership interface costs.

Position and Attitude Determination and Control

GRASP includes a position and attitude determination and control subsystem, which shall be used for various purposes at different times in the mission, all of which shall be carried out autonomously in real-time on-board (in response to high-level commands from ground controllers):

- Controlling GRASP's orientation after release from the mothership, to land right-side up.
- Controlling GRASP's orientation during hops, to orient thrusters in the directions needed, and to land right-side up.
- Determining GRASP's orientation with respect to the stellar frame while on the asteroid's surface, as a step in the process of determining gravity vector directions in an asteroid-fixed reference frame. This is only required when GRASP is in its preferred landing orientation.
- Determining GRASP's attitude if on an escape trajectory, as part of the process of determining GRASP's location with respect to the asteroid.

As a practical necessity, GRASP carries a set of reaction wheels and a star tracker to accomplish these. It also carries an inertial measurement unit, with accelerometers and angular rate sensors, allowing position and orientation to be propagated during the landing process, and during hops.

Navigation

GRASP will carry navigation sensors, to aid in determining GRASP's surface station locations during nominal operations, and during contingency operations (recovering from an escape trajectory) aiding in determining GRASP's location with respect to the mothership and the asteroid. This equipment shall be able to verify that, during a 10-minute-long (TBC) gravimetry measurement, GRASP's orientation with respect to the asteroid has not changed by more than 1 arc-minute (TBC). It shall be able to be used to determine GRASP's location with respect to a nearby boulder to within 10 cm (TBC). It shall be able to be used to determine the direction towards the target asteroid, out to a distance of at least 50 km. Interpretation of the data from these sensors is baselined to be done by ground controllers.

Landing Equipment

GRASP will carry equipment to aid in the process of landing on the asteroid. This shall include legs to fend the outer surfaces of the bus from the surface; of necessity, in order to accomplish that the legs are deployable. This protects delicate equipment on the surface (e.g., photovoltaic cells) from being damaged by impact with possibly-sharp and hard rocks; it also keeps those surfaces from contacting the surface directly, which is one way to mitigate the risk of them becoming contaminated by dust.

The legs shall be arranged to allow GRASP to tolerate an uncontrolled landing without damage, at speeds up to 1 m/s (TBC); a symmetrical leg arrangement allows GRASP to tumble upon landing while still keeping the bus surfaces protected, analogous to the air-bag approach used in some Mars landers. These in combination with the reaction wheels enable GRASP to attempt Pavone-style tumbling mobility experiments.

GRASP shall also carry a short-range LIDAR, to detect the proximity of the asteroid surface just before landing, and to provide landing-speed information, to be used to drive the propulsion system to manoeuvre to minimize landing speed. This is intended to increase the precision of GRASP landings.

Structure and Layout

GRASP's structure is unusual in the number of deployable photovoltaic panels it carries. This is in order to be able to present an adequate amount of PV area towards the Sun, to be able to operate when at 2 AU from the Sun, while still fitting within a 12U stowage volume.

GRASP shall be laid out so that there is at least one orientation in which it can operate with full functionality for an indefinite period of time (days, at least), subject to the surface location meeting certain constraints on the minimum and maximum day/night duty-cycle. The intent is to be able to land GRASP in any orientation, then rotate it to this preferred orientation as soon as possible after landing, after which operational urgency abates.

Power

GRASP shall be able to provide enough power to carry out all functions for an extended period of time, when in its preferred landing orientation, including when not illuminated by the Sun; as with most LEO satellites, this involves a battery, which is charged by PV arrays when in sunlight. This is not required in locations with no sunlight; GRASP shall be able to do this in locations with 30% sunlight, for asteroid rotation periods of up to 14 hours, at a distance of 2 AU from the Sun.

When landed in a non-preferred orientation, GRASP's power subsystem shall provide enough stored energy to give its operators enough time to determine its orientation, and to upload commands to rotate to the preferred orientation; enough margin shall be included to make several attempts. Similarly, if landed in a location with insufficient sunlight, the power subsystem shall provide enough stored energy for operators to determine its location, and upload commands to hop to an adequately-lit location.

Thermal

There are locations on the surface of the target asteroids where the local temperature is far too high for GRASP to be able to remain there indefinitely. GRASP would not be commanded to land in such a location deliberately, but (as Philae demonstrated) in a very low-gravity environment, a land can easily travel long distances in an uncontrolled way, and end up in undesirable locations. GRASP's thermal design shall be such that temperature-sensitive equipment is protected from those high temperatures, for long enough for ground controllers to command GRASP to hop to a better location.

GRASP shall also be able to keep its temperature-sensitive components sufficiently warm when not in sunlight, for up to 48 hours. Accomplishing this involves a combination of passive and active thermal control means.

SYSTEM DESIGN

While the focus of this paper is the logic that drove the setting of the mission and system requirements for GRASP, and the resulting mission design, we also describe here some of the resulting system design details. Space does not permit going into much detail, so we confine ourselves to some of the main design features.

GRASP System Architecture

The overall GRASP system architecture is illustrated in Figure 12. It comprises three Elements:

- The GRASP Spacecraft.
- GRASP equipment which "stays behind" on the mothership. This will appear to the mothership's on-board computer and power subsystem as a mothership payload, with the mothership's OBC relaying commands from the ground (and possibly sending some commands of its own) to an embedded computer in that GRASP equipment. The latter, in turn will control the operation of the GRASP spacecraft deployer, and the mothership-mounted radio and camera equipment, Prior to deployment of the GRASP spacecraft from the mothership, this OBC shall provide power to the GRASP spacecraft, and communicate with it via a

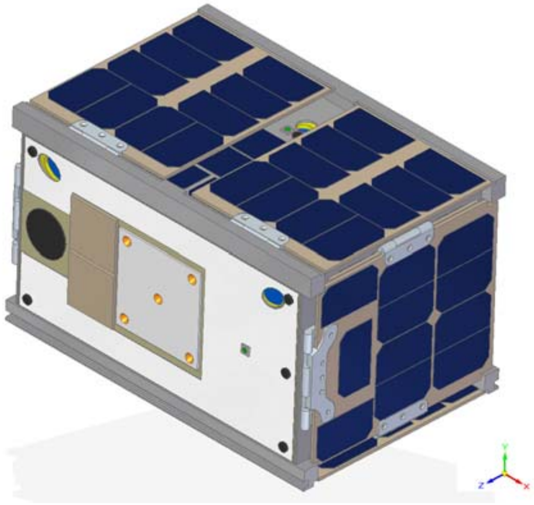

Figure 11: GRASP Spacecraft Stowed Configuration

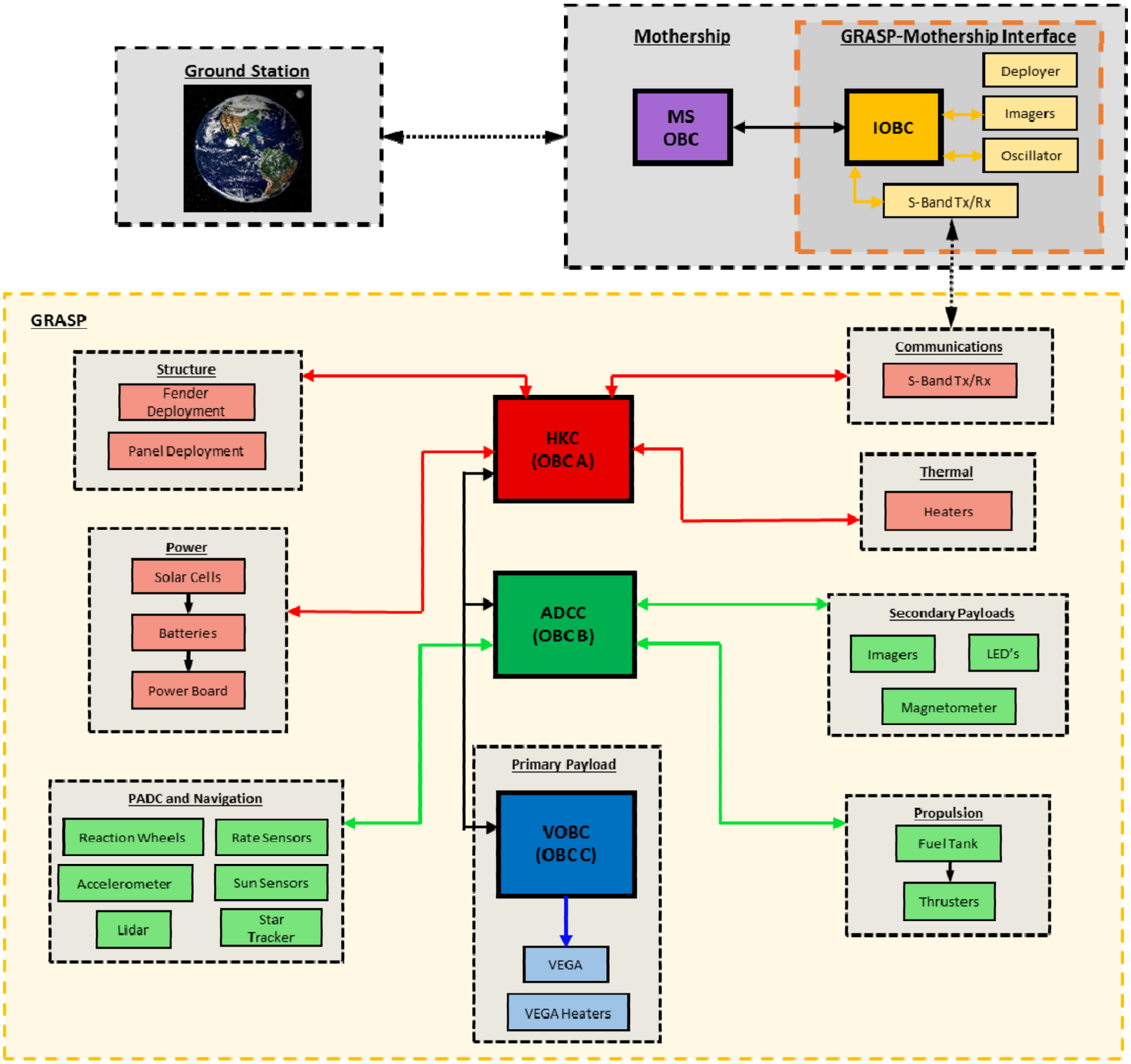

Figure 12: GRASP System Architecture

hard-wired link. This allows the GRASP spacecraft to be partly commissioned *en route* to the asteroid, and to allow its status to be checked periodically, issues to be debugged, new software uploaded, etc.

- The GRASP ground control centre equipment and team. This will interface with the mothership's ground control centre in a TBD mission-specific way; it will likely have a component that is physically on-site with the mothership ground control centre, and another component at SFL, connected via the internet.

The GRASP spacecraft is showed in its stowed configuration in Figure 11. It is compatible with the payload requirements of the PSC 12U cubesat deployer, having dimensions 34.2 x 23.9 x 22.9 cm. It incorporates PSC's "preloaded payload tabs" approach to restraining GRASP prior to deployment and guiding it linearly during deployment. Modifications will be made to the deployer to ensure a reliable ejection at a very slow speed (~ 5 cm/s) without jamming.

The deployed configuration of the GRASP spacecraft is shown in Figure 13 — this view is zoomed-in, in order to emphasize the details of the central bus. It shows all of the PV arrays deployed. It also shows the interior portions of the 6 legs. A zoomed-out view is provided in Figure 14, with some of the external surface equipment labeled.

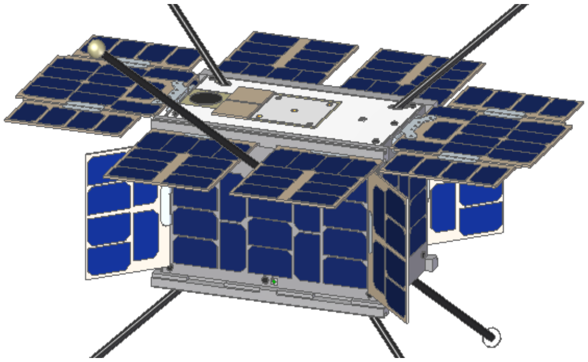

Figure 13: GRASP Bus (zoomed-in)

GRASP design features visible in these drawings include:

Legs: GRASP is equipped with 6 legs, which are deployable booms, each with a foot on its end. These are stowed completely within the mold-line of the bus until after GRASP is deployed from the mothership, after which they in turn deploy automatically. The legs are arranged so that the feet are located at the vertices of a regular octahedron, with each foot 85 cm from the centroid of the bus; the booms range in length from 63 to 70 cm. In each of the 8 stable landing configurations that result (Figure 10), GRASP is thus supported by three feet. This provides a stable support, with no chance of "teeter-tottering," meeting a requirement that GRASP's orientation remain very constant with respect to the asteroid surface during the ~ 10 minutes it takes for VEGA to make a gravity measurement.

Preferred Orientation: The above figures show GRASP in its preferred landing orientation, in which the largest area of PV array surfaces is pointed upwards, as is the star tracker.

PV Panels: In order to generate enough power when 2 AU from the Sun, to be able to operate through 10 hours of night on an asteroid with a 14 hour rotation period (i.e., away from its equator, towards the dark pole), GRASP requires more PV cell area exposed to the Sun than can be fit onto any single face of the bus. Also, there are several other equipment items which need to take up external surface area, principally a set of thermal radiators to keep GRASP sufficiently cool when close to the Sun, and also the star tracker, Sun sensors, cameras and thrusters. Given the 12U stowed volume constraint that we have adopted, the only solution is to deploy PV panels. The panel configuration shown has been optimized to generate an average of 13 W of power when in the preferred orientation, at 2 AU from the Sun.

Imagers: GRASP is equipped with a large number of very compact imagers, in order to be able to collect imagery in all directions. This capability will allow full imaging of the asteroid surface at each landing location, which will not only have strong scientific and public relations value, but will also be useful in determining landed orientation, and in monitoring for any changes in GRASP attitude relative to the asteroid during VEGA measurement operations. It will also allow GRASP to collect images containing the asteroid if and when GRASP finds itself on an escape trajectory, without needing to slew around to search of the asteroid. Of course, such a wealth of imagery could easily overwhelm the data communications channel to Earth; a strategy including on-board compression, and possibly some limited on-board image interpretation, will be used to triage the images that are sent to Earth.

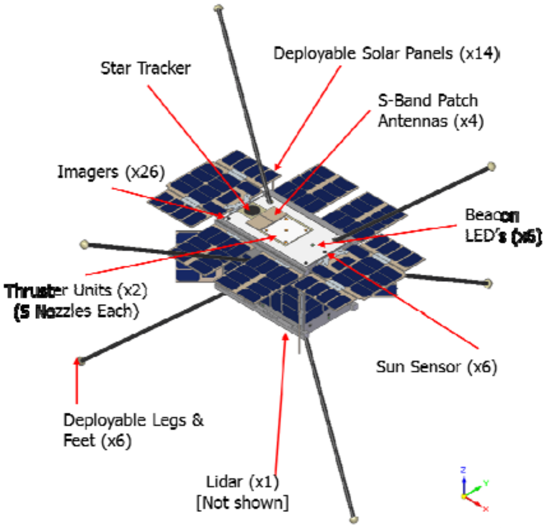

Figure 14: GRASP Spacecraft (zoomed-out)

Table 1: Mass Budget

Mass Budget Summary		
Subsystem	Mass [g]	Fraction
Structure	8673	46%
Landing/Mobility	1763	9%
Thermal	776	4%
PADCS	798	4%
Power	890	5%
C&DH	938	5%
Communications	524	3%
Propulsion	2843	15%
Payloads	1557	8%
Subtotal	18759	99%
Integration	188	1%
Total	16814	-
Target	24000	-
Margin	7186	29.9%

The mass budget for the GRASP spacecraft is shown in Table 1; the equipment left behind on the mothership is estimated to have an additional mass of < 7 kg.

The largest contributor to the spacecraft mass is the Structure subsystem; the structural mass fraction of 46% appears high even for a microsat. However, this includes the mass of the panels upon which the PV cells are mounted. The structure design has not yet been optimized, and we see room for reducing this mass somewhat in the next design iteration.

The propulsion subsystem contributes 2.8 kg of mass, of which half is propellant. This is sized for the largest, densest asteroid, and there is scope to reduce this mass if GRASP is sent to a smaller asteroid.

CONCLUSION

The era of asteroid lander missions is nearly upon us, and this is a domain in which much can be accomplished by spacecraft that are much like LEO microsats and nanosats. The scientific objectives of gravimetric geophysical surveying on an asteroid can be accomplished by this class of lander. The GRASP system is small enough to be carried as a secondary payload on all but the smallest asteroid rendezvous missions, and is robust enough to overcome the difficulties encountered by previous small-body lander missions. Near-term flight prospects for GRASP include NASA's ARRM mission, and ESA's AIM mission. Longer-term prospects include commercial asteroid resource prospecting missions.

Acknowledgments

The design work reported here was led by the authors. Significant contributions were made to the design presented here by Simon Laurin, Adam Svatos, Mehdi Sabzalian, Robert Spina, Michael Chapman and Damon Gogul, M.A.Sc. students at UTIAS. Young-Young Shen, Shahil Kanji, Houman Hakima, Jordan Backs, Brent Brakeboer, Seung-Yun Choi and Paris Ang contributed significantly to an earlier iteration of the GRASP design.

References

1. Baker, K. (KB1SF) & Jansson, R. (WD4FAB), "Space Satellites from the World's Garage -- The Story of AMSAT," National Aerospace and Electronics Conference, Dayton, Ohio, 23-27 May 1994, http://www.amsat.org/amsat-new/AboutAmsat/amsat_history.php.
2. J.-P. Bibring, M. G. G. T. Taylor, C. Alexander, U. Auster, J. Biele, A. Ercoli Finzi, F. Goesmann, G. Klingelhoefer, W. Kofman, S., Mottola, K. J. Seidensticker, T. Spohn & I. Wright, "Philae's First Days on the Comet," (July 30, 2015), *Science,* V.349, Issue 6247, p.493. [doi: 10.1126/science.aac5116].
3. Biele, J., Ulamec, S., *et al.*, "The landing(s) of Philae and inferences about comet surface mechanical properties," (July 30, 2015), *Science,* V.349, Issue 6247. [doi: 10.1126/science.aaa9816]
4. Carroll, K.A., "Asteroid Surface Gravimetry," *LPS XLV* Abstract #2352, Houston, 2014.
5. Carroll, K.A., "Asteroid Mineral Prospecting via Surface Gravimetric Surveying," Planetary and Terrestrial Mining Sciences Symposium (PTMSS), CIM 2015 Convention, Montreal, May 11-13, 2015.
6. Chacin, M. & Tunstel, E., "Gravity-Independent Locomotion: Dynamics and Position-Based Control of Robots on Asteroid Surfaces," in Applications, Control and Programming, Dr. Ashish Dutta (Ed.), InTech, DOI: 10.5772/25751.
7. The Cubesat Program, Cal Poly SLO, "6U CubeSat Design Specification Rev. PROVISIONAL," revision X1, 04/20/16, http://static1.squarespace.com/static/5418c831e4b0fa4ecac1bacd/t/573fa2fee321400346075f01/1463788288448/6U_CDS_2016-05-19_Provisional.pdf
8. Duncan, C., Smath, A. & Aquirre, F., "Iris Transponder – Communications and Navigation for Deep Space," paper SSC14-IX-3, 28th Annual AIAA/USU Conference on Small Satellites, Logan, UT, Aug. 4-7 2014.
9. Fleeter, R., **The Logic of Microspace: technology and management of minimum-cost missions**, Microcosm Press, El Segundo, California, 2000.
10. Funase, R., Inamori, T, Ikari, S., Ozaki, N., Koizumi, H., Tomiki, A., Kobayashi, Y & Kawakatsu, Y., "Initial operation results of a 50kg-class deep space exploration micro-spacecraft PROCYON," paper SSC15-V-5, 29th Annual AIAA/USU Conference on Small Satellites, Logan, UT, Aug. 10-13 2015.
11. Hirata, N. & Ishiguro, M., "Properties and possible origin of black boulders on the asteroid Itokawa," *LPS XLII* Abstract #1821, Houston, 2011.
12. Hokamoto, S. & Ochi, M., "Dynamic Behavior of a Multi-Legged Planetary Rover of Isotropic Shape," 6th Int. Symp. on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS), Montreal, Canada, 18-22 June 2001.

13. Klesh, A. & Krajewski, J., “MarCO: Cubesats to Mars in 2016,” Paper SSC15-III-3, 29th Annual AIAA/USU Conference on Small Satellites, Logan, UT, Aug. 10-13 2015.

14. Mazanek, D. et al., “Asteroid Redirect Mission (ARM) Formulation Assessment and Support Team (FAST) Final Report,” NASA/TM-2016-219011, NASA Langley Research Centre, Hampton VA, Feb. 2016.

15. Maskelyne, N., “"An Account of Observations Made on the Mountain Schiehallion for Finding Its Attraction,” Philosophical Transactions of the Royal Society, V.65 (0), pp.500–542, 1 January 1775, doi:10.1098/rstl.1775.0050.

16. Michel, P., Kueppers, M., Carnelli, I., Galvez, A., Mellab K. *et al.*, “Asteroid Impact Mission (AIM): the European component of the AIDA space project,” *LPS XLVII* Abstract #1204, Houston, 21-25 March 2016.

17. Murdoch, N. et al., “Low-velocity, low-gravity landing experiments,” presentation at the AIDA International Workshop, Nice, France, 1-3 June 2016.

18. Planetary Systems Corp., “PAYLOAD SPECIFICATION FOR 3U, 6U, 12U AND 27U,” 3 Aug. 2015, downloadable from http://www.planetarysystemscorp.com/web/wp-content/uploads/2016/04/2002367C-Payload-Spec-for-3U-6U-12U-27U.pdf.

19. R. L. McNutt, et al., “Near-Earth Asteroid (NEA) Scout,” in AIAA SPACE 2014 Conference and Exposition, American Institute of Physics Conference Series, 2014. doi:10.2514/6.2014-4435.

20. Pavone, M., Castillo-Rogez, J.C., Nesnas, I.A., Hoffman, J.A. & Strange, N.J., “Spacecraft/Rover Hybrids for the Exploration of Small Solar System Bodies,” pp.1-11, 2013 IEEE Aerospace Conference, Big Sky, MT, 2-9 March 2013, DOI: 10.1109/AERO.2013.6497160.

21. Reill, J., H.-J. Sedlmayr, P. Neugebauer, M. Maier, E. Krämer, & R. Lichtenheldt, “MASCOT – Asteroid Lander with Innovative Mobility Mechanism,” 13th Symposium on Advanced Space Technologies in Robotics and Automation (ASTRA 2015), 11-13 May, 2015, ESA/ESTEC, Noordwijk, the Netherlands.

22. Richter, L., “Principles for robotic mobility on minor solar system bodies,” Robotics & Autonomous Systems, V.23, 1998, pp.117–124.

23. Spangelo, S., Castillo-Rogez, J., Frick, A., Klesh, A., & Sherwood, B., “JPL’s Advanced CubeSat Concepts for Interplanetary Science and Exploration Missions,” Cubesat Workshop, Logan, UT, August 2015.

24. Tsay, M., Frongillo, J., Hohman, K. &Malphrus, B.K., “LunarCube: A Deep Space 6U Cubesat with Mission Enabling Ion Propulsion Technology,” paper SSC15-XI-1, 29th Annual AIAA/USU Conference on Small Satellites, Logan, UT, Aug. 10-13 2015.

25. Wilcox, B.H. & Jones, R.M., “The MUSES-CN Nanorover Mission and Related Technology,” pp.87-295, 7th IEEE Aerospace Conference, 18-25 March 2000, Big Sky, MT, DOI: 10.1109/AERO.2000.879296.

26. Yoshimitsu, T, Kubota, T., Nakamati, I., Adachi, T. & Saito, H., “Hopping rover MINERVA for asteroid exploration,” ISAIRAS 1999, 5th Int. Symp. On Artificial Intelligence, Robotics and Automation in Space, 1-3 June 1999, ESTEC, Noordwijk, The Netherlands.

27. Yoshimitsu, T., Kubota, T. & Nakatani, I., “MINERVA rover which became a small artificial solar satellite,” Paper SSC06-IV-4, 20th Annual AIAA/USU Conference on Small Satellites, Logan, UT, Aug. 14-17 2006.