Gravity-Independent Locomotion: Potential Approaches to Robotic Mobility on Asteroid Surfaces

Edward Tunstel, *Senior Member, IEEE* and Luther R. Palmer III, *Member, IEEE*

Abstract—**Robotic mobility solutions are deemed important for traversing small bodies in our solar system such as asteroids and small moons to enable their comprehensive *in situ* exploration. This paper discusses the issue of robotic mobility on asteroid surfaces and provides surveyed coverage of concepts focused on controlled mobility on surfaces in weak gravitational fields. Feasibility and potentially viable approaches are discussed while drawing attention to developments in robot locomotion for applications on Earth that may be brought to bear on the problem. A selection of promising mobility concepts recently proposed for locomotion on small body surfaces are covered along with various solutions pursued to date for broad surface coverage or global access. Related technical issues and challenges are also highlighted.**

I. INTRODUCTION

EXPLORATION of asteroids, comets, and small moons is of high scientific priority. To date, few missions have been completed that access the surfaces of these bodies or perform extended operations *in situ* such as acquiring measurements up close or deploying mobile science instrument systems for extended periods. This is due in part to the difficulty of locomotion in persistent contact with such bodies in their weak surface gravity regimes, not to mention sparse knowledge of their surface properties.

The NEAR mission [1] to asteroid 433 Eros and the more recent Hayabusa mission [2] to asteroid 25143 Itokawa revealed an apparent diversity among asteroids and their varied surface compositions and complexities. It is generally believed that wheeled mobility on bodies such as these is infeasible due to the difficulty of achieving sustained traction on the surface in the absence of significant normal forces on wheels in microgravity. To the contrary, computer simulation studies predicted the feasibility for wheeled mobility by a nanorover (~400 g mass) on asteroid Nereus (1.6 km diameter, 20 micro-g gravity field) based on wheel-terrain interaction models involving Coulomb friction alone as well as combined friction and adhesive forces [3]. The Japan Aerospace Exploration Agency (JAXA) developed a hopping rover, MINERVA, for the Hayabusa mission that was unfortunately not successfully deployed from the spacecraft to the Itokawa asteroid surface. MINERVA was designed to use a reaction wheel inside a nearly cylindrical body to induce a somewhat random hop motion as an inertial reaction to impulses of the internal reaction wheel [4]. The position of a vehicle of this design after a hop maneuver is very difficult to predict or control, and more precise positioning of its onboard science sensors or instruments may be desired for certain missions. Hopper concepts tend to operate open-loop in the sense that they execute unguided hops to somewhat random destinations subject primarily to passive reactions of the hopper to small body physics. Controlled position of mobile systems that are intended to explore small body surfaces for extended periods is important when the intent is to deliver *in situ* instruments and sampling devices to specific surface locations designated by scientists. In such cases, controlled traversal while maintaining contact with the small body terrain in weak gravity fields is desired. A capability to maintain secure surface contact offers certain independence from gravitational forces, or lack thereof, as a facilitator of controlled locomotion.

This paper discusses issues of robotic mobility on such bodies – its feasibility and potentially viable approaches – while drawing attention to developments in robot locomotion for Earth-based applications that may be brought to bear on the problem. Do mobility concepts exist that are amenable to deliberate control of motion *and* position on small body surfaces as opposed to solutions that may be effective for mobility but less effective for position control due to passive reaction to small body physics? Can finer spatial coverage than expected from hopping locomotion be achieved with small increments in technology development relative to the state of the art? Motivated by a realization that the robotics community at large may be converging toward components of viable solutions in this area, this paper aims to draw attention to such questions and to stimulate discussion. It is organized as follows.

Section II provides motivation and context. Section III discusses current and proposed approaches to rolling and hopping on asteroids while Section IV suggests certain merits and issues associated with crawling and climbing approaches. Section V highlights relevant research being advanced for Earth applications of gravity-independent locomotion that represent components of potential solutions to asteroid surface mobility. Challenges of developing such solutions and how some can be addressed are discussed in Section VI followed by conclusions.

Manuscript received March 7, 2010. This work was supported in part by the Civilian Space Business Area of the Johns Hopkins University Applied Physics Laboratory.

E. Tunstel is with the Space Department at the Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723 USA (+1 240-228-9740; e-mail: edward.tunstel@jhuapl.edu).

L. R. Palmer, III is with the Biomorphic Robotics Lab, Department of Computer Science and Engineering at the University of South Florida, Tampa, FL 33620 USA (e-mail: palmer@cse.usf.edu).

II. MOTIVATION

It is asserted here that the small body surface mobility problem has not been penetrated to appreciable depth by more than a few space roboticists, and that the planetary science community may be settling on the notion that hopping is the only feasible approach in this domain (perhaps as an indirect result). More investigation is warranted. With advances over the last decade in Earth applications of climbing robots (including some that operate upside down and on concrete, brick, and natural surfaces) it is clear that more locomotion approaches may apply for development toward applications where a mobility system must work against minimal gravity on asteroids. A related application domain where recent developments seem to apply is access to steep irregular terrain such as cliffs and crater walls on planet surfaces (e.g., Mars) in which case a mobility system must work against substantial gravity. In both cases the objective is to maintain contact and traversability in order to deliver science instruments or sampling devices to locations of high science interest.

The focus here is on *gravity-independent locomotion* approaches and technologies other than those intended specifically for mobility on space structures or for coarsely-controlled hopping. These are discussed, however, in relation to concepts germane to the focal area of finer controlled mobility on natural surfaces. Landing technologies and deployment of rovers to asteroid surfaces are not addressed here. Most asteroid rover designs proposed to date are intended to survive free-fall deployment from a spacecraft.

The current body of knowledge about the nature of asteroid surfaces and surface gravitational forces leaves much to be desired as a basis for deriving engineering requirements for mobile robots. Some theories use what we know about lunar regolith to postulate that regolith on large asteroids (kilometers in largest dimension) is similar. Less can be said about small asteroids (e.g., Itokawa, 540m x 270m x 210m) relative to larger asteroids (e.g., Eros, 33km x 13km x 13km) except that gravity should dominate surface processes on the latter but not on the former and that the structure of small asteroids tends to resemble rubble piles while that of even smaller asteroids (< 100m) tends to resemble monolithic rocks [5]. Asteroid shapes tend to be irregular and may have correspondingly irregular gravitational fields. Their surfaces are generally believed to contain many craters with rocky, hilly and steep topography possibly blanketed by regolith. Current theories suggest that regolith layers on the largest to smallest asteroids could be kilometers deep to thin or absent [6]. In any case, the weak gravity (micro-g to milli-g) characteristic of all asteroids makes it difficult to achieve normal forces usually required for stable surface locomotion. A means to traverse subject to low ground contact pressure or to cling or stick the surface is needed. Various approaches are discussed below.

III. ROLLING AND HOPPING

The most prevalent mechanisms for planetary rover locomotion have been wheels. Wheels are not an obvious solution for asteroid surface mobility but studies have suggested their viability in certain cases and for rovers with mass less than one kilogram. The study by Baumgartner et al [3] emphasized that the analysis of whether adequate tractive forces can be achieved for rolling mobility depends on the wheel-terrain interaction model employed. Based on separate considerations of Coulomb friction alone and a combined Coulomb friction and adhesive force model (due to cohesion within and electrostatic attraction to a fine layer of regolith), traction sufficient for a JPL nanorover to traverse at 1 cm/sec was shown to be feasible via dynamic simulations (albeit with initial occurrence of front-wheelies and significant wheel slippage).

Concept vehicles have been proposed that provide intermittent walking, rolling, and hopping using a collection of individually actuated prismatic joints oriented radially around a polyhedron or pseudo-sphere. One of these vehicles uses a dodecahedron shape with 12 prismatic leg joints [7]. Another uses an icosahedron shape with 12 prismatic leg joints [8] and for which incorporation of sampling mechanisms has been investigated.

Behar [6] proposed a colony of small robots that would traverse asteroid surfaces while connected to a common net that was anchored to the asteroid. Such architecture was arrived at following dynamic computer simulation studies of hopping and wheeled vehicles. Both types were concluded to be of limited use due to complexity of thruster control for accurate maneuvers and pose estimation for hoppers, and due to difficulty maintaining wheels on the surface when undesired surface reactions led to long periods of ballistic floating before touching down. Robots connected to the physical, anchored net would use wheeled locomotion to traverse along dedicated strands of the net. Hardware experiments with this concept employed Khepera robots.

Hopping is perhaps the simplest means of mobility for reaching discrete patches of asteroid terrain. In concert with a capability for local exploration in continuous contact with the surface, hopping can serve as a long range capability for global asteroid access. To date, the aforementioned MINERVA vehicle is the only asteroid hopping rover fully developed for a space flight mission. It is a ~600g vehicle designed for several asteroid days of autonomous operation involving ballistic hopping with variable hop speed and some control of hop direction depending on its attitude on the surface [4]. Other designs are in development or have been proposed as viable concepts.

A 1.3 kg JPL nanorover was at one point considered a payload for the Hayabusa mission on which MINERVA flew [9, 10]. While it is a wheeled rover, its novel mobility mechanism also enables ballistic hopping as well as a capability to self-right in response to inevitable tumbling in low gravity [11]. The nanorover design would thus provide global and local mobility at 1.5 mm/sec perhaps subject to lesser difficulty, observed by Behar [6], of maintaining wheels on the surface during local rolling mobility.

Another hopping vehicle intended for asteroids is the Asteroid Surface Probe (ASP) developed by Ball Aerospace & Technologies Corporation [12]. Recent designs consist of an 8 kg battery-powered (100 hours) self-righting spherical body of 30 cm diameter that uses thrusters to hop. When stationary, the sphere opens up using 3 petals to expose a science instrument payload. The petals also provide the means to self-right the probe [13]. A similar, in principle, 12 kg thruster-propelled ballistic free-flyer concept designed by DLR as part of a ESA study is described in [14]. Other hopping robots proposed for asteroid exploration include a pyramid-shaped, 533 g prototype with four single degree-of freedom flippers at its base for jumping plus a lever arm for self-righting [15] and a spherical 1 kg robot with internal iron ball actuated by electro-magnets to induce hopping [16].

A recent study comparing wheeled and hopping locomotion in weak gravity and under ideal conditions (e.g., flat terrain and no loss of contact between wheels and terrain) concluded that both modes of are comparable in locomotion speed [17]. A similar conclusion regarding energy consumption was reached in a comparative study of wheeled and hopping rovers for Mars gravity [18].

IV. CRAWLING AND CLIMBING

Viable solutions may exist among locomotion approaches that are more similar to crawling or climbing than rolling or hopping to achieve mobility across asteroid surfaces. Limbed locomotion solutions are obvious alternatives; and nature, in the form of animals and insects, offers many existence proofs for solutions capable of traversing rough terrain against forces of gravity. While certain limbed mobility solutions for planetary rovers had been dismissed in the past for reasons of lower efficiency as compared to wheeled systems, related arguments are less persuasive when dealing with the microgravity environment encountered on small bodies as well as when considering locations on planetary surfaces that are impossible to access using conventional wheeled systems. On asteroids, a means to cling to the surface [19] would offer a critical capability for controlled motion and fine positioning. Limbs can also be beneficial as an active suspension that damps and prevents "bouncing" during traverse or upon landing after a hop.

A. Limbs with gripping end-effectors

Limbed approaches employing gripping end-effectors as feet/hands can enable traversal while maintaining contact with small body surfaces. Such "grapple-motion" approaches enable natural surface traversal by clawing into regolith or forming grasping configurations against rough, hard surfaces of high friction.

During the past decade, prototypes of such limbed systems have been under development at NASA/JPL and more recently focused on the problem of climbing steep terrain on Mars. A representative example of the state of the art for such applications is LEMUR IIb, an 8 kg four-limbed planetary rover for which several types of climbing end-effectors have been investigated [20]. The locomotion functionality for LEMUR class of robots evolved (kinematically) from 6-limbed walking on space structures in orbit to 4-limbed free climbing on steep terrain. Technologies addressed during the development of the LEMUR IIb free climbing capability (e.g., gripping end-effectors, force control, and stability-based motion planning) should be useful for gravity-independent locomotion on asteroids as well.

More specific to asteroid surface mobility is recent work at Tohoku University spearheading limbed locomotion solutions and prototypes to explore feasibility of statically stable grapple-motion in microgravity [21]. Finer and more deterministic control of motion and position are motivations of this work. The focus thus far has been a 6-legged rover with 4 degrees-of-freedom per leg and gripper end-effectors for grasping the asteroid surface. Motion control complexities are handled using a behavior-based control approach in addition to bio-inspired central pattern generators for rhythmic motion and sensor-driven reflexes. Dynamic simulation results showed that static locomotion is feasible when grasping forces on the surface can be achieved [21]. A 2.5 kg prototype of the Tohoku asteroid rover was built using a piercing spike at the tip of each limb to serve as momentary anchors in soft regolith or as contact points of a static grip on hard surfaces when used in combination [22]. Crawling gaits feasible for locomotion in microgravity environments using this system are analyzed in [23] for stability (in the sense that they hold the rover to the asteroid surface).

The above are examples of maturing technologies that offer mechanical means for gripping with robot limbs or momentarily anchoring robot limbs to enable secure surface contact while crawling or climbing. Next we consider adhesive means of achieving the same based on examples of technology proposed for space and planetary rovers.

B. Use of adhesive contacts or shearing pads

Dry adhesive and electro-adhesion approaches that permit walking or climbing systems to "stick" to natural surfaces hold promise for gravity-independent locomotion. With astronaut assistant robots in mind, Northrop Grumman Space Technologies started development of the Automated Walking Inspection and Maintenance Robot (AWIMR) intended to operate on the exterior of crewed space vehicles or structures in space rather than on planet or small body surfaces [24]. While space vehicle exteriors are not natural surfaces of interest here, the relevance of the project hereto lies in the technology investigated for sticking to them in the zero gravity of space. The AWIMR project established feasibility of walking on such surfaces with the aid of prototype sticky feet, inspired by gecko feet, which used dry adhesive polydimethylsiloxane for adhesion. Its sticky feet could walk on any clean, non-fragile surface (of the types found on space vehicle exteriors) and required a pull-off force. The AWIMR project also tested electrostatic means of sticking to surfaces, finding that greater shear forces were possible and that 2-3 kV was suitable for locomotion in this case [24].

With the aim of securing ballistically delivered microprobes to asteroid surfaces upon landing, Bombardelli [25] proposed artificial dry adhesives inspired by geckos and spiders. The preliminary study suggests that multilevel conformal adhesive structures may be key to the performance of the microprobe attachment system for unknown asteroid terrain. The concept is motivated and encouraged by the successful fabrication and application of several engineering prototypes of artificial reusable gecko adhesives. It is reported that the strongest such dry adhesive was recently fabricated using bundles of carbon nanotubes exhibiting four times the stickiness of natural gecko foot hairs [25, 26]. Developers of the carbon nanotube-based gecko tape suggest that it offers an excellent synthetic option in robotics and space applications [26]; they report a capability of similar shear stresses on both hydrophilic and hydrophobic surfaces. Some researchers have found carbon nanotubes to be intrinsically brittle but express confidence in their near-term robustness for climbing robots [27].

Among the desirable characteristics of synthetic, gecko-like dry adhesion for asteroid traversal is its effectiveness for many surface types (as its basis is van der Waals forces) and in vacuum, the fact that no additional energy is required to maintain an established grip on a surface, and their potential for reproducing the self-cleaning or dust resistant property of natural gecko footpads [27, 28]. The applicability of this technology for space and planetary robotic vehicles that would walk or climb on in-space structures and terrestrial surfaces is highlighted in [27]. What could be considered early phases of suitable asteroid robot designs are briefly described in that work.

V. RELATED SOLUTIONS FOR EARTH APPLICATIONS

Recent developments in robot locomotion for applications on Earth are, to varying extents, relevant to the asteroid surface mobility problem. Examples include advances over the last decade in capabilities of climbing robots that may be brought to bear on the problem.

The primary Earth-based applications that drive research into climbing systems are military reconnaissance and time-critical search and rescue. Other climbing robots for pipe inspection, window washing and ship welding have yielded interesting results, but the attachment mechanisms for these applications are specific to a single substrate and are not intended to be used on multiple surfaces. For military and search and rescue operations, machines are being pursued that can climb vertically and inverted (on ceilings) on man-made structures such as stucco, brick and glass, and also natural structures such as trees and rocks. As such, the direction of this related work is approaching relevance to the surface roughness regime of geological formations on planetary and small body surfaces.

Biological strategies such as the previously mentioned gecko-inspired dry adhesives are being pursued because of their potential for rapid and low-energy attachment and detachment capabilities on a variety of surfaces. Stickybot uses dry adhesive pads to climb vertically up smooth glass [29]. The adhesive pads for this system are directional in operation, as recent insight into gecko toes has revealed that the setae hairs used for attachment only produce the necessary attachment forces normal to the surface when shear force is created in a singular direction tangential to the surface [30]. Detachment occurs in the absence of this force, which has the potential to be a very rapid and low energy detachment method. Other systems such as WaalBot [31] and investigations by Ron Fearing [32] utilize this type of pad, but only on surfaces with microscopic roughness profiles. The manufacturing process for these adhesive pads does not yet allow for the level of compliance needed for these pads to conform to larger roughness profiles. With the feasibility of different mechanical prototypes successfully demonstrated, recent effort is being focused on advancing the critical dry adhesives technology and fabrication [33].

Another biologically-inspired attachment mechanism that has yielded promising research has been the microspine array, or the single spine or claw. A single spine is modeled after the cockroach claw, both shown in Figure 1, and is used to latch onto asperities in the surface or dig into soft substrates to achieve adhesion. The claw shown on the right of Figure 1 is from DIGbot, an 18-DOF hexapod that can climb vertically and inverted on mesh screen [34]. The passive spring in each leg replicates the cockroach tarsi, which is necessary to keep the claw oriented correctly with the ground as the animal moves.

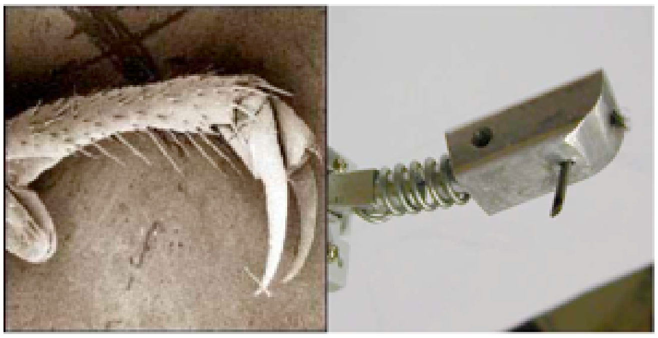

Fig. 1. The cockroach claw is used to grab onto asperities in the surface or dig into soft substrates. The claw shown on the right is from DIGbot [34].

The RiSE (Robots in Scansorial Environments) robot also employs a claw to climb inverted and make a transition onto a horizontal surface [35]. This project also developed microspine arrays for climbing in which each foot distributed the climbing force across multiple spines. Each spine bore less of the load during climbing so it could be smaller than the claws used for single-spine feet. The smaller size allowed the spine to seek out and attach to smaller asperities in the substrate. Using microspine arrays, Spinybot was able to climb vertically up brick, stucco and trees [36].

In addition to the biological strategies, another adhesion technology of note is electroadhesion [37], which provides a low power approach to achieving electrically controllable adhesion between compliant electrodes and a variety of surfaces. Electroadhesion has been applied to wall climbing robots designed for tracked and inchworm locomotion and shown to be effective on flat building material surfaces such as concrete, wood, steel, glass, and drywall. The low power characteristic of electroadhesion would be attractive for asteroid rovers. As research to date on electroadhesion for robots has not been driven by requirements to traverse natural rugged terrain surfaces, the extent of needed technology advancement is not apparent.

The challenge for Earth applications is still to produce a single foot and adhesion paradigm that can climb on a variety of both man-made and natural surfaces. This also includes the ability to perform complex maneuvers on these surfaces. Many of the previously-described robots cannot turn or overcome even a small obstacle on the climbing surface, but research continues into more advanced dry adhesive manufacturing strategies, control algorithms implementing single spines or microspine arrays, and electroadhesion. While current technology is more effective on man-made surfaces it holds promise of effective solutions on natural terrain of asteroids, particularly considering the lower demand on force, power, etc. due to operation in weak gravitational fields.

VI. CHALLENGES

Interested researchers are met with a rich set of challenges involved in developing and evaluating prospective solutions for gravity-independent locomotion on asteroids.

The mechanics of controlled ballistic hopping on rotating asteroids and in non-uniform gravity fields expected of their irregularly shaped bodies deserves attention. The dynamics of hopping vehicles is modeled by Bellerose et al [38, 39] to enable hops covering designated distances by computing and controlling initial hop velocity. The model accounts for distance covered by residual bounces as the vehicle comes to rest (considering surface friction coefficient and restitution). One noted challenge is that some asteroid shapes may have surface locations where a vehicle could stay in equilibrium affecting vehicle dynamics on the surface [38, 39]. Conceivably, a hopping rover could be perturbed away from predicted ballistic trajectories by such equilibria. Stable and unstable equilibrium locations could possibly constrain the accessibility of some surface regions by purely hopping vehicles that operate primarily at the mercy of small body physics. Bellerose's model also provides insight into the effects of non-uniform gravity fields and how centripetal and Coriolis forces due to asteroid rotation may assist or hinder hop performance [39].

Control and robotics techniques can also be brought to bear to address the challenge of landing after hopping in such a way as to avoid rebound. One robot concept employs a spring and linear actuators with horizontal velocity control to achieve this [40], while other research is experimenting with active grappling of the surface upon landing [41-43].

The related challenge, central to gravity-independent locomotion, is maintaining grip or temporary anchoring while controlling force for closure and compliance. Chacin et al [43] have examined motion/force control and dynamic modeling germane to the problem of stable crawling and force closure needed to maintain contact/grip with an asteroid surface under microgravity conditions. Their rover hardware experiments reveal the utility of force feedback for maintaining contact during execution of compliant motion. Kennedy et al [20] address active force control to achieve anchoring associated with stable free-climbing motion control. Tactile sensing and related motion planning algorithms [44] have been implemented on the LEMUR IIb robot mentioned earlier.

Determining, updating and maintaining knowledge of rover position and orientation on an asteroid surface can be important for recording spatial context for surface science measurements and for certain mission concepts of operation. Due to the weak gravity environment and its effect on surface vehicles whether hopping, crawling, or climbing, this presents a challenge. Localization approaches for hopping robots have been proposed with some reliance on ranging to an orbiting or station-keeping mother spacecraft [4] and via use of more general approaches such as particle filters [45], Kalman filters with landmark geo-referencing [46], and optical flow as well as visual odometry without continuous terrain feature tracking while tumbling [47, 48]. Tailored applications of localization approaches for rolling or walking robots could be applied during local navigation across the terrain based on extended Kalman filtering of fused celestial sensing and optical flow measurements [3].

Finally, testing and verification of gravity-independent locomotion systems to ensure confidence in their technology readiness will be a challenge, as is always the case for space systems and particularly those intended for operation in microgravity domains. Affordable testing facilities and approaches will be of significant benefit. Chacin and Yoshida have begun work in this area with a microgravity emulation test equipment for experimenting with locomotion on asteroids [42]. Their prototype rover, ASTRO, has been mounted on the end-effector of a fixed-base industrial manipulator interfaced with a force torque sensor. Counter-balanced systems to suspend the rover have been employed to reduce its effective weight in the laboratory and asteroid surface mockups have been employed.

Beyond the fundamental feasibility of controlled surface mobility in weak gravity fields of small bodies, certain matters of high relevance and importance remain to be addressed by advanced research and technology development. These include terrain hazard detection and avoidance as well as techniques such as model-predictive and kino-dynamic control.

VII. SUMMARY AND CONCLUSIONS

In summary, mobility solutions for traversing small bodies over extended periods are deemed important for enabling operations such as close-up and comprehensive *in situ* measurements, sampling at multiple designated surface locations, global emplacement of distributed sensors, and potentially subsurface access.

A focused survey of mobility and locomotion concepts for controlled mobility on surfaces in weak gravitational fields is provided with an objective to draw attention to a collection of developing concepts and research directions that may spawn viable solutions for missions to asteroid surfaces.

The following conclusions and insights are drawn from this partial overview of related work: technical challenges of asteroid surface mobility can be met with recent technological advances from various sectors of robotics research; the space of candidate technologies that could be developed toward future capabilities is rich; Earth-based robotics research is advancing dry adhesive, electroadhesion, and gripping spine designs that would be useful for gravity-independent locomotion on asteroids; more attention to the asteroid mobility problem from the space robotics community is warranted to provide the most capable solutions for science support, and it is anticipated that technology solutions for small body mobility would also be applicable for hard-to-access terrain (e.g., cliff faces, crater walls, and caves) on planet surfaces with strong gravity wells.

REFERENCES

[1] R.W. Farquhar, D.W. Dunham and J.V. McAdams, "NEAR Shoemaker at Eros: Rendezvous, orbital operations, and a soft landing," in *Proc. AAS/AIAA Astrodynamics 2001*, Quebec, Canada, Advances in the Astronautical Sciences, vol. 109, B. Spencer, C. C. Seybold, A.K. Misra, and R.J. Lisowski, Eds., Univelt, Inc., San Diego, CA, 2002, pp. 953-972.

[2] H. Yano, T. Kubota, H. Miyamoto, T. Okada, D. Scheeres et al, "Touchdown of the Hayabusa Spacecraft at the Muses Sea on Itokawa," *Science*, vol. 312 (5778), June 2006, pp. 1350-1353.

[3] E.T. Baumgartner, B.H. Wilcox, R.V. Welch and R.M. Jones, "Mobility performance of a small-body rover," in *Proc. 7th International Symposium on Robotics and Applications*, *World Automation Congress*, Anchorage, Alaska, 1998.

[4] T. Yoshimitsu, T., Kubota, S., Akabane, et al, "Autonomous navigation and observation on asteroid surface by hopping rover MINERVA," in *Proc. 6th International Symposium on Artificial Intelligence and Robotics & Automation in Space*, Quebec, Canada, 2001.

[5] C.R. Chapman, "What we know and don't know about surfaces of potentially hazardous small bodies," in *Mitigation of Hazardous Comets and Asteroids*, M.J.S. Belton, T.H. Morgan, N.H. Samarasinha and D.K. Yeomans Eds., Cambridge University Press, UK, 2004, pp. 104-112.

[6] A. Behar, G. Bekey, G. Friedman and R. Desai, "Sub-kilogram intelligent tele-robots (SKIT) for asteroid exploration and exploitation," in *Proc. SSI/Princeton Conference on Space Manufacturing*, Space Studies Institute, Princeton, NJ, May 1997, pp. 65-83.

[7] S. Hokamoto and M. Ochi, "Dynamic behavior of a multi-legged planetary rover of isotropic shape," in *Proc. 6th International Symposium on Artificial Intelligence, Robotics, and Automation in Space*, St-Hubert, Quebec, Canada, June 2001.

[8] R.M. Johnson, D. Ferguson, J. Kegelman et al, "Senior design project: Miniature actuator for throwable robot," *Johns Hopkins APL Technical Digest,* vol. 28, no. 3, 2010, pp. 272-273, http://techdigest.jhuapl.edu/td2803/14ArmandSenior.pdf.

[9] B.H. Wilcox and R.M. Jones, A ~1 kilogram asteroid exploration rover," in *Proc. IEEE International Conference on Robotics and Automation*, San Francisco, CA, 2000.

[10] J. Kawaguchi, K. Uesugi and A. Fujiwara, "The MUSES-C mission for the sample and return—its technology development status and readiness," *Acta Astronautica*, vol. 52, 2003, pp. 117-123.

[11] E. Tunstel, "Evolution of autonomous self-righting behaviors for articulated nanorovers", in *Proc. 5th International Symposium on Artificial Intelligence, Robotics & Automation in Space*, Noordwijk, The Netherlands, June 1999, pp. 341-346.

[12] C.M. Cottingham, W.D. Deininger, R.W. Dissly, K.W. Epstein, D.M. Waller and D.J. Scheeres, "Asteroid Surface Probes: A low-cost approach for the in situ exploration of small solar system objects," in *Proc. IEEE Aerospace Conference*, Big Sky, MT, 2009.

[13] D. Ebbets, R. Reinert and R. Dissly, "Small landing probes for in-situ characterization of asteroids and comets," in *Proc. 38th Lunar and Planetary Science Conference*, League City, TX 2007, Paper # 2106.

[14] L. Richter, "Principles for robotic mobility on minor solar system bodies," *Robotics and Autonomous Systems*, vol. 23, 1998, pp. 117-124.

[15] K. Yoshida, "The jumping tortoise: A robot design for locomotion on micro gravity surface," in *Proc. 5th International Symposium on Artificial Intelligence, Robotics & Automation in Space*, Noordwijk, The Netherlands, June 1999, pp.705-707.

[16] Y. Nakamura, S. Shimoda and S. Shoji, "Mobility of a microgravity rover using internal electro-magnetic levitation," in *Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems*, Takamatsu, Japan, 2000, pp. 1639-1645.

[17] T. Kubota, K. Takahashi, S. Shimoda, T. Yoshimitsu and I.. Nakatani, "Locomotion mechanism of intelligent unmanned explorer for deep space exploration," in *Intelligent Unmanned Systems: Theory and Applications*, vol. 192, Springer, Berlin, 2009, pp. 11-26.

[18] S. Schell, A. Tretten, J. Burdick, S.B. Fuller and P. Fiorini, "Hopper on wheels: Evolving the hopping robot concept," in *Proc. International Conference on Field and Service Robotics*, Helsinki, Finland, 2001, pp. 379-384.

[19] K. Yoshida, T. Maruki and H. Yano, "A novel strategy for asteroid exploration with a surface robot," in *Proc. 3rd International Conference on Field and Service Robotics*, Finland, 2002, pp. 281-286.

[20] B. Kennedy, A. Okon, H. Aghazarian, M. Badescu, X. Bao, Y. Bar-Cohen, et al," "LEMUR IIb: A robotic system for steep terrain access," in *Proc. 8th International Conference on Climbing and Walking Robots,* London, UK, 2005, pp. 595–695.

[21] M. Chacin and K. Yoshida, "Multi-limbed rover for asteroid surface exploration using static locomotion," in *Proc. 8th International Symposium on Artificial Intelligence, Robotics and Automation in Space*, Munich, Germany, Sept. 2005.

[22] M. Chacin, K. Nagatani and K. Yoshida, "Next-generation rover development for asteroid surface exploration: System description," in *Proc. 25th International Symposium on Space Technology and Science* and *19th International Symposium on Space Flight Dynamics*, Kanazawa, Japan, June 2006.

[23] M. Chacin and K. Yoshida, "Stability and adaptability analysis for legged robots intended for asteroid exploration," in *Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems*, Beijing, China, 2006, pp. 1744-1749.

[24] R. Wagner and H. Lane, "Lessons learned on the AWIMR project," presented at the *IEEE International Conference Robotics and Automation*, Space Robotics Workshop, Rome, Italy, April 2007.

[25] C. Bombardelli, M. Broschart and C. Menon, "Bio-inspired landing and attachment system for miniaturised surface modules," in *Proc. 58th International Astronautical Congress*, Hyderabad, India, 2007, Paper IAC-07-A2.8.01.

[26] L. Ge, S. Sethi, L. Ci, P.M. Ajayan and A. Dhinojwala, "Carbon nanotube-based synthetic gecko tapes," in *Proc. National Academy of Sciences*, vol. 104 no. 26, June 2007, pp. 10792-10795.

[27] C. Menon, M. Murphy, M. Sitti and N. Lan, "Space exploration – Towards bio-inspired climbing robots," in *Bioinspiration and*

Robotics: Walking and Climbing Robots, M.K. Habib, Ed., Vienna, Austria: I-Tech Education and Publishing, 2007, pp. 261-278.

[28] M.F. Silva and J.A. Tenreiro Machado, "New technologies for climbing robots adhesion to surfaces," in Proc. *International Workshop on New Trends in Science and Technology*, Ankara, Turkey, Nov. 2008.

[29] S. Kim, M. Spenko, S. Trujillo, B. Heyneman, V. Mattoli and M.R. Cutkosky, "Whole body adhesion: Hierarchical, directional and distributed control of adhesive forces for a climbing robot," in *Proc. IEEE International Conference on Robotics and Automation*, Rome, Italy, April 2007, pp. 1268-1273.

[30] K. Autumn, A. Dittmore, D. Santos, M. Spenko and M. Cutkosky, "Frictional adhesion: A new angle on gecko attachment," *Journal of Experimental Biology*, vol. 209, 2006, pp. 3569-3579.

[31] M. Murphy and M. Sitti, "Waalbot: An agile small-scale wall climbing robot utilizing dry elastomer adhesives," *IEEE/ASME Transactions on Mechatronics*, vol. 12, no. 3, June 2007.

[32] J. Lee and R.S. Fearing, "Contact self-cleaning of synthetic gecko adhesive from polymer microfibers," *Langmuir*, vol. 24, no. 19, 10 Sep. 2008, pp. 10587-10591.

[33] B. Aksak, M.P. Murphy and M. Sitti, "Gecko inspired micro-fibrillar adhesives for wall climbing robots on micro/nanoscale rough surfaces," in *Proc. IEEE International Conference on Robotics and Automation*, Pasadena, CA, May 2008, pp. 3058-3063.

[34] L.R. Palmer III, E.D. Diller and R.D. Quinn, "Design of a wall-climbing hexapod for advanced maneuvers," in *Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems*, St. Louis, MO, Oct. 2009, pp. 625-630.

[35] M.J. Spenko, G.C. Haynes, J.A. Saunders, M.R. Cutkosky, A.A. Rizzi, R.J. Full and D.E. Koditschek, "Biologically inspired climbing with a hexapedal robot," *Journal of Field Robotics*, vol. 25(4–5), 2008, pp. 223–242.

[36] A.T. Asbeck, S. Kim, M.R. Cutkosky, W.R. Provancher and M. Lanzetta, "Scaling hard vertical surfaces with compliant microspine arrays," *The International Journal of Robotics Research*, vol. 15, no. 12, 2006, pp. 1165-1180.

[37] H. Prahlad, R. Pelrine, S. Stanford, J. Marlow and R. Kornbluh, "Electroadhesive robots — wall climbing robots enabled by a novel, robust, and electrically controllable adhesion technology," in *Proc. IEEE International Conference on Robotics and Automation*, Pasadena, CA, May 2008, pp. 3028-3033.

[38] J. Bellerose, A. Girard and D.J. Scheeres, "Dynamics and control of surface exploration robots on asteroids" in *Proc. 8th International Conference on Cooperative Control and Optimization*, Gainesville, FL, pp. 135-150, Jan. 2008.

[39] J. Bellerose and D.J. Scheeres, "Dynamics and control for surface exploration of small bodies" in *Proc. AIAA/AAS Astrodynamics Specialist Conference and Exhibit*, Honolulu, HI, Paper 6251, Aug. 2008.

[40] S. Shimoda, A. Wingart, K. Takahashi, T. Kubota and I. Nakatani, "Microgravity hopping robot with controlled hopping and landing capability," in Proc. *IEEE/RSJ Intl. Conference on Intelligent Robots and Systems*, Las Vegas, NV, Oct. 2003, pp. 2571-2576.

[41] M. Chacin, *Landing stability and motion control of multi-limbed robots for asteroid exploration missions*, Ph.D. dissertation, Dept. of Aerospace Engineering, Tohoku University, Tohoku, Japan, 2007.

[42] M. Chacin and K. Yoshida, "A microgravity emulation testbed for asteroid exploration robots," in *Proc. 9th International Symposium on Artificial Intelligence, Robotics and Automation in Space*, Los Angeles, CA, February 2008.

[43] M. Chacin and K. Yoshida, "Motion control of multi-limbed robots for asteroid exploration missions," in *Proc. 2009 IEEE International Conference on Robotics and Automation*, Kobe, Japan, May 2009.

[44] T. Bretl, S. Rock and J.-C. Latombe, Motion planning for a three-limbed climbing robot in vertical natural terrain, *IEEE International Conference on Robotics and Automation*, Taipei, Taiwan 2003, pp. 2947–2953.

[45] R. Martinez-Cantin, "Bio-inspired multi-robot behavior for exploration in low gravity environments," in *Proc. 55th International Astronautical Congress*, Vancouver, Canada, 2004.

[46] P. Fiorini, C. Cosma and M. Confente, "Localization and sensing for hopping robots," Autonomous Robots, vol. 18, 2005, pp. 185–200.

[47] E.W.Y. So, T. Yoshimitsu and T. Kubota, "Relative localization of a hopping rover on an asteroid surface using optical flow," in *Proc. Intl. Conf. on Instrumentation, Control, and Information Technology*, SICE Annual Conference, Tokyo, Japan, Aug. 2008, pp. 1727-1732.

[48] E.W.Y. So, T. Yoshimitsu and T. Kubota, "Hopping odometry: Motion estimation with selective vision," in *Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems*, St. Louis, MO, Oct. 2009, pp. 3808-3813.