Overview of Area-of-Effect Softbot (AoES) Surface Operations on Rubble Pile Asteroids

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Introduction: This paper continues the discussion of the development of a new type of soft robotic spacecraft that is specifically designed to move and operate efficiently on the surface of, and in proximity to, rubble pile asteroids. These spacecrafts, termed Area-of-Effect Soft-bots (AoES), have large, flexible surface area that provide three key advantages for this environment: it conforms to the surface to provide adhesion-based anchoring; it enables surface mobility via crawling without pushing itself off the asteroid; it enables fuel-free orbit and hopping control using forces generated by solar radiation pressure (SRP).

The purpose of these radical new robots is to enable a realistic and robust in-situ resource utilization (ISRU) mission to a near-Earth asteroid (NEA). An illustration of the AoES design and the concept of operations at the asteroid is pictured in Fig. 1. In this concept, one or more AoES are deployed from an orbiting spacecraft to the surface of the target asteroid. Once landed, the AoES move to find and liberate desirable material via a digging mechanism located in the central bus of the AoES, which is then launched from the surface for collection by the orbiting resource processing spacecraft.

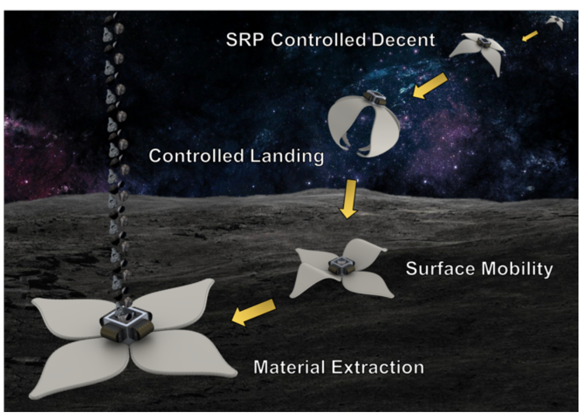

Figure 1 - AoES carrying out their mission concept to robustly land, relocate, dig, and launch material off a rubble pile asteroid.

Current Work: Previous work on this project has provided a high-level overview of the initial AoES spacecraft design and mission concept. This paper looks more in-depth at two areas of the AoES surface operations: surface mobility and surface material liberation.

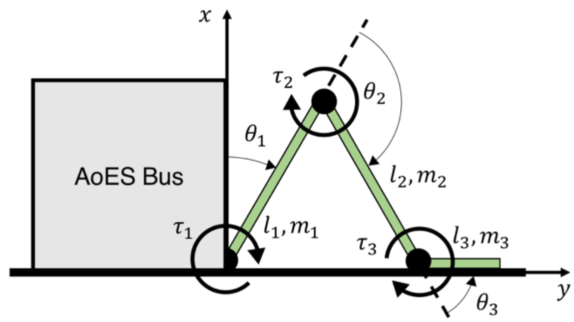

Figure 2 – AoES limb modeling using a connection of *n* rigid links and HASEL actuators at their connection.

The surface mobility of the AoES depends on the crawling and anchoring ability of the spacecraft. In order to leverage the dynamical environment at rubble pile asteroids, the AoES limbs are made of a flexible silicone elastomer, which allows for accommodation of rough asteroid surfaces to keep significant surface area in contact. This allows the AoES to operate using adhesive forces, both naturally arising from van der Waals forces between the AoES and the asteroid regolith, and by using active electroadhesion.

In this paper, both the crawling motion and the electroadhesion capabilities of the AoES limb are investigated. Fig. 2 shows an initial model of the AoES limb, where the limbs are actuated using HASEL actuators - a necessary component for enabling surface mobility. A basic 2D crawling profile is designed and implemented on a flat asteroid surface. In addition, the AoES electroadhesion capabilities are quantified using regolith simulation obtained from the Exolith Lab at the University of Central Florida and the miniature pads shown in Fig. 3.

As previously mentioned, the AoES limbs are actuated by HASEL actuators - a robust new platform for soft actuator technology that merges two predominant existing technologies, electrically-powered dielectric elastomer actuators (DEAs) and fluidically-powered actuators (e.g., McKibben actuators), to synergize their strengths while solving many of their issues. While current fluidic actuators are incredibly versatile and capable of numerous modes of actuation, they require a supply of pressurized gas or liquid (from a compressor or external reservoir) which must be transported through systems of tubes and control valves. This limits their

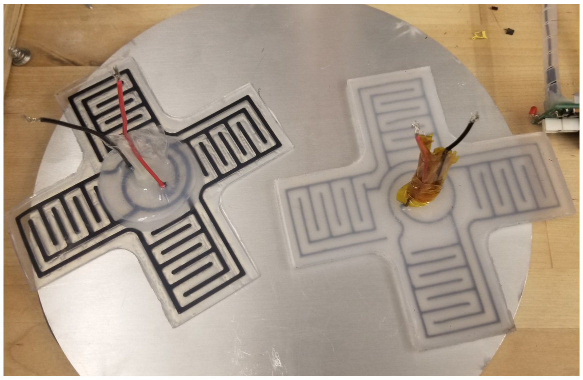

Figure 3 – Miniature electroadhesion pads used to test the AoES ability to adhere to asteroid regolith simulant.

speed and efficiency, and increases system weight and complexity. Electrically-powered actuators, such as DEAs, are energy efficient, offer high actuation speed, high strain (> 100%), and can self-sense their position, but they have limited modes of actuation and generally require actuators to be stretched over a frame for effective operation. Composed of a flexible polymer shell filled with liquid dielectric, HASEL actuators combine the versatility of soft fluidic actuators with the performance of DEAs by applying electorstatic forces directly to the insulating hydraulic fluid. These new actuators can be arranged to perform a bi-directional bending motion perfectly suited for the AoES mission.

A final major component of the AoES design is the capability for AoES to liberate and loft asteroid material. The current design for the AoES digging/launching mechanism is shown in Fig. 4.

The digging mechanism relies on two counter-rotating bucket wheels to pick up regolith by scraping the surface with scoops. While Fig. 4 currently shows a 4-scoop design, a 3-scoop design is also being considered. The bucket wheels can also be linearly actuated vertically allowing the buckets to be either lowered to increase depth of cut or raised depending on the phase of operation. This also allows the spacecraft to collect more regolith from a certain site without needing to move to a different location. The regolith is then transferred from the scoop to the launch mechanism by bringing the bucket wheels to a halt at a predetermined location causing the regolith in the scoop to fly out and collect in the launch bucket.

The launching mechanism comprises of a launch bucket into which the digging mechanism transfers extracted regolith. Once the launch bucket has a predetermined volume of regolith, the launch bucket is accelerated upwards using linear actuators and then decelerated quickly to impart an upwards momentum on the collected regolith. Once lofted from the asteroid surface, a separate orbiting spacecraft will then intercept the regolith material to process and extract the resources of interest. Note that escape speeds on NEAs of Bennu's size are on the order of 10 cm/s, which can easily be achieved by such a mechanism. A scale prototype of the launch system is currently fabricated for a proof-of-concept experiment.

In total, the AoES concept elegantly overcomes many of the difficulties typically encountered when trying to design an ISRU mission which necessitates operating on, and interacting with, the surface of a rubble pile asteroid by taking advantage of the natural forces found in system.

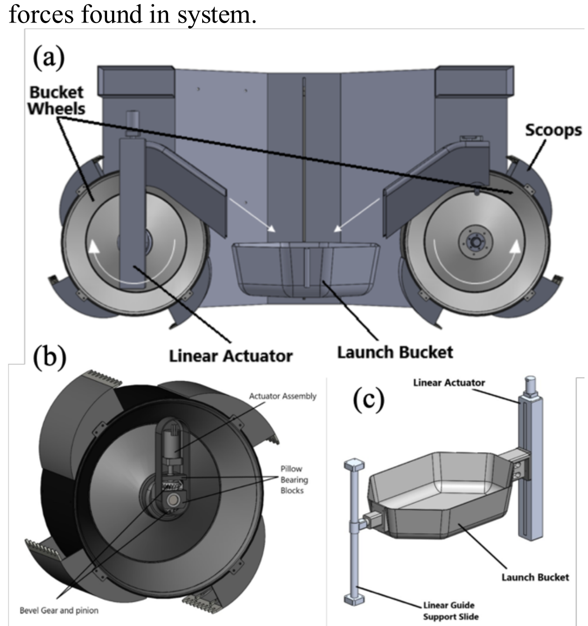

Figure 4 – The AoES excavation design with (a) the entire excavation assembly, (b) the digging mechanism, and (c) the launching mechanism.