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Abstract

Here we describe a small (12U cubesat) sized spacecraft designed to make geophysical measurements on the surface of an asteroid, and the asteroid science objectives which can be addressed using those measurements. The "Geophysical Reconnaissance Asteroid Surface Probe" (GRASP) spacecraft is designed to be a low-cost means for conducting 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 has been used on many successful, very low-cost and high-capability nanosats and microsats in low Earth orbit (LEO). This design approach enables GRASP to be robust against many types of operational failures. Previous and current asteroid exploration missions have carried primarily instruments which measure the surface properties of the asteroid target, determining geomorphology and surface geochemistry. Surface observations alone leave many important questions unanswered, for example questions about the composition and structure of the interiors of asteroids and comets, to the extent to which the interiors of these bodies are not completely reflected in their surface composition. Answering these questions will shed further light on the evolution of the Solar system, and techniques which can "see" interior properties can help do so. Such techniques will also be valuable in future asteroid resource-prospecting endeavours, in places where bulk composition varies significantly from proximate surface composition. This is the domain of *geophysics*, the branch of geoscience that uses instruments sensitive to subsurface properties, analyzing data from those to infer subsurface composition and structure. GRASP employs two geophysical techniques, *surface gravimetry* and *magnetometry*; the former using the "Vector Gravimeter/Accelerometer" (VEGA) instrument to measure the gravity vector on the asteroid's surface, the latter employing magnetometers at the ends of GRASP's legs, in close proximity to any magnetized rocks on the asteroid's surface. GRASP is equipped with a rocket-based propulsion system allowing it to rove by hopping, capable of visiting 100 stations spread about the surface of an asteroid 1 km or smaller in size; gravity measurements from these stations can be inverted to estimate the asteroid's internal density distribution. GRASP would be carried to its target asteroid as a secondary payload aboard a larger asteroid-rendezvousing "mothership" mission, which would release GRASP to land on the asteroid's surface, after which it would provide communications relay between Earth and GRASP, eliminating the need for GRASP to carry a high-delta-V propulsion capability or a long-range communications capability.

Keywords: asteroids, geophysics, surface gravimetry, magnetometry

1. Introduction

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) at the University of Toronto Institute for Aerospace Studies (UTIAS) are developing the "Geophysical Reconnaissance Asteroid Surface Probe" (GRASP) spacecraft (see Fig. 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 geophysical instruments — a gravimeter and a set of magnetometers — are intended to take their 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 around, land on and move about an asteroid's surface — which leads to 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 0.85 AU to 1.5 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. For the small asteroids, surface gravity levels are very low, on the order of 10 μg – far smaller than the surface gravity levels for previous planetary rovers. The mechanical properties of asteroid surfaces – very important to the performance of many surface-mobility concepts – are almost completely unknown. Surface 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.

2. Background

2.1 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 (22 of those being SFL missions), with some flying to even higher Earth orbits. However, until recently secondary payload

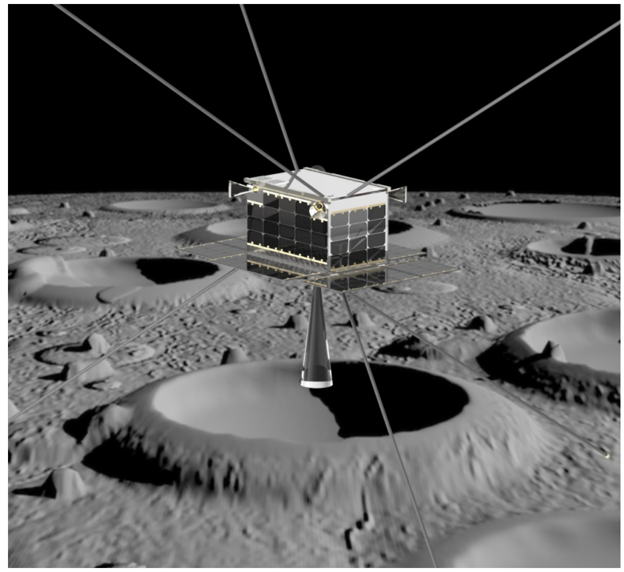

Fig. 1. GRASP Asteroid Lander/Rover

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.

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, the first interplanetary nanosats are now flying — JPL's two MarCO cubesats [2], *en route* to Mars after launching with NASA's InSight Mars lander mission on 5 May 2018. There are also several organizations world-wide actively planning other secondary-payload missions to destinations beyond Earth orbit including Lunar orbit [3] and asteroid flybys [4][5].

2.2 Asteroid Exploration Geoscience

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 and OSIRIS-REx, with DART, Lucy and Psyche in development), plus several attempted missions to the asteroid-like moons of Mars (Phobos 1 &2, Phobos-Grunt). Some missions to other targets have also included incidental asteroid flybys.

Early asteroid missions were flybys, with later missions proceeding to rendezvous, then landing, then sample collection and return. 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, but have left important questions unanswered. One

Fig. 2. Hayabusa-2 and MINERVA-II (image courtesy Akihiro Ikeshita)

category of such 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. Techniques which can "see" below the surface can help address such questions, and will also be valuable in future asteroid resource-prospecting endeavours.

Geophysics is the branch of geoscience that uses instruments sensitive to subsurface properties, and analyzes data from them 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 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 must be made on the surface, and so can only be carried out on lander missions. While there have been no successful asteroid lander missions flown to date (aside from NEAR Shoemaker's improvised end-of-mission setting down on asteroid 433 Eros), several are now underway or in planning. For example, JAXA's Hayabusa-2 sample-return mission (Fig. 2) has now rendezvoused with asteroid 162173 Ryugu, and will soon attempt to deploy several small landers and rovers (MINERVA-II which will deploy ROVER-1A and ROVER-1B on the surface, and DLR/CNES's MASCOT). Planners for ESA's Hera mission (Fig. 3) to the binary asteroid 65803 Didymos are contemplating carrying along similar landers/rovers.

GRASP is intended to conduct surface gravimetry on small asteroids. Gravimetric measurements made on the surface of an asteroid can determine its mass more

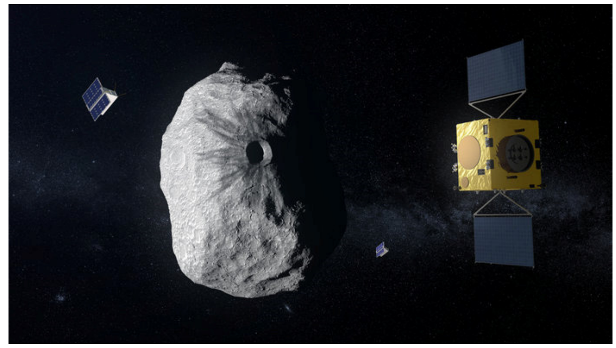

Fig. 3. Hera at Didymos (image courtesy ESA)

accurately than radio tracking techniques [6] can. They can also be used to produce a much higher-resolution model of an asteroid's internal density distribution than could be produced via radio tracking methods [7]. GRASP will carry a space gravimeter being developed by Gedex, the VEctor Gravimeter/Accelerometer (VEGA) instrument (Fig. 4). VEGA is a very compact (10x10x20 cm), low-mass (2.1 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.

2.3 *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 [8][9]. Unfortunately, due to an operations error, MINERVA was deployed in a direction which caused it to miss Itokawa. Lacking propulsion, it was unable to recover, and floated away into an independent Solar orbit.
- Rosetta (ESA, launched in 2004) rendezvoused with comet 67P/Churyumov–Gerasimenko in 2014,

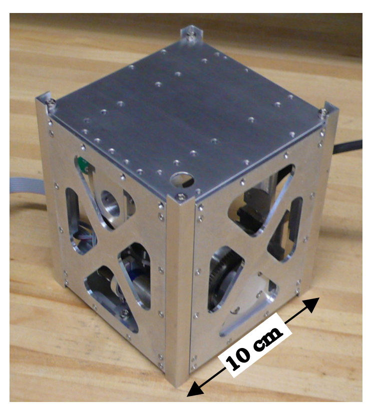

Fig. 4. VEGA Gravimeter Mechanical Breadboard

after which it flew formation with the comet for many months. It also carried the large-microsat-sized (100 kg) lander Philae [6][10] (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 mostly shadowed from the Sun. With no propulsion, it could not move from that location. Unable to recharge its batteries, it was able to operate for only a few days (versus the planned 1-6 weeks), although it nonetheless accomplished some of its science objectives.

- Hayabusa-2 (JAXA, launched 2014) which rendezvoused this year with asteroid 162173 Ryugu, will collect surface sample material and return that to Earth in 2019. It carries the small-microsat-sized (11 kg) MASCOT [11] (DLR/CNES), 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 drop the MINERVA-II lander (carrying a pair of nano-rovers) to the asteroid's surface, and 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 [4] (JAXA) was a microsat-sized (70 kg) spacecraft, launched in 2014 to perform a flyby of asteroid 2000 DP107 in 2016 – a plan abandoned after its ion propulsion system failed.

PROCYON was a stand-alone deep-space microsat, carried as a secondary payload on the same launch vehicle which launched Hayabusa-2, and was 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 secondary payloads by their primary mission spacecraft, which carried them to their targets. On reaching the target bodies each was released by their "mothership", which then provided communications relay services to and from Earth. This approach enables major simplifications in the design, and reductions in size and mass, of such small spacecraft. GRASP's design uses 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 relay communications for it after release. 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 in 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 fly as a daughter payload on even small-microsat motherships, with a view to supporting future asteroid prospecting activities.

3. GRASP Mission Objectives

GRASP's primary 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 surface magnetometer measurements, and doing high-resolution visible-light imaging – for immediate mission needs (characterizing the asteroid's size, shape, morphology and spin state), science, and public relations.

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, 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

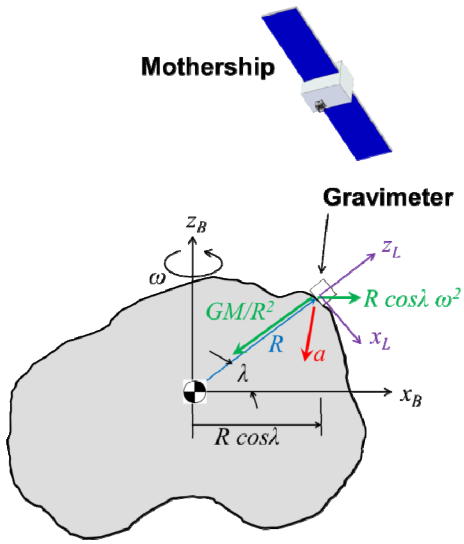

Fig. 5. Weighing an Asteroid Gravimetrically

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.

3.1 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.

An alternative means for determining an asteroid's mass is to place an accurate gravimeter on its surface, and measure the surface gravity [12]. Given knowledge of the location of the gravimeter and the asteroid's rotation axis and rotation rate, this permits solving for the asteroid's mass (assuming constant bulk density). The relationship between the variables involved is shown schematically in Fig. 5.

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

This 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 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. Such a mission might only have enough time to make a single measurement; that is sufficient in principle, but if there are any glitches in its operations, there may not be sufficient time to debug them before the lander dies.

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.

3.2 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. Fig. 6 illustrates 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.

Performing such a survey drives a requirement for

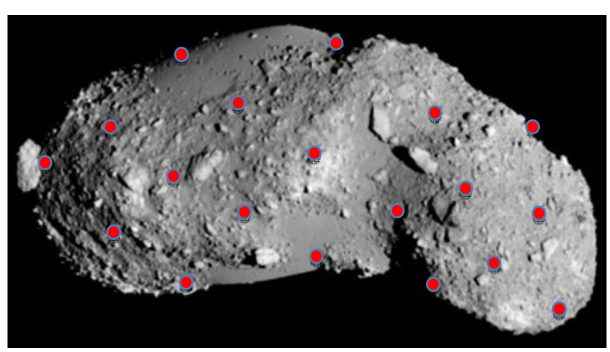

Fig. 6. Asteroid Global Gravimetry Survey

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 routinely carried out by geophysicists 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. As a byproduct, this will estimate the asteroid's mass significantly more accurately than from a single measurement station (by correcting for internal density variations). 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 would 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."

3.3 Asteroid Surface Magnetometry

We have identified an additional asteroid geophysical science investigation that can be carried out by GRASP, without significantly driving the design of the GRASP spacecraft or mission operations. This investigation uses magnetometers to address a peculiar contradiction regarding asteroid magnetic fields.

Prior to the first visits of spacecraft to asteroids, much of what was conjectured about the nature of asteroids was extrapolated from examining meteorites, which after all are remnants of asteroids which have come to Earth. It is known (e.g., Herndon, & Rowe [22]) that many meteorites possess remanent magnetization, which seemingly must have been imposed early in their formation history. This makes it plausible that some asteroids might possess global magnetic fields; however, none such has yet been detected. Acuña et al. [23] found no magnetic field associated with the asteroid 433 Eros, even after the NEAR Shoemaker spacecraft landed on the asteroid, leaving its magnetometer only about 2 m above the surface. Spacecraft which have flown magnetometers past other asteroids have not unambiguously detected any significant magnetic field.

We conjecture that small (dm-sized) rock fragments with meteorite-like remanent magnetization exist on asteroid surfaces, but in random orientations, so that their magnetic fields mostly cancel out even at a distance of only 2 m away. Placing magnetometers on GRASP's legs, much closer than that to the surface, would allow such remanent fields from individual rocks to be detected.

GRASP is designed to carry magnetometers at the outboard ends of three of its six legs, such that in any stable orientation on the surface, at least one of those sensors will be very close to the surface. This placement has the added advantage of maximizing the distance between the magnetometers and GRASP's bus, which will minimize magnetic "noise" from bus electrical equipment. We have made laboratory measurements with a candidate magnetometer near (within a few cm of) several meteorite samples which possess remanent magnetizations, measuring signals ranging from 100 nT to several thousand nT, well within this instrument's level of sensitivity.

This investigation involves making measurements with all of these magnetometers whenever GRASP is at a gravimetry measurement station; some magnetometers will be very close to the ground, possibly near magnetized rocks, while others will be "in the air" above the ground, providing a magnetic gradiometer capability that will help resolve the distance scale to any detected source. This will be done at each of many (baseline 100) stations on the surface of the asteroid. One simple objective is to compare the statistics of the measured field strengths, with those of known magnetized meteorites. This comparison could help determine if passage through Earth's atmosphere preferentially selects for or against magnetized meteorites, a subject of ongoing speculation. Another objective is to look for geographical correlations between stations, giving an idea of homogeneity at the regolith-rock level. Local concentrations could be diagnostic of impact dynamics, if a particularly strongly-magnetized impactor disintegrated on impact, then left magnetized debris concentrated about the impact site. Field strengths could also be interpreted to give some ideas of composition of surface rocks, by comparing them against measurements made from meteorites. As noted by Carporzen et al. [24] and Weiss et al. [25], there have been conjectured several possible sources for remanent fields, each of which have different time-scales and strengths, so measured strengths of remanent fields could potentially be used to differentiate between these to some extent, perhaps offering clues as to the sources of magnetic fields in rocks on the surface of GRASP's target asteroid, and from those into the history of the Solar system's evolution.

A more-dynamic investigation involves making measurements during GRASP's initial descent, then again during subsequent hops. As GRASP moves through its trajectory, if there's a measurable field, then the magnetometers will presumably see some spatial variations in that field as it moves through them over a short time interval, allowing exploitation of the instrument's sensitivity, rather than being limited by its accuracy. This is somewhat reminiscent of the terrestrial practice of airborne magnetometry surveying. Magnetic-field inversion techniques could then reveal the sources of larger-scale magnetic features.

4. GRASP 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.)

4.1 Target Asteroid Class Requirements

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

4.1.1 Orbit Range

GRASP shall meet its requirements for missions to asteroids whose orbits range in distance from the Sun between 0.85 and 1.5 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 operations at Solar distances somewhat outside that envelope.

4.1.2 Asteroid Size and Density

GRASP shall meet its requirements when operated on a Worst-Case Heavy asteroid of 900 m diameter and 2300 kg/m^3 density, and on a Worst-Case Light asteroid of 150 m diameter and 1500 kg/m^3 density. GRASP shall be capable of more limited operations (including takeoff and landing) on an Extreme-Case Heavy asteroid of 1000 m diameter and 8000 kg/m^3 density, and on an Extreme-Case Light asteroid of 100 m diameter and 400 kg/m^3 density, with mobility possibly impaired and landing accuracy possibly reduced.

4.1.3 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.

4.1.4 Asteroid Albedo

GRASP shall meet its requirements when operated on asteroids whose albedo is within the range 0.03 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.

4.2 Other Mission Requirements

4.2.1 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.

4.2.2 Payload

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

[*] Fleeter [13] introduced the term Microspace 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.

asteroid, and a set of magnetometers mounted close to the ends of GRASP's legs to measure remnant magnetic fields from rocks on the asteroid's surface.

4.2.3 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.

4.2.4 Lessons Learned from MINERVA and Philae

GRASP shall be capable of recovering from plausible operations mishaps, such as accidentally departing from the asteroid, or landing in a location with little or no sunlight.

4.2.5 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).

4.2.6 Productivity

For asteroids within the Worst-Case limits, GRASP shall be able to make measurements at up to 100 stations distributed evenly over the asteroid. This has implications on the mass of propellant carried for hopping, and the amount of time taken making each measurement.

4.2.7 Mission Performance

GRASP shall be able to determine an asteroid's mass to within 10% with a single surface gravity measurement. This mostly drives 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.

4.2.8 Size

GRASP shall fit within a 12U cubesat volume and mass specification, in particular that from PSC [14]: 23x24x37cm, 24 kg. This requirement is levied to maximize the compatibility of GRASP with various potential primary missions. While there is not yet wide consensus on a 12U cubesat specification, CalPoly's recent 6U spec [15] indicates willingness on the part of the community to adopt specifications developed by PSC and others.

4.3 Surface Mobility Approach Requirements

As yet, nobody has any experience operating a mobile robot on the surface of an asteroid. Extrapolating from experience with terrestrial, Lunar and Mars rovers, we expect that the uncertain properties of surface material, and the very low gravity, will be problematic for many mobility systems. 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 which bypasses it. 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," are not expected to be usable in this environment [16]. In recognition of this, researchers have devised several alternate concepts for surface mobility in a very-low-gravity environment, including:

- Richter [16] described using a rocket propulsion system to do short ballistic hops.
- The Nanorover [17], proposed by JPL as a payload on Hayabusa, was to use wheels on a pair of axles that could be drawn rapidly together, allowing the rover to jump about the asteroid's surface. It could also right itself if it landed on its back. (The Nanorover project was cancelled before flight.)
- Several groups have proposed to rotate either a reaction wheel or an eccentric mass, creating a torque that would cause the rover to tumble; with suitable surface traction, this tumble could result in either rolling motion staying in contact with the surface, or hopping motion with a translational component. MINERVA carried a flywheel which was intended to accomplish this [8][9]. MASCOT has a rotatable, motor-operated eccentric arm, which will produce both a torque and a force. Pavone [18] is currently exploring the use of 3 orthogonal reaction wheel actuators for tumbling, in combination with multiple symmetric legs.
- Hokomato and Ochi [19] described equipping a rover with radially extendable and retractable legs. Chacin and Tunstel [20] described a multi-limbed walking locomotion system.

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 which your spacecraft can hit.

That said, design choices still affect mission and system robustness, and the choice of mobility method is a prime example. 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. We know much about the properties of lunar regolith, thanks to the Apollo missions. However, the low surface gravity of asteroids could result in very different surface material properties, due to its effects on the behaviour of impact ejecta. For example, the area of Itokawa where Hayabusa briefly touched down is quite different from the lunar surface.

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 results. This would continually tempt all involved into risk-aversion behaviours, consuming much time and money.

Adapting the "no Death Modes" principle to GRASP with this issue in mind thus leads us to adopt a mobility method that does not rely on traction at all: ballistic hopping. 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 routine for microsats.

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 various mission-terminating failures.

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 [18] 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.

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.

5. GRASP Mission Design

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

- GRASP will launch as a secondary payload on a host spacecraft ("mothership") which rendezvouses with the target asteroid, whereupon GRASP will be released to land at a selected point on the surface, with an impact velocity low enough that it will not bounce off of and escape.
- GRASP's ground controllers will command it, and receive data back from it, via its mothership.
- GRASP will attempt to control its impact speed by performing a propulsive manoeuvre immediately prior to impact, to minimize uncontrolled bouncing after impact. GRASP is also designed to survive impact should that manoeuvre not happen, and GRASP operations will be planned to recover from bouncing to anywhere on the asteroid's surface, even a permanently shadowed region.
- Once GRASP has come to rest at some point on the surface, ground controllers will determine if that location is suitable for a gravimetry survey station. If so, they will command it to make a gravimetry measurement and magnetometry measurements. 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.

- If GRASP accidentally 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. This will be done via commands from the ground, not autonomously.
- GRASP will use propulsive hopping for 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 45^0 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 45^0 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 Fig. 7. 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.
- GRASP will collect images during each hop and after each landing, and send them to ground controllers. These will be used to determine position on the surface to high accuracy.
- Although GRASP is designed to tolerate landing in any of 8 stable orientations (Fig. 8), it has a "preferred up" direction (e.g., only one face has a star tracker). GRASP will 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 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.

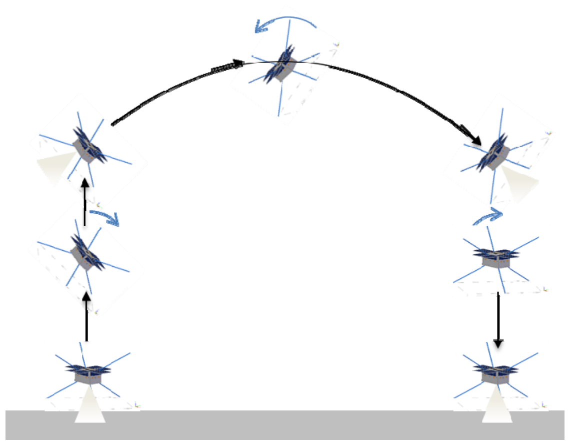

Fig. 7: GRASP Long-Hop Manoeuvre

6. Mission Analysis

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

6.1 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).

6.1.1 Insolation

The amount of Sunlight incident on GRASP (while

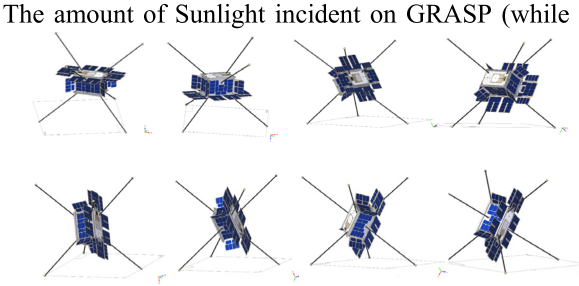

Fig. 8: GRASP Stable Surface Poses

it is in sunlight) on or near the asteroid will range from a high of 138% to a low of 44% 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 3.1) makes for very challenging power and thermal subsystem designs.

6.1.2 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—but high enough (for the largest asteroids or interest) to require a relatively large ΔV to carry out a global asteroid survey. Gravity of the smaller asteroids will be low enough that entering an orbit around the asteroid will be difficult, or even essentially meaningless.

6.1.3 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.

6.1.4 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 landing accelerometers on Hayabusa and Philae. A property that could be crucial to any lander 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. Hayabusa's touchdown site on Itokawa was literally rock-hard, and Philae observed a fairly hard surface on its comet target. On the other hand, recent lab experiments at SUPAERO [21] suggest that landing at speeds of a few cm/s into granular material at low gravity (milli-g) could result in a low coefficient of restitution.

6.1.5 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 be 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.

6.1.6 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 surface of 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.

6.2 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 (900 m diameter) and densest (2300 kg/m^3) target asteroid. This results in the following required propulsion capabilities:

- ΔV: 150 m/s (including 100% margin). This is based on 100x hops of 100 m distance each. 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: up to 30 mN. For a GRASP mass of 15 kg, this provides a thrust to weight ratio

of about 7 on the Worst-Case Heavy asteroid (surface gravity of about 300 micro-g), and of about 2 on the Extreme-Case Heavy asteroid (surface gravity 1.1 milli-g) and a GRASP mass of 15 kg.

7. 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.

7.1 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 housing 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, modified to eject GRASP at a precisely controlled and very low speed (~ 5 cm/s, whereas standard cubesat deployers typically eject at ~ 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.

7.2 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 750 bps. It shall include a receiver, and GRASP shall be capable of sending data to that at a rate of 800 bps. These data rates shall be achieved at a range of 50 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.

7.3 Payloads

GRASP's primary payload is the VEGA gravimeter. It will also carry a set of magnetometers. GRASP will also carry imagers, used for various functions including:

- Imaging the asteroid during descent from the mothership, and during hops across the surface, to provide georeferencing information.
- Imaging the surroundings while on the surface, for science and publicity purposes.
- Imaging the immediate surroundings if landed in a hole or crevice, for design of an escape maneuver. For this purpose, cameras shall have 4π sr coverage.

7.4 Propulsion

GRASP includes a propulsion subsystem, whose main requirements are described above. It will have rather more propulsive capacity (on the order of 150 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.

7.5 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.

7.6 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.

7.7 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. 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 will 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. With the reaction wheels, this enables Pavone-style tumbling mobility experiments.

GRASP will 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.

7.8 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 1.5 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.

7.9 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 limited periods not in sunlight (implying a need for a battery). GRASP shall be able to operate in locations with 30% sunlight, for asteroid rotation periods of up to 12 hours, at a distance of 1.5 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.

7.10 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 lander can easily bounce 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 will also be able to keep its temperature-sensitive components sufficiently warm when not in sunlight for up to 48 hours. This requires a combination of passive and active thermal control.

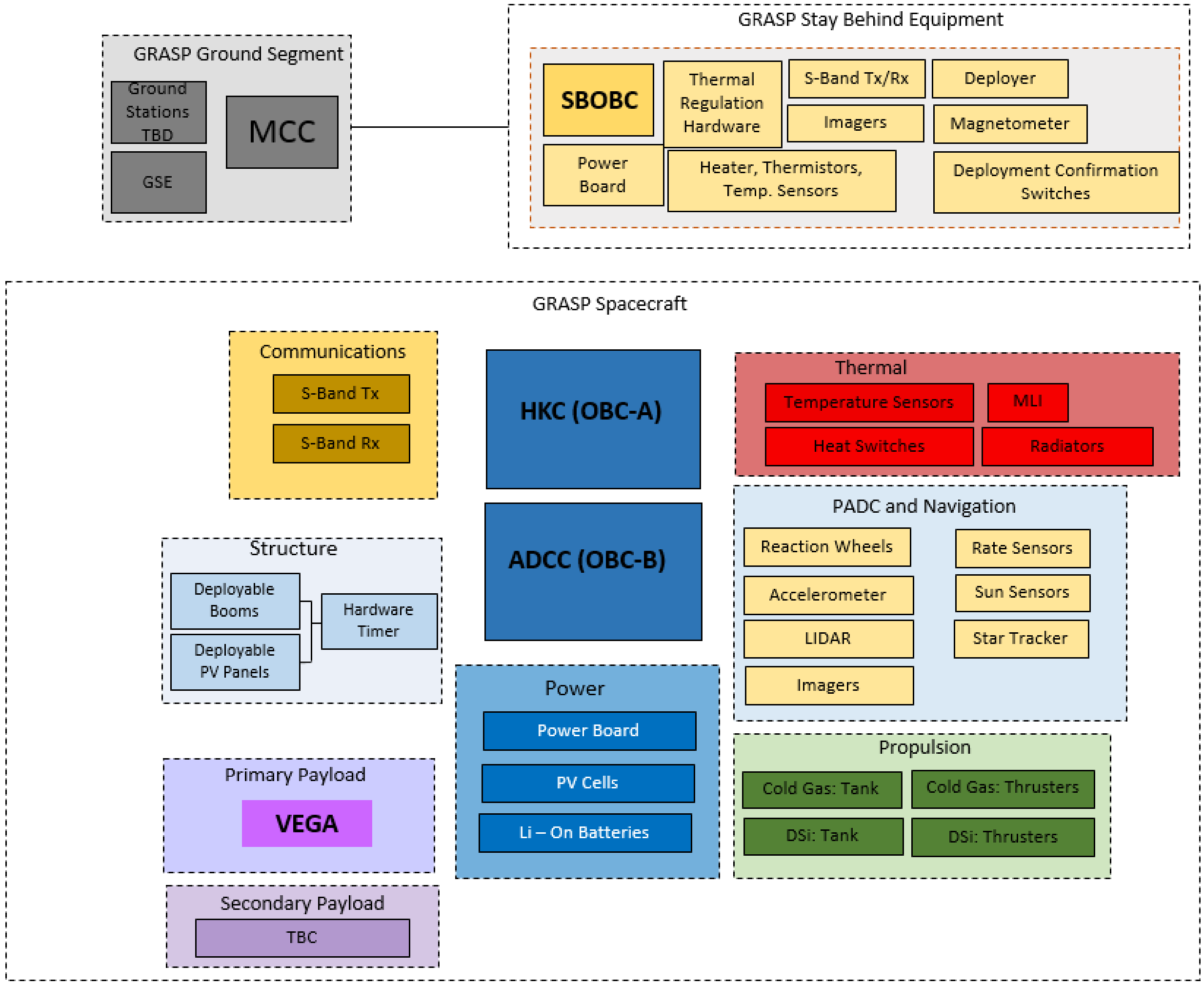

Fig. 9: GRASP System Architecture

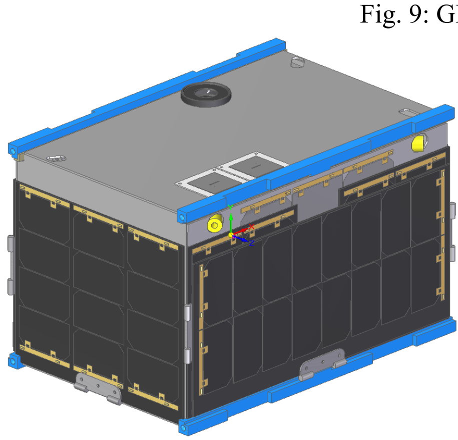

Fig. 10: GRASP Spacecraft Stowed Configuration

8. 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.

8.1 GRASP System Architecture

The overall GRASP system architecture is illustrated in Fig. 9. It comprises three Elements:

- The GRASP Spacecraft.
- GRASP equipment which "stays behind" on the mothership. This will appear to the mothership as a mothership payload, with the mothership 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 associated equipment, Prior to deployment of the GRASP spacecraft from the mothership, this OBC provides power to GRASP, and communicates with it via a 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.

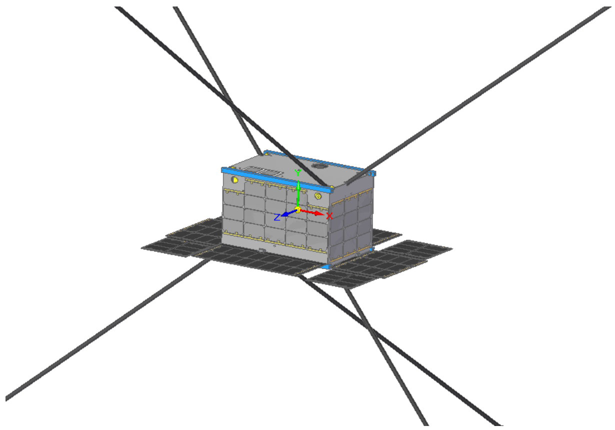

Fig. 11: GRASP Bus (zoomed-in)

- 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 Fig. 10. It fits within a payload volume of 366 x 235 x 246 mm, derived from the PSC 12U cubesat deployer's specifications. Modifications will be made to its 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 Fig. 11—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 Fig. 12, with some of the external surface equipment labeled.

8.1.1 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 167 cm from the centroid of the bus, which provides clearance between the bus and obstacles as tall as 60 cm; the booms range in length from 143 to 170 cm. In each of the 8 stable landing configurations that result (Fig. 8), 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.

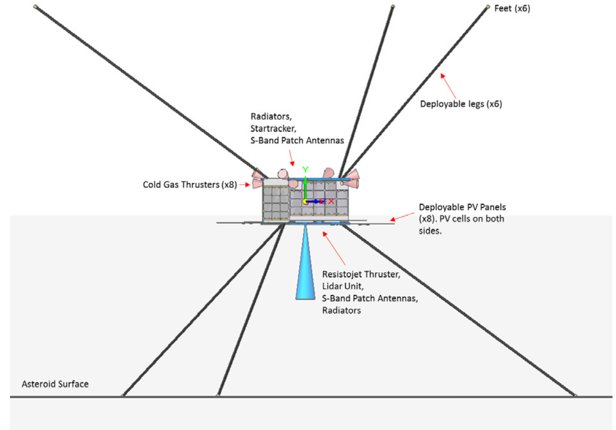

Fig. 12: GRASP Spacecraft Layout (zoomed-out)

8.1.2 Preferred Orientation

Fig. 11 shows GRASP in its preferred landing orientation, in which the largest area of PV array surfaces is pointed upwards, as is the star tracker.

8.1.3 Photovoltaic panels

In order to generate enough power when 1.5 AU from the Sun, to be able to operate through 8.4 hours of night on an asteroid with a 12 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 as much as 43 W of power at 1.5 AU from the Sun.

8.1.4 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. 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.

8.1.5 Magnetometers

GRASP is equipped with a set of three 3-axis fluxgate magnetometers, one 3-axis sensor mounted towards the outboard end of each of 3 of GRASP's legs.

These have been selected to be compact (less than 2.5 cm on a side), and tests with the selected magnetometer confirm that it can maintain an adequate accuracy (500 nT, calibrated sensitivity considerably better than that) over the very wide range of temperatures (absolute accuracy of +/- 150C) that GRASP's feet are expected to experience when deployed on an asteroid's surface. Tests of the selected magnetometer handily detected signals when placed within a few cm of various sample meteorites remanent magnetization.

Mass Budget Summary		
Subsystem	**Mass [g]**	**Fraction**
Structure	5789	38%
Landing/Mobility	1378	9%
Thermal	288	2%
PADCS	1089	7%
Power	1891	12%
C&DH	106	1%
Communications	343	2%
Propulsion	2274	15%
Payloads	2059	13%
Integration	153	1%
Navigation	76	0.5%
Total	15293	100%

Table 1: GRASP Mass Budget

The mass budget for the GRASP spacecraft is shown in Table 1; this does not include margin. The equipment left behind on the mothership is estimated to have an additional mass of <10 kg.

9 Conclusion

The era of asteroid lander missions is 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 ESA's Hera mission. Longer-term prospects include commercial asteroid resource prospecting missions.

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