<table>
<thead>
<tr>
<th>Title</th>
<th>Authors/Contact Information</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALL THESE WORLDS ARE YOURS—EXCEPT EUROPA. ATTEMPT NO LANDING THERE</td>
<td>S. J. Saikia, M. de Jong, and T. Balint <a href="mailto:saragis@gmail.com">saragis@gmail.com</a></td>
<td>1</td>
</tr>
<tr>
<td>Icy Moon Mobility System Analysis Tool</td>
<td>Luis Pablo Podesta <a href="mailto:lpodesta@purdue.edu">lpodesta@purdue.edu</a></td>
<td>2</td>
</tr>
<tr>
<td>Prospecting and Returning Lunar Surface Samples with Volatiles</td>
<td>Robert Buchwald <a href="mailto:robert.buchwald@airbus.com">robert.buchwald@airbus.com</a></td>
<td>3</td>
</tr>
<tr>
<td>Mission Design Challenges of the Asteroid Impact Mission</td>
<td>Ingo Gerth <a href="mailto:ingo.gerth@ohb.de">ingo.gerth@ohb.de</a></td>
<td>4</td>
</tr>
<tr>
<td>Navigation Strategy for the Asteroid Impact Mission (AIM)</td>
<td>João Vasconcelos <a href="mailto:joao.vasconcelos@spinworks.pt">joao.vasconcelos@spinworks.pt</a></td>
<td>5</td>
</tr>
<tr>
<td>Asteroid Geophysical Explorer (AGEX): A Didymos System Exploration Mission Based on Cubesats</td>
<td>David Mimoun <a href="mailto:david.mimoun@isae.fr">david.mimoun@isae.fr</a></td>
<td>6</td>
</tr>
<tr>
<td>Shape Optimization of Small-Body Landers</td>
<td>Stefaan Van wal <a href="mailto:stefaan.vanwal@colorado.edu">stefaan.vanwal@colorado.edu</a></td>
<td>7</td>
</tr>
</tbody>
</table>
ALL THESE WORLDS ARE YOURS—EXCEPT EUROPA. ATTEMPT NO LANDING THERE. S. J. Saikia¹, M. de Jong², and T. Balint³, ¹Visiting Assistant Professor, School of Aeronautics and Astronautics, Purdue University, 701 W. Stadium Ave., West Lafayette, IN, 47907-2045, ssaikia@purdue.edu, ²Thin Red Line Aerospace, 208-6233 Unsworth Rd, Chilliwack BC V2R 5M3, Canada, maxim@thin-red-line.com, ³Ph.D. Researcher, Royal College of Art, Kensington Gore, London SW7 2EU, United Kingdom, tibor.balint@network.rca.ac.uk.

In Arthur C. Clarke’s 2010: Odyssey Two, at the end, the monoliths (built by the enigmatic aliens), acting as self-replicating “von Neumann” machines, increase Jupiter’s density until it triggers nuclear fusion, transforming it into a mini-sun in order to aid the evolution of life on Jupiter’s moon Europa. As Jupiter was transforming, HAL repeatedly broadcasted the message to Earth, “ALL THESE WORLDS ARE YOURS—EXCEPT EUROPA. ATTEMPT NO LANDING THERE [1].”

Starting with science fiction, the scientific interest in Europa has tremendously increased after the discoveries made using data from the Galileo orbiter. Different studies have been proposed or are under planning such as the Europa Jupiter System Mission, Jupiter Icy Moon Explorer, and Jupiter Icy Moons Orbiter. Last year, NASA announced the Europa Multiple-Flyby Mission set for a launch in the 2020s, which will include an orbiter and a possible soft lander. Static landers involve less risk in the overall mission but have a disadvantage in terms of spatial exploration—which can be overcome using a mobility system. So, not only are we ignoring HAL’s message to Earth to not land on Europa, but the proposed work is on the next phase—to traverse on Europa to conduct science both in temporal and spatial terms, which may subsequently lead to the exploration of the subsurface oceans.

Why Explore the Icy Moons? The surfaces of the icy moons—Europa, Ganymede (both Jupiter’s moons), and Enceladus (Saturn’s moon)—are mostly composed of ice. The icy moons are widely believed to harbor sub-surface oceans and the potential for habitable environments, which makes these icy moons of prime interest in the search for life beyond Earth [1, 2]. Evidence have been found from Galileo data on a possible body of liquid water, equal in volume to the North American Great Lakes, beneath the icy surface of Europa [4]. The finding strengthens the argument that Europa’s global subsurface ocean represents a potential habitat for extant life which makes Europa a top destination for the search for life beyond Earth. Therefore, mobility technologies that enable robotic in situ exploration of the surfaces of icy moons are of high interest for NASA’s future missions. The exploration goals of a mobility system are (a) characterization of habitability of ocean world, (b) detection of extant life, (c) geologic understanding and (d) understanding of planetary origins [3].

Challenges of Mobility System to Explore Icy Moons: Icy moons will likely offer regions varying from as smooth as ice to as rugged as high cliffs, deep crevasses, blocky ice boulders, or even tall penitentes. Europa’s highest resolution images (6-12 m/pixel resolution) [5-6] of the surface from the Galileo mission, represent scientifically very attractive places to explore (Figs. 1a, b, and c). These images show a surface that is rough down to the pixel level, containing fractures, slopes, and scarps. In Fig. 1d, Enceladus’s young and active “tiger stripe” region (Cassini, 4 m/pixel) near the south pole is strewn with ice blocks and boulders between 10 and 100 meters across, along with some intervening smooth patches [7]. Europa’s dark lineae (Fig. 1e) are also important science targets as they might be the result of recent (and active) upwellings signifying thinner regions in the ice shell. However, the rugged terrain (caused by eruptions of warmer ice) around these regions may pose particular mobility challenges. Subduction or compression zones on the icy moons would also present severe challenges for mobility. Thera Macula (Fig. 1f) is a region of likely active chaos production via calving (similar to seen in Earth’s glacial regions) above a large liquid water lake in the icy shell of Europa.

Fig. 1 Icy Moons are geological wonderlands: (a) Europa’s Conamara Chaos (b) Thera Macula (Galileo, 220 m/pixel resolution) may be a region of active chaos formation; is low-lying, suggesting subsurface water today (c) A cliff on Europa at 12 m/pixel (Galileo spacecraft) showing evidence of mass wasting [5-6] (d) Enceladus (4 m/pixel) from Cassini showing active “tiger stripe” (e) dark lineae on Europa [7] and (f) Schematic of calving on Europa forming chaos regions as Thera Macula [4].

Requirements of an Icy Moon Mobility System: Autonomous light-weight, cost-effective mobility technologies that enable robotic in situ exploration are important to NASA’s future exploration goals. Such mobility systems should be able to operate on extremely rugged surfaces as well as in extreme environments, including low temperatures (50–100 K) and, in the case of Jupiter’s icy moons, a high radiation flux (> 5 Sv/day.
for Europa) [8]. Because of the likely association of rugged surface characteristics with high value science targets, future icy moon surface explorers will need mobility capabilities that look beyond current state-of-the-art (SoA) systems. The limited height inherent in a roving vehicle constrains the range of imaging and surface navigation systems, posing an additional challenge in locating and traversing to high value science targets on the icy moons. The long telecommunication round-trip between Earth between the Jovian and Saturnian systems necessitates autonomy.

**Comparison with State-of-the-Art (SoA) Systems:** A comparison of the SoA mobility systems vis-à-vis the proposed mobility system are summarized as follows. a) *6-wheel drive rocker boogie:* This system (used in NASA Mars rovers and Chinese Yutu rover) can climb over blocks twice the height of the wheel (e.g. diameter of Curiosity rover wheels is 0.5 m) and a slope of 30 degrees—will not be effective for jagged icy moon features; b) *Snowmobiles and tracked vehicles:* These vehicles, widely used in Earth’s colder climes, are very effective in traversing smooth, wind-blown icy surfaces, but would likely not operate well on icy moons with no atmospheres, especially to reach the high-value science targets located in the roughest terrain; c) *Legged-Hoppers:* Hoppers have been studied extensively for missions to Neptune’s moon Triton, the Martian southern pole geyser, and comets, and present an alternative way to both traverse rugged terrain and travel long distances, but are inherently risky in the landing phase on rugged surfaces; d) *Tumbleweeds for Mars and Airless Bodies:* They can be used to explore the Martian surface, and also on airless bodies. Mars Tumbleweed (inflatable or semi-rigid), deriving wind-driven mobility on Mars, would not clearly function on an airless icy moon; and in airless bodies, a rigid-spiked Tumbleweed design would achieve only limited mobility.

**Mobility System Trade Study:** In this paper, the preliminary results of a comprehensive trade study will be presented that will constrain and guide the design of mobility systems that can enable both temporal and spatial in situ exploration of the icy moons. NASA’s Jet Propulsion Laboratory is currently conducting a large trade study to constrain and guide development of icy moon mobility system. Trade studies include Mobility, sensing and sampling at targeted locations distances ~10 m (projectile sampling, and boom manipulator concepts) and > 1 km (spherical roller and hedgehog concepts) from landing site [9]. A comprehensive effort is currently ongoing at Purdue University and Thin Red Line Aerospace to develop a radically exciting, innovative, game-changing inflatable mobility system that overcomes the constraints of the current SoA mobility systems. A detailed lander and mobility system trade analyses is being performed which includes the landing method; landing navigation methods (Terrain-Relative Navigation, TRN; Hazard Detection and Avoidance, HDA); mobility mechanisms, rover lifetime; radiation shielding mass; power source; rover range; propulsion; attitude control; optimal hopping; system mounting, interfacing, and configuration; and science instruments.

Of the many mobility system concepts being considered, one is a spherical hopper-rover, which has a central inflatable structure. The inflatable structure has a credible heritage (which can be comprised of one of the many inflatable shapes, such as the Thin Red Line’s Ultra High Performance Vessel, Rotundus™, or Radiolaria). Such a mobility concept, yet unexplored, achieves mobility of rolling and hopping via a combination of momentum wheels and thrusters; supported by altitude sensing, TRN and HDA capabilities. Separate pods hold the thrusters, momentum wheels, power source, avionics, sample analyzing instruments including robotic appendages, radiation shielding, and all associated subsystems (e.g. thermal, communication). The inflatable rover design can provide redundancy against single-point failure (puncture) by various methods: double or triple gas containment bladders or use a self-healing bladder.

For surfaces which are relatively smooth or less inclined, momentum wheels are used, and when the rover is trapped in complex terrain (e.g., penitentes or boulder fields) thrusters are used to hop. Figure 2 shows the notional ConOps of mobility via hopping.

**Fig. 2 Notional ConOps for hopping maneuver of an inflatable rover, on either Europa, Ganymede, or Enceladus (adapted from image by NASA/ESA/K. Retherford/SWRI, and [10])**

**References:**

ICY MOON MOBILITY SYSTEM ANALYSIS TOOL. L. P. Podesta1†, S. Vutukuri2†, J. Pouplin3†, S. C. Ho4†, I. Droll5†, and S. J. Saikia6, 1Graduate Student i Podesta@purdue.edu, 2Graduate Student svutukuri@purdue.edu, 3Graduate Student ipouplin@purdue.edu, 4Graduate Student ho73@purdue.edu, 5Visiting Assistant Professor, 6School of Aeronautics and Astronautics, Purdue University, 701 W. Stadium Ave, West Lafayette, IN 47907-2045

Introduction: In December 2013, NASA’s Hubble Space Telescope first observed water vapor above the frigid southern polar region of Jupiter's moon Europa, providing strong evidence of water plumes [1]. When the Cassini and Galileo missions flew by the Icy Moons, it opened us to new perspectives—even small orbiting bodies could present substantial tectonic activity. Using a mass spectrometer, Cassini detected organic compounds on Enceladus and hints of a possible subsurface ocean [2]. Coupled with tidal heating as an energy source, these Icy Moons present all the fundamental characteristics responsible for the formation of life.

Studying these characteristics will allow us to comprehend how life originates in the universe, one of the highest objectives put forth by the latest Decadal Survey “Vision and Voyages for Planetary Science” [2]. While an orbiter would be able to fulfill some of these scientific objectives, a series of in-situ analyses would add a critical data set to confirm the presence of life on the Icy Moons [3].

Challenges of designing a mobility system for the icy moons: Major locations of interest would be the Tiger Stripes on Enceladus that eject water vapor [3] and the chaos regions on Europa as shown in Figs. 1 and 2 respectively [4]. However, these scientific sites of interest present geographic characteristics that make it extremely difficult for current state-of-the-art (SoA) mobility systems to reach.

Penitentes, large boulders, crevasses, high-angled slopes are but some of the challenges that would have to be addressed by any surface exploration system.

Fig.2 - Chaos regions on Europa can be surrounded by obstacles such as highly irregular surfaces and crevasses [5].

No dedicated mission to explore either Europa or Enceladus has been launched. NASA has come up with several mission proposals, of which the Europa Multiple Flyby mission (formerly Europa Clipper) and the Europa Lander are the most prominent. There has been significant work in developing orbiters, static landers, and sub surface ocean explorers, but less emphasis on rover type vehicles to explore the surface [3–4, 6].

Primary proposed surface mobility systems: The chaotic landscape at pertinent science sites leads the design focus away from heritage wheeled rovers such as Mars Exploration Rovers (MERs) and SoA rover such as Curiosity.

Fig.1 - Chaos regions on Europa are marked by obstacles such as penitents and large boulders (a, b)[3], while Enceladus’s Tiger stripes are giant chasms that are surrounded by rugged, uneven terrain (c, d) [4].

Fig.3- Examples of proposed mobility systems: harpoons, articulated arms, inflated spherical rovers and hedgehog [7].
Analysis of Galileo and Cassini high resolution images seen in Fig. 1 compel us to look for vastly different approaches than previous mobility system concepts. In order to overcome the geographic challenges presented by the icy moon surfaces, we need to explore or adapt new designs. Various surface mobility system concepts have already been proposed by JPL and others, as seen in Fig 3, among these: legged, wheeled and hopping rovers. However, the merits and demerits of each concept are yet to be fully explored and understood.

**Interest in an analysis tool:** An icy moon mobility system should be able to overcome scenarios similar to those shown in Fig. 4. This proposal presents a system analysis tool to assess a wide variety of mobility systems for Icy Moons aim to conduct the necessary trade studies for rover design.

![Fig. 4](image1)

Fig. 4 – Some of the possible mobility scenarios on icy moons: a) chasm hopping b) irregular terrain c) ascent out of crevasse.

Four promising mobility systems are being studied: a mechanical hopper using springs, a spherical rover using reaction wheels, a harpoon system, and a thruster based mobile platform as seen in Fig. 5.

![Fig. 5](image2)

Fig. 5 – Examples of the four mobility systems analyzed. Clockwise from top left: harpoon system, thrust hopper, mechanical hopper, roller bot with spikes [8–11].

From these, we extracted the key metrics to be able to objectively measure a rover’s effectiveness at traversing the aforementioned terrain and mobility scenarios. This provides a baseline to compare with other systems.

The mission scenarios we considered are similar to those analyzed in JPL’s study [7]: the ability to sense and sample at chosen locations 10 meters away from the rover in a stationary position, and the ability to move and perform experiments at locations more than 1 kilometer apart.

Detailed lander and mobility system trade analyses will be performed. Among these trades are: landing methods; navigation methods such as Terrain Reconnaissance Navigation (TRN) and Hazard Detection Avoidance (HDA); mobility mechanisms; power source; rover range; propulsion; attitude control and optimal hopping. Detailed parametric scaling will be conducted for the mobility systems to understand the relationships between variables in a multi-dimensional trade space.

The goal of this study is to develop an interactive Icy Moon Mobility System Analysis Tool that allows an intuitive and wide array of variations of rover design variables. The tool will aid to constrain and guide development of the mobility system for icy moons.

**References:**
PROSPECTING AND RETURNING LUNAR SURFACE SAMPLES WITH VOLATILES

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Introduction: ESA is investigating together with ROSCOSMOS the possibility of a joint Lunar Polar Sample Return (LPSR) mission, which shall allow in-situ measurements on the lunar surface and the return of samples in original conditions.

As part of the ESA Lunar Exploration feasibility assessment, a parallel study, the Lunar Volatile Prospector (LVP) study has been initiated. The Lunar Volatile Prospector is a self-contained element implemented as a mobile rover platform to support the exploration of the South Pole of the Moon and possibly a Lunar Sample Return Mission.

Target sites are at a location which receives less than average solar illumination (~7 days per month) and thus presents reduced surface & sub-surface temperatures. These lower regolith temperatures increase the likelihood of obtaining samples containing volatile ices.

Airbus Defence and Space as industrial prime contractor is leading a European team focusing on consolidating the first system and mission assumptions of LPSR and LVP and support the implementation of the future mission in the context of a broader lunar exploration effort.

The presentation will provide first insights in the performed investigations and the achieved results.

LPSR Mission Scenario: In the reference mission architecture two main space segments are defined: the Lander Module (LM) and the Orbiter-Return Module (ORM).

The LM includes all elements required for landing and operating on the lunar surface, and for delivering the sample to the hand-over point with the Orbiter-Return Module.

The Orbiter-Return Module itself consists of all elements required for arriving and operating in lunar orbit, for rendezvousing with the sample and for returning the sample to Earth. One part of the Orbiter-Return Module, the Orbiting Vehicle (OV) remains in a polar orbit around the Moon for providing data relay functionality for further surface activities.

LVP Mission Scenario:

The LVP mission architecture consists principally of 2 main phases:

Launch, transfer, landing and delivery of a mobile platform (Lunar Prospecting Rover (LPR)) to the lunar surface and surface operations of the LPR.

The current early study work on the LVP mission is concentrating on the second phase, i.e. on the surface operations carried out by the LPR and on the definition of the LPR itself.

Special focus is set on sampling and operating in permanently shaded regions which imposes demanding requirements on hardware and operational concepts.
MISSION DESIGN CHALLENGES OF THE ASTEROID IMPACT MISSION (AIM).  I. Gerth¹, B. Burmann², M. Rohrbeck³, M. Scheper⁴, T. Hormigo⁵, F. Ferrari⁶, M. Lavagna⁷
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Abstract: The Asteroid Impact & Deflection Assessment (AIDA) mission is an international collaboration of ESA and NASA, with the primary goals to perform a spacecraft impact on a near-Earth asteroid and to measure and characterize the deflection caused by the impact in order to test the feasibility of asteroid deflection for planetary defense [1]. The mission has two primary elements: NASA’s Double-Asteroid Redirect Test (DART), under investigation at Johns Hopkins University Applied Physics laboratory (JHU/APL), and ESA’s Asteroid Impact Mission (AIM), which two industrial consortia are currently studying [2]. This paper presents key results from the AIM Phase A/B1 study by OHB System. Figure 1 shows an artist’s impression of OHB’s current design.

Figure 1: Artist’s impression of the DART impact as monitored by the AIM spacecraft, MASCOT-2, and the COPINS.

AIM is to be designed on a low-cost approach and is scheduled for launch in 2020. Its primary objective is to characterize the asteroid 65803 Didymos (1996 GT) and then to assess the consequences of an impact from DART on the secondary component (or moonlet) in the Didymos binary system, informally referred to as “Didymoon”. On arrival, AIM will conduct observations to complement and prepare for the DART impact. Further objectives are to release a number of CubeSat opportunity-payloads (COPINS) at the asteroid, place the MASCOT-2 lander on the surface of the secondary asteroid, and to demonstrate deep-space optical communications downlink capabilities. Additional technology demonstrations include an ultra-flat high-gain antenna based on meta-surface technology and infrared vision-based navigation.

The tight schedule, low-cost approach and high performance requirements for the mission and spacecraft design make AIM a very challenging endeavor, especially in context of the high complexity related to deep space missions. This paper presents OHB’s plans to overcome the challenges posed by this unique mission scenario and presents an approach to designing a short-term low-cost interplanetary mission. The focus will be on engineering measures to enable the overall mission schedule by following a design-to-schedule approach for mission and spacecraft design, and how to handle challenges unique to this deep space mission by relying on well-established spacecraft and mission elements.


Acknowledgments: The work presented in this paper has been carried out under a Phase A/B1 ESA contract. The consortium led by OHB System AG also comprises its partners Politecnico di Milano, Spin.Works S.A., and Telespazio VEGA Deutschland GmbH.
**Introduction:** The Asteroid Impact Mission (AIM) is the European contribution to a joint ESA/NASA mission named AIDA (Asteroid Impact and Deflection Assessment), aimed at investigating the double asteroid system 65803 Didymos, a small near-earth Asteroid which will pass within 0.1AU of the Earth in October 2022.

The navigation strategy pursued for the AIM involves the combined use of ground-based measurements (range, range-rate, Delta-DOR) and onboard optical measurements (unresolved and resolved object centroiding, limb extraction, landmark extraction), in a semi-autonomous way (processed on the ground or onboard, depending on the mission phase), in order to obtain an integrated solution for the the complete mission. An especially critical manoeuvre concerns the deployment of a lander built by DLR named MASCOT-2 (an evolution of the MASCOT lander on Hayabusa) from a very close range from Didymoon - less than 200m - and with a very high accuracy (~10m, <1cm/s 1-sigma), which are necessary to avoid the lander escaping the tenuous gravity field of the object.

This work presents the navigation strategy for AIM for the interplanetary transfer, approach, and close proximity phases. The work begins by describing the navigation strategy pursued for the interplanetary transfer phase, where a combination of range, range-rate and Delta-DOR measurements (where necessary) are used. The strategy followed during the approach phase - consisting of a set of five manoeuvres which successively decrease the relative distance between the spacecraft and the Didymos system - is shown next. This phase is characterized by the gradual introduction of optical measurements as the asteroid becomes visible in the navigation camera images, and their use in order to ensure a smooth placement of the spacecraft in the desired geometry at 35km range, for initial observations and Didymos system characterization.

The navigation strategy for the close proximity operations follows. This strategy has been designed to ensure AIM can be feasibly kept within a prescribed region around the baseline observation trajectory relative to Didymos, and is in addition tightly connected to the timeline required to build Didymos/Didymoon shape models and respective landmark databases from the co-flying observation orbit, since the accuracy of the relative navigation is changed significantly after such models and databases become available for use in the orbit determination process.

Finally, the navigation strategy for the lander deployment phase is described. This phase is characterized by a semi-autonomous navigation strategy, relying on ground updates for the non-time-critical portion of the manoeuvre sequence (where a minimum of 8h of turnaround - between measurement collection and orbit determination update - can be accounted for without significant impact on the mission trajectory), and on an autonomous onboard operation period driven by optical observations for the final few hours, during which two trajectory refinements are needed in order to achieve the target deployment accuracy for MASCOT-2.
ASTEROID GEOPHYSICAL EXPLORER (AGEX): A DIDYMOS SYSTEM EXPLORATION MISSION BASED ON CUBESATS. D. Mimoun, O. Karatekin, N. Murdoch, A. Cadu and Jose A Carrasco

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Introduction: Despite the successes of recent space missions such as Deep Impact or Hayabusa (e.g., Cheng et al., 1997; Fujiwara et al., 2006), there is still no clear understanding of the asteroid internal structure(s). Depending on their size, evolution and physical properties, many different asteroid internal structure models have been suggested from completely cohesive bodies, through to rubble pile objects. This information is of primary importance for the understanding of the story of the solar system and for any prospect of collision with Earth mitigation.

Asteroid Geophysical Explorer (AGEX), a COPINS payload selected by ESA, will land a geophysical instrument package on the surface of Didymoon; the secondary object in the (65803) Didymos (1996 GT) binary system (Karatekin et al, 2016). The instruments will characterize the asteroid surface mechanical properties and probe, for the first time, the sub-surface structure of an asteroid.

A ballistic transfer: AGEX will be deployed from AIM on a ballistic transfer to the asteroid surface, several days before the MASCOT-2 package. We expect that AGEX will bounce multiple times before coming to rest on the surface of the asteroid thus providing a unique opportunity to study the asteroid surface properties, perhaps at several locations, using accelerometers. Once stationary, the seismological surface-monitoring phase, using a three-axis set of geophones, can begin.

The high speed DART impact will be a major seismic source on Didymoon. However, the seismic payload may also be able to perform seismological investigations during a shorter life duration, before the impact, using natural seismic sources such as micrometeoroid impacts (e.g., Garcia et al., 2015), thermal cracks (e.g., Delbo et al., 2014), internal quakes due to tidal forces (e.g., Richardson et al. 1998) and other geophysical processes (see Murdoch et al., 2015).

We will present the expected signal characteristics of the landing and also of the natural seismic sources that may occur on Didymoon. An understanding of the amplitude and frequency content of such signals is necessary in order to design the optimal geophysical payload for small body exploration using a CubeSat platform.

We will also describe the considered instrumentation necessary to fulfill the science objectives (gravimeters, accelerometers, geophones, etc.) in terms of measurement dynamics, frequency ranges, acquisition methods and other common budgets for space equipment.

We also present the environment considerations which have to be taken into account for the platform and payload designs. The thermal aspect will be particularly discussed since it is a major issue in the airless body exploration (Lafontaine et al 1996, Ulamec et al, 2010). It implies some modifications in the CubeSat structure, integration and thermal regulation to ensure survival and operations under extreme conditions at the asteroid surface.

We then describe the platform subsystems needed to ensure the operations after the deployment and the associated budgets and accommodation. As a direct consequence of the previous topics, we will finally discuss the possible trades-off to satisfy the main science requirements and the associated concept of operations.

SHAPE OPTIMIZATION OF SMALL-BODY LANDERS. S. Van wal1, S. Tardivel2, and D.J. Scheeres1,
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Introduction: Over the past decade, the small bodies of our Solar System have matured into common targets
for large space missions. Specifically, missions to these asteroids, comets, and small moons aim to address
distance three distinct goals: first, the pristine condition of most small bodies provides insight into the early conditions
of the Solar System, shedding light on its formation. Secondly, the missions provide a way of validating planetary defense strategies to deflect hazardous near-Earth objects. Finally, the analysis of small body surfaces provides insight into the feasibility of in-situ resource utilization techniques.

In the coming decade, the Hayabusa-2, OSIRIS-REx, and AIDA missions will expand our existing knowledge of small bodies through extensive remote sensing and sample return operations at their respective targets. Hayabusa-2 also carries the MASCOT and MINERVA landers, which will carry out surface mobility operations using momentum exchange mechanisms, allowing them to return measurements from multiple sites on their target [1, 2]. Similar cubesat landers are planned to be included on the AIDA mission [3]. In order to design the deployment and surface operation strategy, as well as the hardware of a lander, we require high-fidelity simulation capabilities. Previous work has showed successful, low-risk deployment to a target small body along its unstable manifolds [4]. This strategy has been extensively verified with numerical simulations for spherical landers, in which a stochastic model was applied to account for the presence of rocks on the small body surface [5, 6].

While this provides a tractable approximation to the motion of landers with arbitrary shapes and establishes important simulation techniques, these models have several limitations. In order to be fully confident in analyses of lander motion, we must expand these simulations to be able to handle arbitrary lander shapes and fully generate rock distributions.

In this work, we present an overview of the elements required to carry out high-fidelity simulations of small body landers with arbitrary shapes. In particular, we focus on techniques to reduce the computational burden of handling high-resolution gravity and surface models, as well as collisions of landers with the target surface. This simulation capability enables the design and verification of deployment and surface mobility strategies of small body landers. The software is used to investigate the effects of lander shape on the deployment dynamics. We then use this insight to optimize the lander shape with respect to certain missions goals, e.g. minimizing the settling time, in the presence of uncertainties in the interaction coefficients.

Simulations: The dynamical state of a lander/rover spacecraft is expressed in a rotating reference frame fixed to the target small body. This state is propagated using an RK5(4) propagator with event detection capabilities, in order to converge on collisions between the lander and its target body. We implement this integrator in C++ to enable fast simulations of a large number of trajectories.

The complex and irregular gravitational field of the target small body is expressed using the constant-density polyhedron model, which consists of a large number of vertices and facets. Due to their high resolution, evaluations of these models are computationally expensive. Therefore, we implement two techniques that were developed by [5] and shown to be effective at reducing this computational burden. The first of these techniques is the linearization of the gravity field using the gravity gradient matrix, which can be applied when the distance Δr between successive integration steps is small. Through the selection of some Δrmax, we control the allowable error of the linearization. The second technique approximates the gravity field of a high-resolution shape model with some reduced-resolution model, by applying a shape averaging. By controlling the number of vertices in the reduced model, we control the associated error.

As the shape and orientation of the small body surface strongly affect lander-target interactions, it is necessary to consider high-resolution models of that surface; reduced-resolution models may not capture local topographic variations that, e.g., serve as basins of attraction. Additionally, it has been shown that rocks and boulders on the small body surface play an important role in the energy and topographic dissipation of landers, motivating their inclusion [5, 6] into simulations. In order to make such models numerically tractable, we make use of three techniques. First, we create the atlas of the target small body prior to performing simulations. This atlas consists of a latitude-longitude grid where individual local worlds contains those surface features that fall within their respective span. By only performing distance computations to the closest local world, we enable collision detection with a high-resolution surface at low computational cost. Secondly, these local worlds are further exploited in order to efficiently generate rocks on the surface: using information on the distribution of the rocks, we procedurally generate rocks only on the active local world. By controlling the seed of the random number generator, we ensure that this procedural generation is consistent, i.e., that the same rocks are always created on the same facet. Finally, the efficiency of collision de-
tection can be increased even further through the use of bounding spheres, which are defined for and encompass each individual local world, rock, as well as the lander. Collisions between two objects are possible only when their bounding spheres intersect/overlap; we may therefore use the spheres to trigger more detailed distance computations between the individual features of two objects. This greatly reduced the numerical cost of detecting collisions between a lander and a large number of surface objects.

When a lander-target collision is detected, its effect on the lander velocities must be computed. Although simple, algebraic collision laws can robustly handle collisions of a spherical body, such laws cannot be applied in the non-eccentric collisions of an arbitrary-shaped where the contact point, body center of mass, and normal force are generally not aligned. In order to robustly such collisions, we follow the method of [7] and perform an integration over the (instantaneous) collision, using the normal impulse as a time-like variable. Over the course of this integration, we distinguish between the slip and stick cases of the contact point, and account for the effect of both the normal and friction forces, as governed respectively by coefficients of restitution and friction. Using an additional blow-up transformation, we can robustly handle all possible cases [8].

Shape optimization: By combining all of these elements, we obtain the capability of performing high-fidelity simulations of lander/rover spacecraft in the intricate small body environment. This capability has a wide range of applications, one of which is the verification of release and deployment strategies of landers with an arbitrary shape. As an example, Fig. 1 shows sample deployments of various lander shapes.

More interestingly, we can investigate the effect of lander shape on its dynamics, given some release conditions. As a first step, we perform sets of Monte Carlo simulations of a few simple shapes impacting and settling on a flat surface. In this, we vary both the initial conditions and the coefficients of restitution and friction, and investigate the resulting trajectories. This insight is then applied to perform an optimization of the lander shape, where this shape is adjusted while subject to constraints, e.g., the lander mass and density. This optimization is carried out with respect to various missions goals, such as minimizing the average settling time of a lander, given a particular set of release conditions.

Conclusions: We present the elements required for high-fidelity simulation of lander/rover spacecraft in the small-body environment. This simulation capability enables an investigation of the effects of lander shape on the resulting trajectories. Using simple surface geometries, we develop an algorithm that optimizes the lander shape with respect to certain mission goals, such as minimizing the settling time. This optimization is validated by performing simulations in the full small-body environment. Our results provide insight into the deployment dynamics of small body landers and may establish guidelines in the design of lander hardware.