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Gravity-Independent Locomotion: Potential approaches to robotic mobility on asteroid surfaces

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EXTENDED ABSTRACT

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 low surface gravity regimes, not to mention sparse knowledge of their surface properties. This paper raises the issue of mobility on such bodies – its feasibility and potentially viable approaches – while drawing attention to developments in terrestrial robot locomotion that may be brought to bear on the problem.

A selection of promising mobility concepts recently proposed for locomotion on small body surfaces will be covered along with various solutions pursued to date for broad surface coverage or global access. Related technical issues and challenges will be highlighted for discussion.

The NEAR mission to asteroid Eros and the more recent Hayabusa mission to asteroid Itokawa revealed an apparent diversity of 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. Despite this general belief, computer simulation studies at JPL predicted the feasibility for wheeled mobility by a nanorover under guided assumptions for friction forces on a kilometer-scale asteroid. Colleagues at JAXA developed a flight article for the Hayabusa mission – the hopping rover MINERVA, which was unfortunately lost during deployment. MINERVA was designed to simply 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. The position of a vehicle of this design is very difficult to predict or control, and more precise positioning of sensors or instruments may be desired for certain missions.

Viable solutions may exist among locomotion approaches that are more similar to crawling or climbing than rolling or hopping to achieve surface mobility. Legged 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 gravity forces. Legged approaches employing gripping or adhesive feet will be discussed as well as related solutions for traversal while maintaining contact with small body surfaces. Among them will be recent work by colleagues at Tohoku University who

are pursuing legged locomotion solutions and building physical prototypes to explore feasibility. 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 and when considering locations on planetary surfaces that are impossible to access using conventional wheeled systems. Limbs can be beneficial as either an active suspension that damps and prevents "bouncing" on landing or during traverse, or for forming grasping configurations to assist in keeping the system in contact with the surface. Electro-adhesion approaches that permit walking or climbing systems to "stick" to natural surfaces are promising as are "grapple-motion" approaches that enable the same by clawing into regolith. Concepts that employ telescoping limbs with grappling end-effectors are also emerging. The space of candidate technologies that could be developed toward future capabilities seems richer than we may realize.

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? This paper seeks to draw attention to such questions and stimulate discussion among experts attending the workshop. It is motivated by a realization that the robotics community at large may be converging toward components of viable solutions in this area.

It is asserted that the small body surface mobility problem has not been penetrated to appreciable depth by space roboticists, and that the science community may be settling on the notion that hopping is the only feasible approach in this domain (perhaps as an indirect result). This may be true; but more investigation is warranted. With advances over the last decade in terrestrial 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 small body access applications where a mobility system must work against minimal gravity. A related application domain where recent developments seem to apply is access to steep, irregular terrain such as cliffs and crater walls on planet (e.g., Mars) surfaces 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 will be on gravity-independent locomotion approaches and technologies other than those intended for mobility on space structures or for coarsely-controlled hopping that have been discussed in prior Planetary Rover Workshops, although those will be mentioned in relation to concepts germane to the focal area of finer controlled mobility on natural surfaces. Some of the challenges involved in developing and evaluating prospective solutions will be highlighted to elicit additional challenges (that may be overlooked by the authors) from the workshop discussions.

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 surface locations, global emplacement of distributed sensors, and potentially subsurface access. It is anticipated that technology solutions for small body mobility would also be applicable for hard-to-access terrain on planet surfaces with strong gravity wells (e.g., cliff faces, crater walls, and caves). Therefore, we offer a surveyed coverage of mobility and locomotion concepts for controlled mobility on surfaces in low-gravitational fields with an objective to draw attention to a collection of developing concepts and lines of research that may spawn viable solutions for space missions. The workshop is considered a great venue for this, attended by some of the most appropriate researchers and practitioners with whom to stimulate dialog on this topic. We anticipate that a sharper focus on related problems will result.