

Active Electrostatic Flight For Airless Bodies

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Abstract— The environment near the surface of asteroids, comets, and the Moon is electrically charged due to the Sun’s photoelectric bombardment and lofting dust, which follows the Sun illumination as the body spins. Charged dust is ever present, in the form of dusty plasma, even at high altitudes, following the solar illumination. If a body with high surface resistivity is exposed to the solar wind and solar radiation, sun-exposed areas and shadowed areas become differentially charged. The E-Glider (Electrostatic Glider) is an enabling capability for operation at airless bodies, a solution applicable to many types of in-situ missions, which leverages the natural environment. This platform directly addresses the "All Access Mobility" Challenge, one of the NASA’s Space Technology Grand Challenges. Exploration of comets, asteroids, moons and planetary bodies is limited by mobility on those bodies. The lack of an atmosphere, the low gravity levels, and the unknown surface soil properties pose a very difficult challenge for all forms of know locomotion at airless bodies. This E-Glider levitates by extending thin, charged, appendages, which are also articulated to direct the levitation force in the most convenient direction for propulsion and maneuvering. The charging is maintained through continuous charge emission. It lands, wherever it is most convenient, by retracting the appendages or by firing a cold-gas thruster, or by deploying an anchor. Preliminary calculations indicate that a 1 kg mass can be electrostatically levitated in a microgravity field with a 2 m diameter electrostatically inflated ribbon structure at 19kV, hence the need for a “balloon-like” system. The wings could be made of very thin Au-coated Mylar film, which are electrostatically inflated, and would provide the lift due to electrostatic repulsion with the naturally charged asteroid surface. Since the E-glider would follow the Sun’s illumination, the solar panels on the vehicle would constantly charge a battery. Further articulation at the root of the lateral strands or inflated membrane wings, would generate a component of lift depending on the articulation angle, hence a selective maneuvering capability which, to all effects, would lead to electrostatic (rather than aerodynamic) flight.

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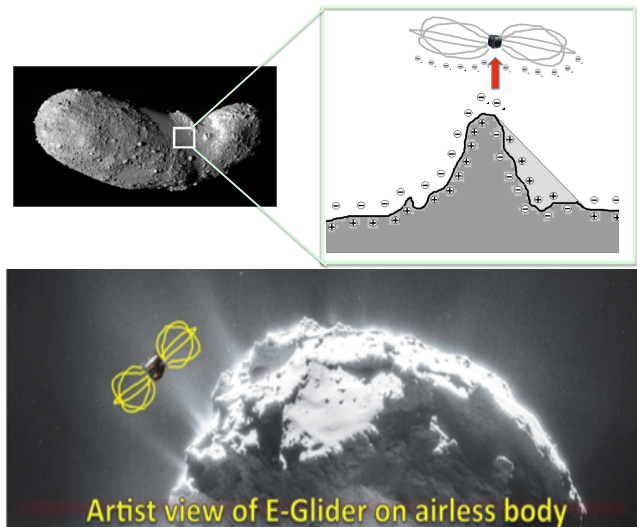


Figure 1. The E-Glider (electrostatic Glider) is a small vehicle that levitates above the surface of an asteroid after extending strands of metallic film, forming the wings, so that it becomes “airborne”, but in the electrostatic vacuum lofting around the asteroid. By articulating the wings, the E-Glider can now hover, and maneuver around, without touching the surface. It is the first circumnavigation of an airless body by electrostatic forces, opening new avenues for low-cost, persistent, reconnaissance of airless bodies, leading to effective global scale prospecting of mineral-rich asteroids.

1. INTRODUCTION

The E-Glider (Electrostatic Glider) is an enabling

capability for exploration of airless bodies, a solution applicable to many types of in-situ missions, which leverages, instead of avoiding, the natural environment. We envisage the global scale exploration of airless bodies with a gliding vehicle that experiences its own electrostatic lift by its interaction with the naturally charged particle environment near the surface. This E-Glider levitates by extending thin, charged, appendages (like some flying spiders on Earth), which are also articulated to direct the levitation force in the most convenient direction for propulsion and maneuvering. It lands, wherever it is most convenient, by retracting the appendages or by firing a cold-gas thruster, or by deploying an anchor. See Figure 1. With the E-Glider, we transform a problem (spacecraft charging) into an enabling technology, i.e. a new form of mobility in microgravity environments using new mechanisms and maneuvering based on the interaction of the vehicle with the environment. Consequently, the vision of the E-Glider is to *enable global scale airless body exploration with a vehicle that uses, instead of avoids, the local electrically charged environment*.

Locomotion in micro-gravity is currently done with hoppers, or micro-gripper locomotion, which depend on having sufficient friction against the unknown surface [25,26,27,32]. Except for hoppers and micro-grippers, which use momentum exchange or mechanical forces to move, no other solutions exist at the present time. E-Glider uses the local environment to its advantage, and keeps the vehicle safe while it conducts its science mission away from the surface. The E-Glider lifts off by extending its electrostatic wings, i.e. thin, charged, appendages, which like the spiders on Earth, mimics Nature, harvests and uses the electrostatic energy abundantly present in the local environment, and it starts the new era of "Solar System exploration by electrostatic flight". The use of electro-static levitation for circumnavigating a Solar System body is still unexplored. Our vision is to develop an enabling capability for operation at airless bodies, a solution applicable to many types of in-situ missions, which leverages the natural environment. A mission based on an E-Glider would truly be a very exciting one, as it would be the first asteroid circumnavigation of an airless body by electrostatic forces, opening new avenues for low-cost, persistent, reconnaissance of air-less bodies, leading to effective global scale prospecting of mineral-rich asteroids.

Exploration of comets, asteroids, and moons (e.g., Phobos, Deimos, Enceladus) is limited by mobility on those bodies [28]. Current robotic [32] and human systems [1] cannot safely traverse a number of prevalent surface terrains, and travel slowly, requiring detailed oversight and planning activities. Consequently, these systems are often limited to exploring areas close to their original landing site. The lack of an atmosphere, the low gravity levels, and the unknown surface soil properties pose a very difficult challenge for all forms of known locomotion. Small body mobility concerns spatial surface coverage on planetary bodies with substantially reduced gravitational fields for the purpose of science and human exploration. This includes mobility on irregular-shaped objects such as NEOs (Near

Earth Objects), asteroids, comets, and planetary moons (e.g., Phobos, Deimos, Enceladus). The National Research Council [7] has designated technologies for small body mobility as a high priority for NASA given its destination potential for human spaceflight, which would likely require precursor robotic missions. Specific technology needs include novel mobility systems together with associated control techniques and novel localization techniques. For science missions, in-situ spatially extended exploration of small bodies would address key priority questions in the Building New Worlds theme. In addition, a variety of observations have recently shed new light on the astrobiological relevance of small bodies, as a source of organics to Earth and/or as potentially habitable objects [24]. Surface mobility platforms for small bodies differ from their planetary counterparts because the microgravity environment largely influences their design. Microgravity can be leveraged as an asset for mobility, as in the case of hopping platforms, or overcome as a challenge, as in the case of anchoring systems. Microgravity mobility could include hoppers, wheeled, legged, and hybrids, but so far no electrostatic solution has been proposed. While there have been several attempts at small body surface mobility, to date, no such system has been designed for the large scale exploration of small bodies. Microgravity environments pose many challenges not only for mobility and manipulation, but also for control, localization, and navigation. Recent observations from both space mission and ground-based telescopes have revealed a more diverse landscape on small body surfaces than previously thought. Small body surfaces can range from areas covered with a thick layer of fine regolith and ones that have boulders and protruded regions, thus making locomotion based on surface interaction very problematic. The E-Glider concept directly addresses the "All Access Mobility" Challenge, one of the NASA's Space Technology Grand Challenges [7], specifically aimed at enabling robotic operations and mobility, in the most challenging environments of our solar system.

2. ENVIRONMENTAL CHALLENGES AT SMALL BODIES

Physics at airless bodies is dominated by four physical fields [15,28]: a) microgravity, responsible for locomotion; b) cohesion forces, which can dominate particle interactions through van der Waals forces; c) solar radiation, which is constantly acting; and d) electrostatics, which is strongest at terminator where it can lead to significant dust transport. The highly irregular shapes of many asteroid and other small bodies lead to unique modeling and dynamics challenges. In contrast to the gravitational fields of spherical and ellipsoidal bodies, those produced by Near Earth Objects (NEOs) are frequently much more complex. The gravitational fields of these irregular bodies exhibit high levels of variation at both the surface and locations near the bodies. These gravitational fields are often orders of magnitude weaker than Earth's. In addition to exhibiting irregular shapes, the gravitational fields produced by small

bodies often have milli-G or micro-G order magnitudes. As a result, escape velocities from these bodies are exceptionally low and must be carefully considered when maneuvering landers or spacecraft. Another consequence of these low gravitational magnitudes is that the rotational period, some times as fast as a fraction of minute, may impact spacecraft motion. It may be possible to take advantage of this behavior to aid in motion between surface locations on a small body. This could potentially be achieved by applying an impulse to the lander such that it hops away from the surface without an orbital velocity component while the small body continues to rotate. This maneuver would lead to a change in position when gravity pulls the lander back to the surface. As the topics examined illustrate, it is necessary to understand the impacts of both small gravitational magnitudes and irregular gravitational field shapes to ensure successful spacecraft interactions with small bodies.

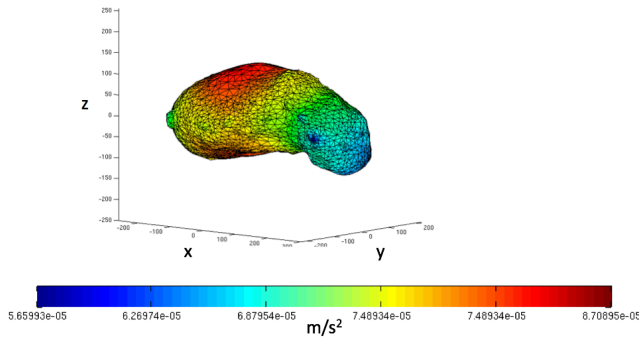


Figure 2. Surface acceleration at Itokawa [26].

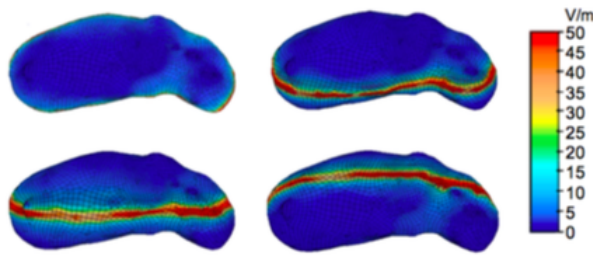


Figure 3. Electric field at terminator of Itokawa [2].

The environment near the surface of airless bodies (asteroids, comets, Moon) is electrically charged due to interactions with the solar wind plasma and UV radiation. Charged dust is ever present, in the form of dusty plasma [6]. Comets have a gas tail and a second electrostatic tail. This environment is also largely unexplored. Electrostatically levitating dust grains have been hypothesized to exist above 10's of meters above the dayside surface [11, 12, 18]. If a body with high surface resistivity is exposed to the solar wind and solar radiation, sun-exposed areas and shadowed areas become differentially charged (see Fig. 3). Charging on the dayside

surface is dominated by photoelectrons emitted due to solar UV radiation that create a positive surface potential, while the shadowed side accumulates electrons and acquires a negative surface potential. Recent work [12,17,35] shows that, on the Moon, soft solar X-rays with wavelengths smaller than 25 Å can remove electrons with energies of 500 to 1500 eV from the surface and create cm-scale electric fields which may reach levels of ~50-150 kV/m. The spokes in Saturn's rings are most likely clouds of particles electrostatically levitated from the surfaces of larger bodies in the rings [9], and electrostatic dust transport processes have been proposed on the surface of Mercury [13] and comets [19,20]. Asteroid electric charge has never been measured, but simple estimates predict that an electric potential difference of ~1 kV can be attained on the dark side compared to the sunlit side, which becomes slightly positively charged by photoelectron emission. These differences are enhanced further at the terminator (the day/night boundary), when fields could reach ~100-300 kV/m [2] (Figure 1) with results obtained by simulation). Millimeter-size particles can be most easily lifted from the surface of Itokawa [11]. As these particles are lifted, they dislodge smaller particles that are harder to lift due to their strong cohesive forces [12]. Once separated from the surface, grains can either travel on ballistic trajectories, escape from the asteroid, or levitate. During these migrations the larger particles can get trapped in topographic lows, as observed in [20]. As a surface element on a resistive asteroid rotates into and out of view of the sun, electrostatic levitation may agitate its uppermost particulate layer. Larger levitated particles remaining gravitationally bound to the asteroid are redistributed across its surface following local electrostatic and gravity gradients. Consequently, the study of levitating dust is relevant in that it provides some insight into the plasma environment and confirms the possibility of levitation. An intriguing example from nature discussed in [10], refers to existing observations and the physics of spider silk in the presence of the Earth's static atmospheric electric field (~120 V/m negative) to indicate a potentially important role for electrostatic forces in the flight of Gossamer spiders. A compelling example is analyzed in detail, motivated by the observed "unaccountable rapidity" in the launching of such spiders from the vessel H.M.S. Beagle, recorded by Charles Darwin during his famous voyage, on a day without wind, and far away from the shore [10]. It is believed that such spiders are able to emit threads that are either pre-loaded with a static electric charge, so that the presence of this charge will lead both to mutual repulsion among the emitted threads, and an additional overall induced electrostatic force on the spider, providing a component of lift that is independent of convection or aerodynamic effects. The E-Glider biomorphically behaves like one of these spiders, greatly favored by the charged environment, in absence of aerodynamics and convection, and in the microgravity fields at small bodies.

3. PROPOSED SCIENCE INSTRUMENTATION

Many science objectives can be addressed at small bodies, such as NEOs, also shown in Figure 4. Figure 5 maps Decadal science priorities to small instrument availability for science to be conducted at NEOs. Thanks to recent advances in miniaturization, several science-grade instruments are becoming available for implementation on small vehicles such as Cubesats. Some of these instruments, which could be suitable for use on the E-Glider, are [15]: quadrupole ion trap spectrometers (2.5 kg, with isotopic accuracy < 1%), snow and water imaging spectrometers (with high-throughput, low-polarization, high-uniformity, in the 350-1700 nm spectral range), Advanced infrared photodetectors (thermal sensitivity 0.2 degrees), high-resolution visible camera (used for science, optical navigation, and Autonomous Navigation demonstration), and micro-seismometers.

Objectives	Observations	Measurements	Architecture
Determine surface mechanical properties	Soil competence, granularity at all scales, gravity	High resolution imaging, gradiometer, mechanical tester	Reconnaissance with orbiter, track rover's motion and interaction with dust
Search for in-situ resources	Chemical and mineralogical composition	NIR, GRAND, APXS	Remote sensing from orbiter, in-situ characterization at selected sites
Characterize risk and search for mitigation approaches	Waves and fields (e.g., electrostatic field), dust dynamics	UV imaging, high-res imaging	In situ
Understand and simulate human activities in low-gravity environment	Simulate digging, sampling	Performance	In situ

Figure 4. Science objectives at NEOs.

THEME	MEASUREMENTS	OPPORTUNITY FOR CUBESAT/SMALLSAT	INSTRUMENTS
Building New Worlds	Isotopic, elemental, mineralogical composition	In situ, extreme environments	APXS, TLS, IR Spec, Submm Spec, UV Spec, Gamma Ray/ NeutronSpec, Dust Spec, MassSpec
		Returned sample (small bodies)	Sample Return Capsule (possibly Acquisition as well)
Planetary Habitats Ocean Worlds	Composition (volatiles, organics) endogenic activity, heat budget, environment	In situ	MassSpec, Micro-XRF, Imaging, IR Spec, Seismometer, heat probe, radar
Processes	Atmospheric structure, fields, plasma, dust	Close proximity, in situ, multiple data points	Imaging, IR Spec, Mag, Transponders, Langmuir probes, Mass Spec, TLS, Plasma Spec.
Human Exploration	Dust, fields, radiations, Gravity field, orbital properties Regolith mechanical properties ISRU (composition)	Close proximity, in situ, risky environments	Dust Counter, Neutron, Geophysics Inst., IR Spec, APXS, Transponders, radiations spec, Surface perturbation, radar, seismometer

Color code: Green = exists; Blue = in development; Red = does not exist yet

Figure 5. Decadal Science [7] mapping and instrument availability

4. E-GLIDER PHYSICS

The E-Glider charging is maintained through continuous charge emissions of either electrons or ions, depending on the desired polarity to achieve a repulsive force with the local asteroid surface E-field. Therefore, we need to consider the interaction with the plasma. In a plasma environment, an oppositely charged sheath forms about a charged space object. The electron Debye Length is defined as:

$$\lambda_D = \sqrt{\frac{\epsilon_0 k T_e}{n_e e^2}}, \quad (1)$$

Assuming the object's potential is small compared to the plasma temperature, the potential about a sphere drops off as:

$$\Phi(r) = \frac{V_A R_A}{r} e^{-(r-R_A)/\lambda_D}. \quad (2)$$

If the spacecraft potential is large compared to the ambient plasma temperature, then the Debye length can be several times larger [33]. The E-field is the gradient of the potential, and is about a sphere as expressed as [33,34]:

$$E(r) = -\nabla_r \Phi(r) = \frac{V_A R_A}{r^2} e^{-(r-R_A)/\lambda_D} \left(1 + \frac{r}{\lambda_D}\right) \quad (3)$$

The Debye Shielding increases the local gradient of the potential, and thus can increase the capacitance of the surface. This can yield a strong E field, thus force, near a surface, but at some distance the shielding dominates:

$$F = \frac{V_A R_A q_B}{d^2} e^{-(d-R_A)/\lambda_D} \left(1 + \frac{d}{\lambda_D}\right) \quad (4)$$

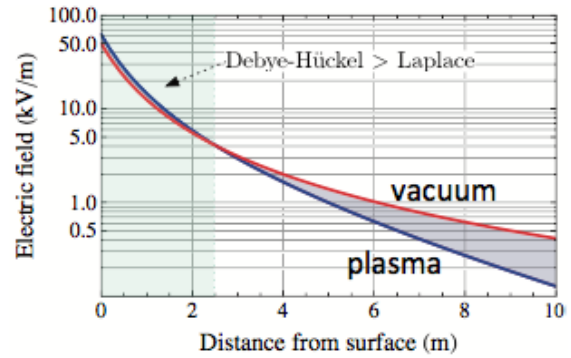


Figure 6. Electric field on 1 meter diameter sphere with 4 meter Debye length [35].

[2] shows that electric fields of E~100-300 kV/m could take place on Itokawa, and Figure 3 shows expected Itokawa surface E-fields around 5-50V/m. As a comparison, an electric field of E=-10 V/m has been measured on the surface of the Moon under full Sun's illumination. Therefore a wide range of E has been considered in this study.

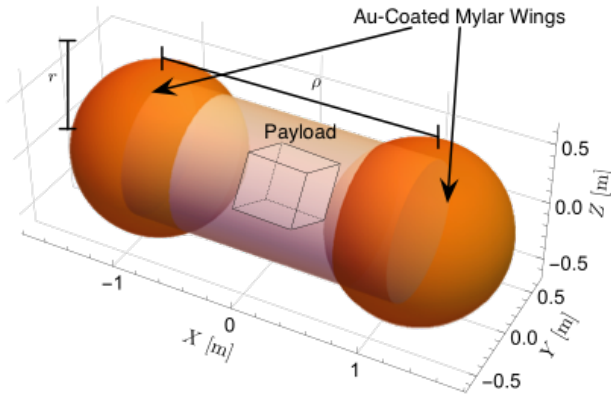


Figure 7. Electrostatic lifting capability as a function of wing radius.

A simplified E-Glider model is shown in Figure 7 where r is the Au-coated Mylar wing radius, and ρ is the center to center separation. Here $\rho = 2r + 0.5m$ is used to allow for a payload between the Mylar wings. Using the Multi-Sphere-Method (MSM) [4] assuming 2 charged spheres, the self-capacitance is given by

$$C_s = 4\pi\epsilon_0 \frac{2r\rho}{r+\rho} \quad (5)$$

where ϵ_0 is the permittivity of vacuum. To estimate the Debye sheath modified capacitance about a sphere or radius is approximated by [33]

$$C = 4\pi\epsilon_0 r_{eff} \left(1 + \frac{r_{eff}}{\lambda_D}\right) \quad (6)$$

where λ_D is the effective Debye sheath. The plasma shield increases the objects capacitance, but will also partially shield the E-field experienced due to a neighboring charged object. The effective radius of the single-sphere representation is found using

$$r_{eff} = \frac{C_s}{4\pi\epsilon_0} \quad (7)$$

The Debye sheath reduced local E-Field is obtained assuming E_0 is the surface E-field of a locally flat plate (good assumption is asteroid is much larger the E-Glider), and the sheath causes an exponential E-field drop [34]

$$E(h) = E_0 e^{-h/\lambda_D} \quad (8)$$

where h is the height above the asteroid surface. In this study this is set to $h = r + 1m$ to cause the E-Glider to have a 1 meter height above the surface, regardless of the Mylar wing size. Finally, let ϕ be the Glider potential that is maintained through active charge emission. A rough order of magnitude mass estimate that can be levitated is given by

$$m = \frac{C(r) \phi E(r)}{g} \quad (9)$$

The local gravitational acceleration level of $g=10\text{-}5 \text{ m/s}^2$ is typical of asteroids such as Itokawa.

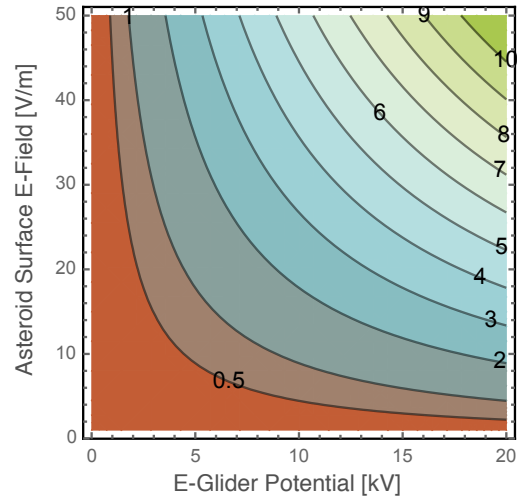


Figure 8. Levitated mass estimates in kg assuming massless Mylar wings of radius 1m, an effective Debye length of 2.5 meters.

The resulting rough estimates of levitated masses are shown in Figure 8 assuming an effective Debye length of 2.5 meters. If the asteroid surface E-fields are low around 5V/m, it would take about 19kV to levitate 1kg of mass. In contrasts, considering the terminator regions shown in Figure 3 with 50V/m of E-fields, the 1kg mass can be levitated using only 2kV.

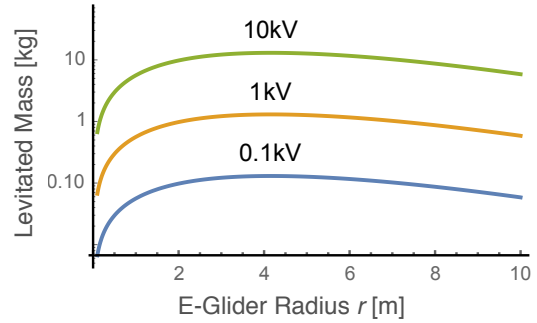


Figure 9. Levitated mass estimates considering a range of wing radii and, an effective Debye length of 2.5 meters.

Next the impact of the wing radius is investigated. Figure 9 illustrates the levitated mass estimates of three E-Glider potential levels. As the wing radius increases, so does its capacitance, and levitated mass becomes larger. However, as an increase wing radius requires the Glider to hover further from the surface, the local E field is reduced exponentially through the Debye sheath. As a result, Figure 9 illustrates that there are optimal wing sizes that provide the largest payload mass for a given E-Glider potential. Note that these results assume a fixed local gravitational acceleration value. Naturally, as the asteroid shape is non-spherical, the g values will vary across the surface. The rough order of magnitude mass levitation estimates are performed making several strong assumptions and simplifications. However, the resulting values look promising as only kV levels of charge are required. Such

charging potentials are commonly achieved on GEO and deep space objects with their natural interaction with the space weather.

5. E-GLIDER SYSTEM CONCEPT

The wings could be made of very thin charged Mylar film, or long charged Mylar strands, which are electrostatically inflated, like in the Earth's Gossamer spiderwebs, as demonstrated in Figure 10 taken from [21,22,23], and would enable lift via electrostatic repulsion. Since the E-glider follows the Sun illumination, the solar panels on the vehicle constantly charge a battery. Due to differential charging of the exposed and shielded sides of the vehicle chassis, which has one side exposed to the Sun's UV photons, and another side shielded from the UV photon exposure [8], electron emitter arrays discharge electrons from the surface on the shielded side when a voltage difference in excess of a threshold voltage develops between a field emission array gate and the emitter array. The emitted electrons are used to selectively and differentially charge the various surfaces of the glider to match the ambient electrostatic charge level, so that the E-Glider can acquire a specific force/moment distribution to enable the glide, and follow a planned path. Figure 11 shows a CAD model depicting a preliminary design of the E-Glider.

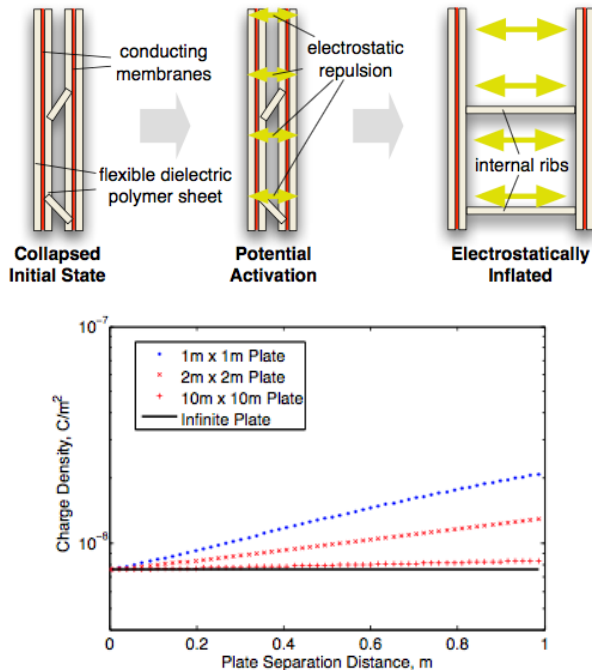


Figure 10. (top) sample open-ended membrane rib structure undergoing electrostatic inflation [22]. (bottom) charge density required to inflate a shell in GEO [22].

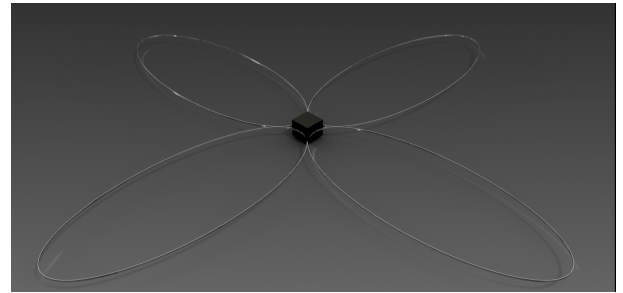
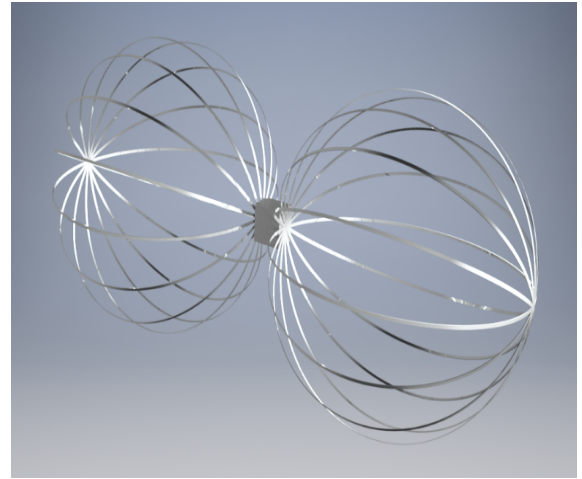


Figure 11. Preliminary CAD models of E-Glider system design.

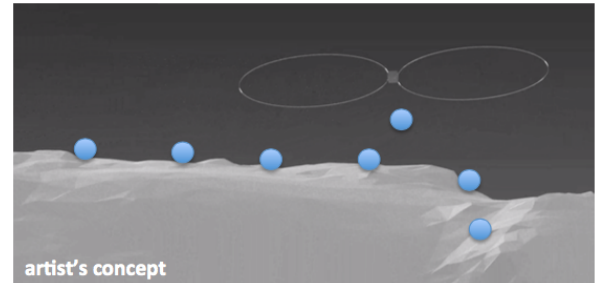


Figure 12. E-Glider as mothership.

In addition to carrying onboard science instruments, the E-Glider could also serve as a mothership for small rovers that could be ejected from the E-Glider and used for in-situ analysis of the body surface, as shown in Figure 12. For small bodies, the force of gravity is nearly negligible, preventing the use of wheeled or hopping mechanisms for locomotion. A soft, deformable rover, however, may be able to roll around the surface through deformation of the rover body via electroactive polymers and controllable adhesion to the surface via electrostatic attraction. Figure 13 shows the principle of “dielectric rolling”, based on bending the shell of the balloon, which acts as a dielectric capacitor. Once there is an offset between the geometric center and the center of “electrostatic pressure”, a torque is possible. Certain electroactive polymers have been shown to work in space-like conditions, including under vacuum and down to

-100 °C, as shown in Table 1 [5]. Each rover would be covered in patches of actuators made of dielectric elastomers. The rover would be inflated pneumatically to a small initial positive pressure to provide a spherical shape. Actuation of the dielectric elastomer patches that are in proximity or in contact with the surface of the body would cause the patches to expand outward, pushing against the surface of the body and causing the rover to roll. In the case of negligible gravity, the skin of the rover could be biased electrically such that the side of the rover that is in contact with the surface could be charged to the opposite polarity of the surface, enabling electrostatic attraction and allowing the rover to roll along the surface of the body.

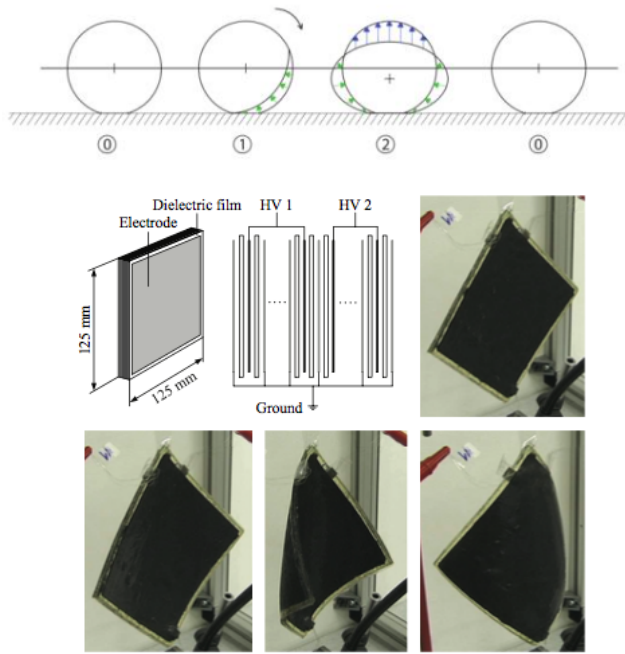


Figure 13. (top) Principle of “dielectric rolling”.
(bottom) Bending of dielectric shell [41].

Table 1. Environmental compliance of tested EAP materials [5].

Material	Elastic down to -100 °C ¹⁾	Elastic down to -40 °C	Temperature dependence of mechanical properties	Temperature dependence of electric properties	Outgassing properties: TML ₉₀ < 1%	Withstand cooling to -150 °C
TC5005	x	✓	weak ²⁾	strong ²⁾	x	x
E625	x	✓	weak ²⁾	weak ²⁾	x	✓
LR3162	x	✓	weak ²⁾	weak ²⁾	✓	✓ ⁵⁾
RTV567	✓	✓	weak ³⁾	weak ³⁾	✓	✓

6. METHODS FOR CHARGING THE E-GLIDER

The overall concept for the E-Glider is to develop a small vehicle/structure that can be charged relative to an asteroid and the resulting electric field differences used to maneuver the object over the immediate surface of the asteroid. A primary requirement for accomplishing this is to be able to control the charge on the object and indeed manipulate the differential potential on its surfaces to allow not only movement over the asteroid but the ability to orient the structure relative to the surface. To do this, the E-Glider must be able to both generate charge and alter that charge in real time on its surfaces. The following briefly reviews and evaluates several possible methods that might be considered for accomplishing this.

METHOD 1: CHARGE EJECTION. A standard method for charging/discharging spacecraft is by emitting beams of electrons or positively charged ions. Indeed, the ability to emit neutral beams of ions has been highly developed and is now used for electric propulsion for missions like Deep Space One and Dawn. Typically atomic species such as argon or xenon are ionized and accelerated by high voltage electric fields to provide low thrust but high efficiency propulsion. The emission of only positive ions, however, typically leads to high negative potentials (~kV's) on the emitting vehicle equivalent to the potential on the accelerating grids. Similarly, electron beams can be used to emit negative charge causing the vehicle to go negative. The grounding scheme for the vehicle, the local magnetic or electric fields, or even physical shadowing can all affect the returning beam particles so that isolated (electrically) surfaces can become differentially charged. Given the complex return patterns and resulting differential charging, mono-energetic beams are usually not used to control charging unless the body is totally conducting in which case the absolute potential can be adjusted in real time to the desired level. Instead, the ejected beam is usually “neutralized” in the case of an ion beam by emitting low energy electrons to keep the absolute vehicle potentials as low as possible. Thus while electron and ion beams can be used to control potential on electrically isolated spacecraft surfaces, it is difficult to determine the detailed charging of the overall vehicle accurately given the uncertain return current pathways. Also the systems for generating ion beams in particular can be relatively cumbersome compared to the E-Glider.

METHOD 2: ELECTRON FIELD EMISSION DEVICES. A method that has seen some utilization in controlling surface charging is that associated with electron field emission devices. An example would be a surface consisting of a layer of very small carbide or similar cones etched into the surface. A negative potential on the surface will cause the points to freely emit electrons thereby driving the surface positive. Such devices are available but currently are limited to negative charge emission. They are also typically low potential devices, though they could be used to mimic photoelectron emission currents on shadowed surfaces. The electron emitters would need to be hard mounted on or electrically coupled to the surfaces to be

charged. Though typically requiring a power source to actively emit electrons and charge a surface positive, various designers have proposed using such surface emitter in a passive mode to discharge negative surfaces.

METHOD 3: MATERIAL SELECTION. Though very much a function of the ambient environment, spacecraft surface materials all have unique photoemission, back scatter, and secondary emission properties. Several well know materials for example emit many times more electrons at very low energies (e.g., ITO coatings) then impact the surface so that the surface will stay near zero potential. Some materials are profuse photoelectron emitters and will drive surfaces positive (~ 10 V) in sunlight. Other materials such as aluminum actually emit few secondary electrons and will charge negatively when impacted by electrons. By the selective choice of surface materials (and/or perhaps interchangeable surfaces), surfaces could be designed to charge to different potentials in the solar wind, when exposed to sunlight, in the asteroid plasma wake, etc. Although basically a passive process, this method of generating differential charging is very dependent on the ambient environment as the sunlight, impacting electrons, and solar wind plasma would be highly variable. In addition, the asteroid would provide a highly variable shield to sunlight and plasma and would have a varying plasmasheth.

METHOD 4: DIRECT BIASING. Differential potentials can be induced on electrically isolate surfaces relative to the spacecraft bus by using active sources to bias the different surfaces. This biasing can be accomplished by batteries/solar cells or by a compact Van De Graff generator. Batteries/solar cells have the advantage of passive components though energy storage needs to be carefully considered. A compact Van De Graff generator could be adapted to produce high surface potentials but would require moving components (and their resulting torques) such as a small electric motor and the static charging method (moving belt, spinning parallel plates, etc.). Similarly, it would need to be continually powered by a battery or solar cell.

In summary, surfaces in space will naturally charge differentially relative to each other in the space environment based on differences in surface materials and exposure conditions. These are typically very low levels (<100 V) and will vary rapidly with the changes in the space environment. Several methods offer the capability to actively charge isolated spacecraft surfaces. All have drawbacks ranging from mechanical complexity (the Van De Graff) to size/power (ion beams). Further, any system will need to be able to rapidly detect the ambient electric field environment and respond appropriately. Of the methods discussed, the simple Van De Graff approach may prove the most reliable. Issues still remain, however, as to the details of the electric fields generated and the effects of return currents and photoemission on surface potential variations. Finally, the sheath of the E-Glider and its interaction with the asteroid's plasma sheath will need to be carefully modeled in real time to allow rapid changes in the E-Glider's surface fields. The latter is a complex but doable

problem given current computing power and available plasma models such as NASCAP-2K.

7. APPROACHES FOR DIFFERENTIAL SURFACE CHARGING

For small bodies in the interplanetary environment, the main source of surface charging is the Solar Wind plasma and sunlight. Typically surfaces in sunlight are dominated by photoelectron emission currents so that the typical potentials are on the order of ~ 10 V positive. Given the expected shadowing of the flowing Solar Wind plasma and the insulating nature of the asteroidal material, the plasma wake of asteroid is expected to be largely devoid of Solar Wind plasma leading to differential surface potential variations around the asteroid. The wake region can, in the absence of the Solar Wind plasma, charge negatively with values of -100 V having been observed on shadowed spacecraft surfaces (note: some simulations imply that potentials as high as -1000 V may be possible, however). The sunlight and Solar wind, however, can cause charge neutralization within a fraction of a second on exposed spacecraft surfaces. It will be the same or worse around an asteroid with higher plasma densities expected close to the asteroid and a complex terminator and wake region in the anti-sunward direction. As a result the E-Glider electrostatic inflation and levitation concept will have to provide continual charge emission to control the spacecraft potential relative to the space environment and asteroid. Here we will describe the characteristics of that charge control system and how the differential charging will be modeled.

Any charge control system will need to maintain the absolute potential of the spacecraft relative to the asteroid to control levitation and be able to generate differential potentials to control attitude. The former can be accomplished by using combinations of small electron (to bias the vehicle positive) or ion (to bias the vehicle negative) current emitting systems such as provided by ion engines or electron beams (more recently electron-emitting surfaces have become available that may also be an option). The large, differential potentials required for attitude control may be produced by a small Van De Graff generator or by battery/solar cell power bias sources. In any case, the complex interactions of these active charge control systems with the ambient plasma and the E-Glider will need to be modeled in real time. Previous work at JPL on the plasma dynamics of a 150 m solar sail [38] studied the charging characteristics of large bodies in the Solar Wind and is applicable to the E-Glider concept. To do this, the spacecraft charging analysis program NASCAP-2K was used to model differential potentials of many tens of volts across the thickness of the solar sail membrane and its insulating back in the Solar Wind environments. NASCAP-2K [39,40] is a widely used interactive toolkit for studying such plasma interactions with realistic bodies in three dimensions. It can model interactions that occur in tenuous and in dense plasma environments. Capabilities include surface charging in geosynchronous and interplanetary

orbits and sheath and wake structures. The JPL/NASA Nascap-2k study results demonstrated that the complex charging interactions and differential charging of a large body (a solar sail) and a small spacecraft can be readily modeled. In addition to NASCAP-2K, the Immersed-Finite-Element PIC (IFE-PIC) algorithm [37] has been developed which allows the modeling of the effects of differential charging on dust particles in space. Using the IFE-PIC algorithm, recent work [37] has investigated the numerical modeling of dust dynamics around small asteroidal bodies. In that work, a numerical investigation on the charged dust distribution around small spherical asteroids with the implementation of a 3D IFE-PIC plasma-asteroid interaction model and a 3D dust transport model was conducted. In all simulation cases analyzed, charged dust was observed to tend to migrate toward the dayside at high altitudes, with the exception of the ultra fine grain case. Near the surface, there is a preference to gravitate towards the dayside. At large altitudes, gravity would appear to be the dominant player in dust transport, while the electric field has a strong influence on dust dynamics at low altitudes. An increase in the electrostatic force would be more efficient at perturbing the density profile between the low and high altitude. For smaller grains, solar radiation pressure may have a greater role on dynamics around an asteroid. Figure 14 shows a representative electrostatic field distribution around a spherical asteroidal body applicable to the current study.

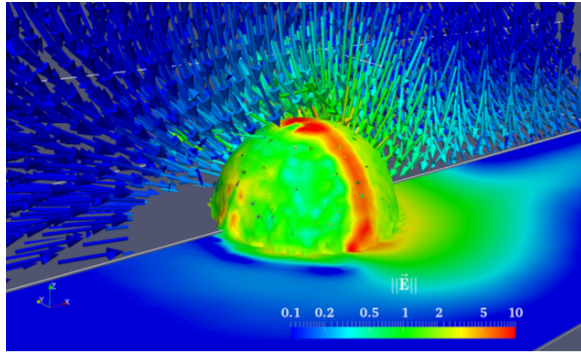


Figure 14. Electrostatic vector field around spherical asteroidal body, from [Yu, Wang, Han, 2015].

To summarize, an E-Glider will need to actively control its differential and absolute potentials. Mechanisms exist for producing charged beams and differential surface potentials. While challenging perhaps to fit into the expected E-Glider mass and power constraints of a Cubesat-like spacecraft, the real problem will be to calculate the detailed electric fields produced by these systems in real time. To date various spacecraft charging models have been developed that allow detailed estimates of the induced differential potentials (Nascap-2k) and the charged dust environment (IFE-PIC) around an asteroid and the spacecraft. Thus the technical elements necessary to develop and control differential charging in principle exist though their capability to work together in real time is still to be demonstrated.

8. APPROACHES FOR AUTONOMY

Figure 15 shows a functional block diagram of the E-Glider autonomy functions. Through an array of Langmuir probes, which measure the spatial distribution of the charges surrounding the vehicle, an “electrostatic map” is thus generated. Once the electric potential has been mapped, the E-glider is able to use this “electrostatic topographic map” for path planning and navigation. Further articulation at the root of the lateral strands or inflated membrane wings, would generate a component of lift depending on the articulation angle, hence a selective maneuvering capability which, to all effects, would lead to electrostatic (rather than aerodynamic) flight. A potential field approach to path planning for navigation [16,29,30,31] is one candidate to be explored, see Figure 16. The autonomy aspects of guidance, estimation, and control, will be investigated by introducing the possibility of optimizing the trajectory of the E-Glider to a desired science target [30,31, while simultaneously the E-Glider tracks the Sun, communicates with the Earth, and optimally re-allocates control commands to the wings for flight maneuvering. Figure 17 shows a proposed algorithm to estimate the E-Glider electrostatic cartographic map. Once measured by Langmuir probes, the charges are compared to the estimated charges from an on-board model (see Figure 12). The map is the result of the differentials between the model and the measurements, which is continuously updated in flight.

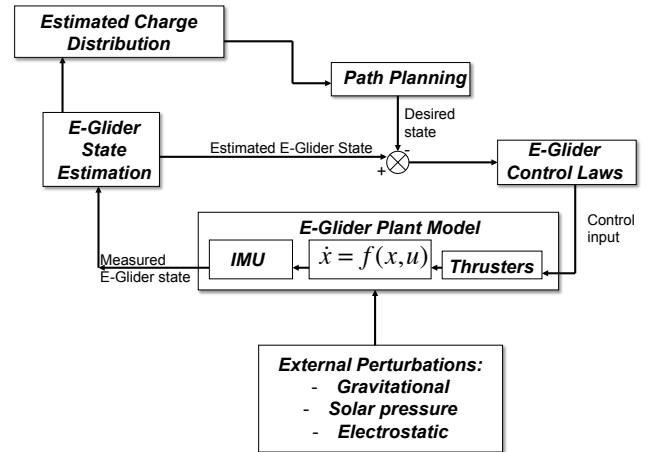


Figure 15. Block diagram of E-Glider autonomy.

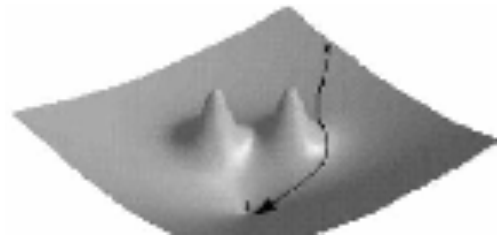


Figure 16. Navigating a potential field distribution.

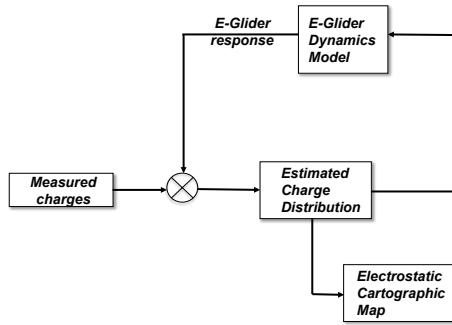


Figure 17. E-Glider scheme for electrostatic cartographic map generation.

9. TESTING APPROACHES

Tests will be needed to verify that the E-Glider wings can indeed inflate and levitate the vehicle. These tests will have to be done in air first, then in vacuum. Small scale inflation tests were already done by one of the authors in [21,22,23]. Figure 18 shows the results of test of electrostatic inflation, from [21]. The test setup consists of an aluminized Mylar ribbed sandwich structure resting on a conducting surface, which is connected to a high voltage power source. In this 1-g test environment, the normal force of the object upon which it rests always balances the forces on the lower plate. The other plate is subjected to the Coulomb force to inflate, the compressive force of gravity, and tension in the ribs to hold the structure together. The structure used in the test shown in Figure 18 consists of two 12x15 cm plates of 75 gauge aluminized Mylar. Three ribs of the aluminized Mylar connect the two plates. Charge was applied to the conducting sphere on which the sandwich structure rested. In the sandwich structure inflation experiment, inflation occurred between 7 and 13 kV. Figure 18 shows snapshots of the charging experiment. The duration of the inflation shown between the first and last frames of Figure 18 is approximately 5 seconds. This experiment clearly shows how a collapsed sandwich membrane structure can be inflated with kilo-Volt levels of potential. It should be noted here that the rib structures were simply glued to the outer membrane plates. This results in some bending stiffness of the ribs that is not accounted for in the earlier models. Despite these challenges, the experiments indicate that such self-supporting membrane structures can repeatedly and reliably be electrostatically inflated in a laboratory environment. Higher fidelity modeling of such lightweight structures is very challenging due to the strong nonlinear coupling between charge distribution and membrane shape. Adding the plasma space environment complicates the matter even further. Such experimental results are critical to explore experimentally appropriate material properties, construction methods, packing methods, and charging behaviors that lead to desirable membrane motions. Further, such testing would be used for validation and verification purposes to be developed higher fidelity modeling of charged membrane

structures. Figure 18 shows the inflation of a gossamer ribbon structure, an example of a structure with large open surface segments. This ribbon structure was initially compacted to height of approximately 2 cm, then inflated to a height of 25 cm. The experiment shows the potential of high deployed-to-stowed volume ratios with the electrostatic inflation concept. Notice in this photo series that the structure has obtained the fully inflated shape at 5 kV, yet gravity is preventing the structure from standing upright. As the voltage increases to 9 kV, the electrostatic repulsion between the ribbon structure and the conducting surface to which it is attached cause the entire structure to become upright as well as inflated to the desired shape.

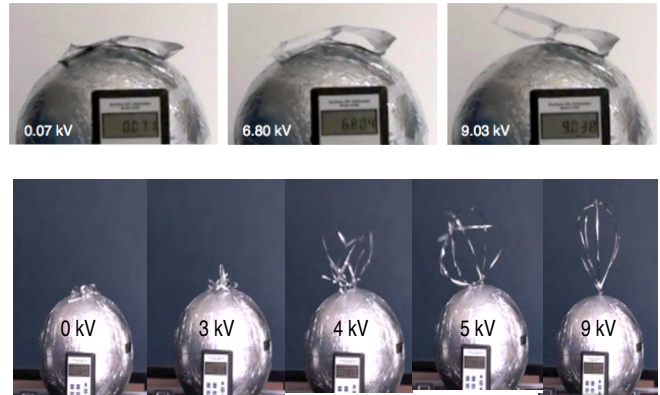


Figure 18. Test of electrostatic inflation [21].

The large vacuum bell jar at JPL is a possible experimental facility to conduct larger scale tests. This facility (Figure 19) has an inside diameter of 72.13 inches, is 78.00 inches high at the center, and is made of 1.250 inches thick acrylic plastic that is both RF and optically transparent. The entire facility is enclosed in an RF shielded room, including a control room and a 15 ft x 15 ft RF anechoic chamber around the bell jar. The vacuum system operates from normal atmospheric pressure to 2×10^{-5} torr at room temperature, with local chilling possible using LN₂ and/or local heating possible using a heat-plate inside the bell jar. It includes a 52,000 liter per second oil diffusion pump, liquid nitrogen chilled chevron baffle cold trap, mechanical pumps, blower and high vacuum valves. The facility has supported the testing of spacecraft antenna system hardware since 1968. It has also supported the German HELIOS project and other NASA and non-NASA programs. Power monitoring and data logging is computer automated. The system is certified for flight hardware tests.

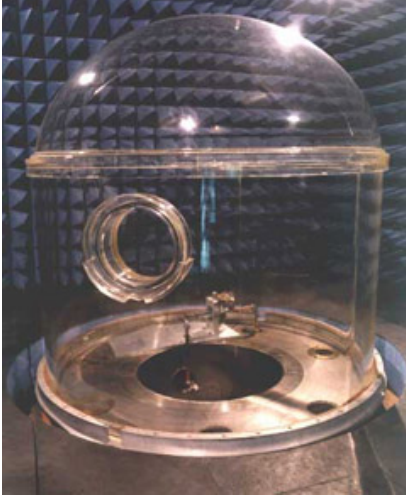


Figure 19. Vacuum bell jar at JPL.

10. MODELING AND SIMULATION RESULTS

In this section restrictive assumptions have been used for the current models being used for simulation. The goal of the simulation studies was to investigate how prototypical hoop structures could be considered for levitation. Potential theory has been used to model the interaction. First, the bodies are modeled as rigid bodies under spherical gravity and spherical distribution of charge. Second, no intervening plasma electric field is included. Third, the charge of the body is set to be equal the charge of the hoop. The latter is a very strong assumption and decouples these results from the direct asteroid application. However, they do provide insight on how the E fields behave about hoops because the wings of the E-Glider can be modeled as hoops, at least to a first approximation. The hoop is aligned so that it is normal to the body. In the case of the hoop, the analytical expression of the potential that can be found in [36] was used, and it is:

$$V = \frac{2\kappa^2 M}{\pi} \int_0^{\frac{\pi}{2}} \frac{d\omega}{\sqrt{\rho_1^2 \cos^2 \omega + \rho_2^2 \sin^2 \omega}} \quad (6)$$

where κ^2 is the gravitational constant, M is the mass of the glider, ρ_1 and ρ_2 are the distances from the opposite edges to the body, and ω is the angle between the line between points 1 and 2 and any test point along the hoop. When the hoop is aligned to be normal to the body at a distance of ρ_a , the potential simplifies to:

$$V_a = \frac{\kappa^2 M}{\rho_a} \quad (7)$$

and the force is then given by:

$$F = -\frac{\kappa^2 M_{hoop} M_{body}}{\rho_a^2}$$

(8)

A similar approach can be used to find the electrostatic potential and forces by replacing the gravitational constant and masses with Coulomb's constant and charges. We find that, for a 1 cm tall, 1 m diameter, 500 μm thick hoop, the equilibrium charge is $\sim 22 \mu\text{C}$. With an additional payload mass of 10 kg, a 20 m diameter hoop that begins at 10 m above the surface needs a little less than 55 μC of charge to hover. These calculations are important, since once we know the charge required to levitate, we can compute the power needed to deliver that charge. Figure 20 shows the total force on the hoop and the equilibrium value of forces required for levitation. Figure 21 shows the trajectory of the levitated hoop as a function of charge, and Figure 22 shows the same trajectories as a function of initial altitude. Figure 23 shows the total force on the levitated hoop as function of charge, size, and distance from surface. These plots are the result of a sensitivity study that was conducted to gain insight into the influence of various parameters affecting the behavior of the E-Glider in the relevant environment at an airless body.

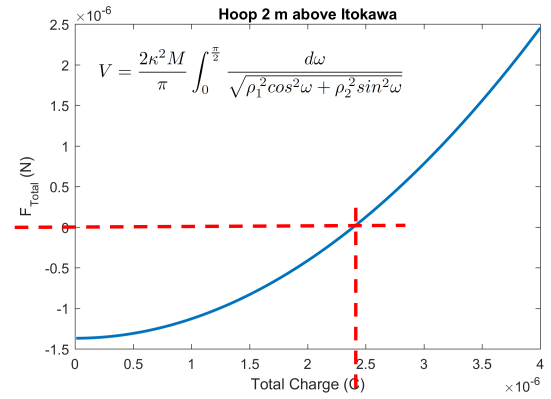


Figure 20. Total force on hoop and equilibrium value for levitation.

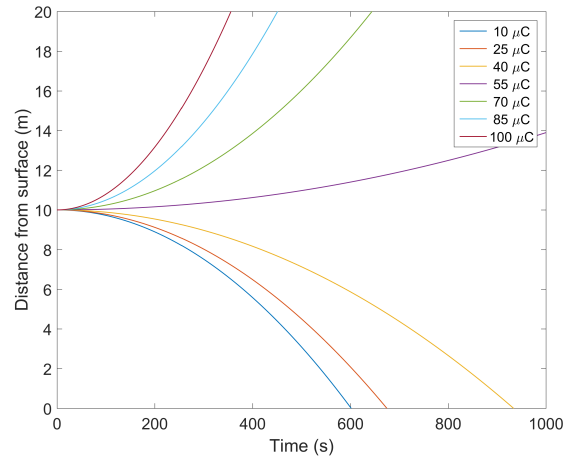


Figure 21. Trajectory of levitated hoop as function of charge.

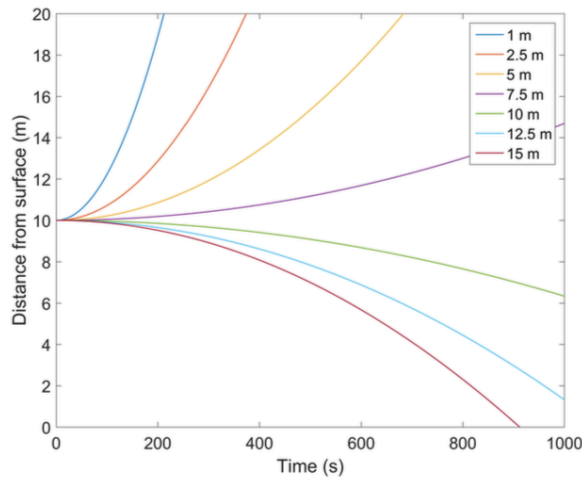


Figure 22. Simulation results for levitated hoop.

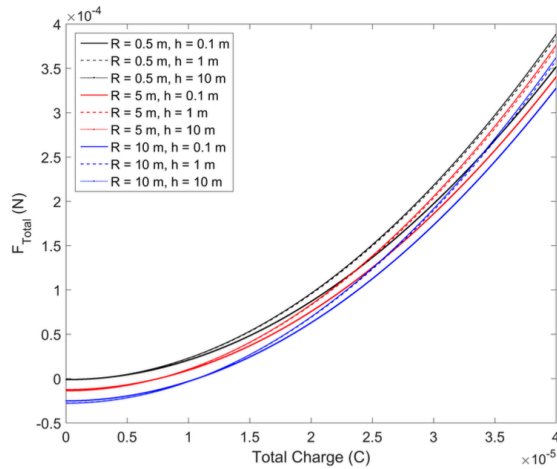


Figure 23. Total force on levitated hoop as function of charge, size, and distance from surface.

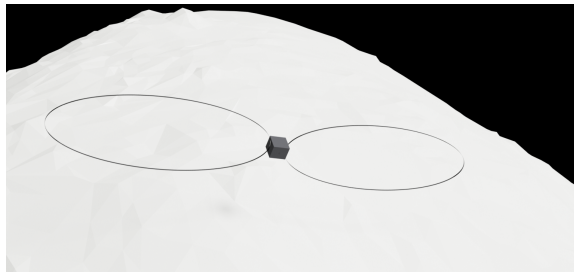


Figure 24. Implementation of E-Glider CAD model.

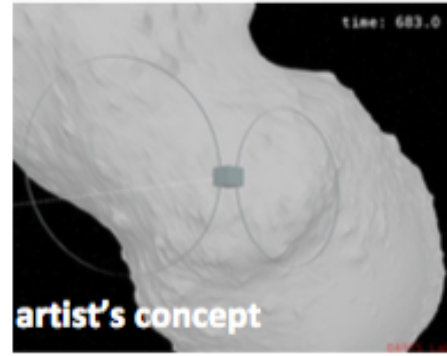


Figure 25. Implementation of E-Glider model in JPL's DSEDS simulator.

Figure 24 shows a CAD model of the E-Glider in flight. JPL has developed the Dynamics Simulator for Entry, Descent and Landing (DSEDS) [3] as a high-fidelity spacecraft simulator for Entry, Descent, and Landing (EDL) on planetary and small astronomical bodies. It is an extension of a core set of software tools (Darts/Dshell) that is capable of modeling the dynamics of complex multi-body systems with flexible nodes. The core tool set is in use for multiple interplanetary and science-craft missions (Cassini, Galileo, SIM, and Starlight). DSEDS has been heavily used by Mars Lander missions to test precision landing and hazard avoidance functions for those missions. High-fidelity, physics-based engineering simulations of a spacecraft interacting with its environment are crucial in the analysis, development, test, validation, and operation of space flight missions. JPL's simulation framework (DSEDS) was developed for the simulation of spacecraft ascent, orbit, deep-space flight, rendezvous, proximity operations, atmospheric Entry, Descent and Landing (EDL), and planetary surface mobility. The DSEDS simulator incorporates physics-based models for articulated multi-body systems with flexible modes, aerodynamics, environments such as the atmosphere and planetary topography, spacecraft devices, and on-board flight guidance, navigation and control. The simulator allows the user to set up multi-spacecraft and mission configurations using elements from a modular library of components and determine the system trajectory and related quantities of interest. Simulation parameters may be selected from a dispersed set to determine variations in trajectories for either Monte-Carlo or parametric analysis. The gravitational model of the asteroid is obtained from a polyhedral model. Figure 25 and Figure 26 show snapshots of the DSEDS simulation of the E-Glider in flight around Itokawa. Figure 27 and Figure 28 show snapshots of the simulation of the trajectory of the E-Glider contacting the surface of the asteroid, and in Figure 28 the rebounds at the surface are clearly visible from the simulation results. While these are only preliminary results, future work will include an extension of these models including the effect of radiation pressure and electrostatic interactions, with autonomy.



Figure 26. Implementation of E-Glider model in JPL's DSEDS simulator.

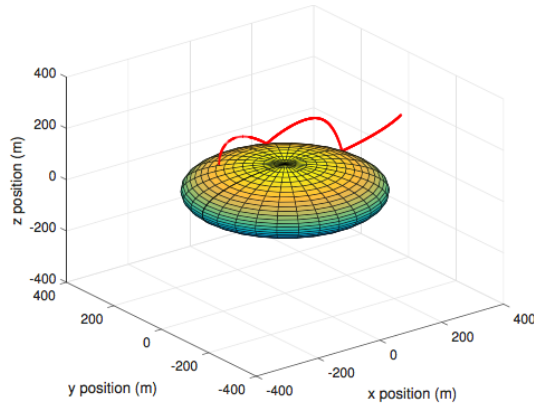


Figure 27. Trajectory of point mass during drop on Itokawa surface.

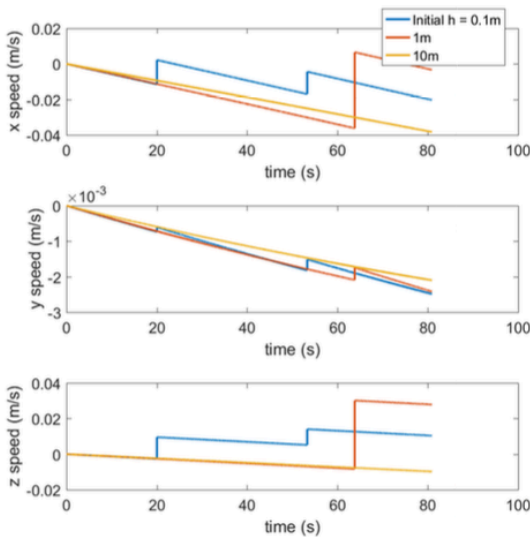


Figure 28. Trajectory of point mass during drop on Itokawa surface.

11. SUMMARY

Exploration of comets, asteroids, moons and planetary bodies is limited by mobility on those bodies. The

E-Glider concept directly addresses the "All Access Mobility" Challenge, one of the NASA's Space Technology Grand Challenges, specifically aimed at enabling robotic operations and mobility, in the most extreme environments of our solar system. In our work to date, we have: a) started to gain insight into physics of electrostatic levitation in plasma environment; b) explored analytical solutions and investigated critical parameters for levitation under restrictive assumptions; c) designed 3D CAD model of E-Glider; d) implemented an E-Glider simulation in DSEDS to investigate dynamics in non-spherical micro-gravity; e) identified what type of science investigations E-glider could perform; f) introduced an approach for autonomy. Future work will include: further developing the simulation model, refining the E-Glider system design, improving the levitation model with plasma physics, continuing the analytical studies to gain insight in the engineering behavior, developing approaches for path-planning and navigation, and conceiving plans to build and test a prototype at a later phase of the project.

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BIOGRAPHY

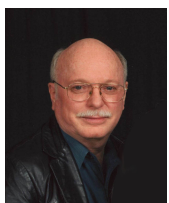


Marco Quadrelli is an internationally renowned expert in modeling for dynamics and control of complex space systems. He has a Masters Degree in Aeronautics and Astronautics from MIT and a PhD in Aerospace Engineering from Georgia Tech. He was a visiting scientist at the Harvard-Smithsonian Center for Astrophysics, and a lecturer at the Caltech Graduate Aeronautical Laboratories. After joining NASA JPL in 1997 he has contributed to a number of flight projects including the Cassini-- Huygens Probe, Deep Space One, the Mars Aerobot Test Program, the Mars Exploration Rovers, the Space Interferometry Mission, the Autonomous Rendezvous Experiment, and the Mars Science Laboratory, among others. He has been the Attitude Control lead of the Jupiter Icy Moons Orbiter Project, and the Integrated Modeling Task Manager for the Laser Interferometer Space Antenna. He has led or participated in several independent research and development projects in the areas of computational micromechanics, dynamics and control of tethered space systems, formation flying, inflatable apertures, hypersonic entry, precision landing, flexible multibody dynamics, guidance, navigation and control of spacecraft swarms, terramechanics, and precision pointing for optical systems. He is an Associate Fellow of the American Institute of Aeronautics and Astronautics, a NASA Institute of Advanced Concepts Fellow, and a Caltech/Keck Institute for Space Studies Fellow.



Hanspeter Schaub is the Alfred T. and Betty E. Look Professor of Engineering at the University of Colorado. He has about 20 years of research experience in aerospace dynamics and control applications, of which 4 years are at Sandia National Laboratories working on the motion estimation, modeling and control of autonomous systems. His research interests are in nonlinear dynamics and control, astrodynamics, relative motion dynamics, as well as relative motion sensing. This has led to about 116 journal and 175 conference publications, as well as a 3rd edition textbook on analytical mechanics of space systems. In the last decade he has developed the emerging field of charged

astrodynamics. He has 15+ years experience with charged spacecraft concepts (free-flying networked nodes, tethered nodes, charged substructures, charge Gossamer structures, etc.), and has published over 50 journal and 72 conference papers in the field of charged spacecraft astrodynamics and is a recognized leader in this field. The University of Colorado has made him the Alfred T. and Betty E. Look Professor of Engineering, awarded him an H. Joseph Smead Fellow, the Provosts Faculty Achievement Award, the faculty assembly award for excellence in teaching, as well as the Outstanding Faculty Advisor Award. In his field, among other appointments, Dr. Schaub has served as an Editor for the AIAA journal of Guidance, Control and Dynamics, is an associate fellow of AIAA and fellow of AAS.



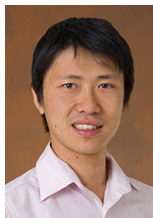
Henry B. Garrett was born on February 15, 1948 in San Francisco, CA. He was raised in Roswell, NM, graduating from Roswell Senior High School in 1966. He received a B.A. degree in physics (phi beta kappa, magna cum laude) in 1970 and M.S. and Ph.D. degrees in space physics and astronomy from Rice University in 1974. He subsequently spent 6 years in the US Air Force before joining the Jet Propulsion Laboratory, California Institute of Technology in 1980. Col. Garrett retired from the Air Force Reserves after 30 years in 2002. He is currently a Principal Scientist in the Office of Safety and Mission Success. Dr. Garrett is a Member of AIAA, AGU, and AAS. He has published 4 books and has over 135 publications in the areas of space environments and their effects on space systems.



Adrian Stoica has thirty years of R&D experience in autonomous systems, developing novel adaptive, learning and evolvable hardware techniques and embedding them into electronics and intelligent information systems, for applications ranging from measurement equipment to space avionics to robotics. He has done pioneering work in humanoid robot learning by imitation, hardware security including anti-tamper, brain-computer interfaces including multi-brain fusion for joint decision making, shadow biometrics, shape-changing robots, human-oriented robotics. He is a member of the board of Governors of IEEE Systems, Man, and Cybernetics Society (since 2015). He founded 3 conferences: NASA/ESA Conference on Adaptive Hardware and Systems (AHS, since 1999), Emerging Security Technologies (since 2006) and the AT-EQUAL series (Advanced Technologies for Enhanced Quality of Life) which included the HUMASCEND conference (Human-Machine Systems, Cyborgs and Enhancing Devices 2011-2014). NIAC Fellow: 2013, 2015.



Julie Castillo-Rogez is a planetary scientist specializing in water-rich objects from a modeling and experimental perspectives applied to the formulation, design, and planning of planetary missions. Her current activities focus on Ceres, target of the Dawn mission, Mars' moons in the frame of the Human exploration program, and small asteroids as science principal investigator for the Near Earth Asteroid Scout CubeSat mission.



Masahiro Ono is a Research Technologist in the Robotic Controls and Estimation Group. He is particularly interested in risk-sensitive planning/control that enables unmanned probes to reliably operate in highly uncertain environments. His technical expertise includes optimization, path planning, robust and optimal control, state estimation, and automated planning and scheduling.



Caleb Christianson is a PhD student in the Bioinspired Robotics and Design Lab at the University of California, San Diego. He received his MS in nanoengineering in 2015 from UC San Diego and his BS in engineering physics in 2014 from the University of Kansas. He has co-authored 12 journal and conference publications on robotics, superconductors, and nanomaterials. As an intern at JPL, he was involved in simulating and modeling the electrostatic and gravitational forces on the E-Glider.



Dario Lusso is a graduate student in Mechatronic Engineering at Politecnico di Torino. As an intern at JPL, he was involved in simulating and modeling the electrostatic and gravitational forces on the E-Glider.