Dismantling Rubble Pile Asteroids with Area-of-Effect Softbots (AoES).

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Introduction: This paper discusses 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 spacecraft are termed Area-of-Effect Soft-bots (AoES) for their large, flexible surface area that provides 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 solar radiation pressure (SRP) forces. The central bus of AoES contain a mechanism to liberate material from the asteroid and launch it off the surface.

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 would be deployed from an orbiting spacecraft to the surface of the target asteroid. The AoES will move after landing to find and liberate desirable material, which is then launched from the surface for collection by the orbiting resource processing spacecraft.

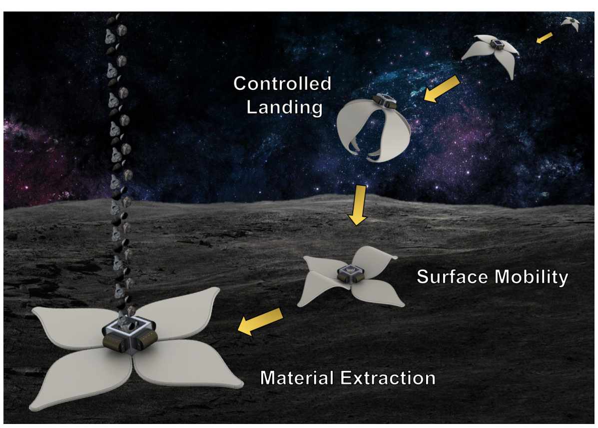

Figure 1 - AoES carrying out their mission concept to robustly land, relocate, dig, and launch material off a rubble pile asteroid.

AoES Overview: AoES are soft-robotic spacecraft that are designed with a large, flexible surface area to leverage the dynamical environment at rubble pile asteroids. In particular, this surface area allows AoES to use adhesive forces, both naturally arising from van der Waals forces between the AoES and the asteroid regolith, and by using active electroadhesion, as well as using SRP forces to provide fuel free orbit and hopping trajectory control. The main purpose of the bus structure is to house a digging and launching mechanism that can liberate and launch asteroid regolith off the surface of the asteroid to be collected in orbit.

It has been well established at this point that van der Waals cohesion plays a major role in holding rubble pile asteroids together, becoming a dominant force in microgravity environments AoES are designed to take advantage of this force as a controllable means of adhering to the asteroid surface, similar to how geckos walk up walls. In this environment, centripetal accelerations on the surface, caused by the spin of the asteroid, ω, can equal or overcome the net gravitational force at the surface. The cohesive forces between the components of the rubble pile asteroid help to hold it together. AoES will take advantage of similar physics to keep from being launched off the surface by centripetal or reactionary forces.

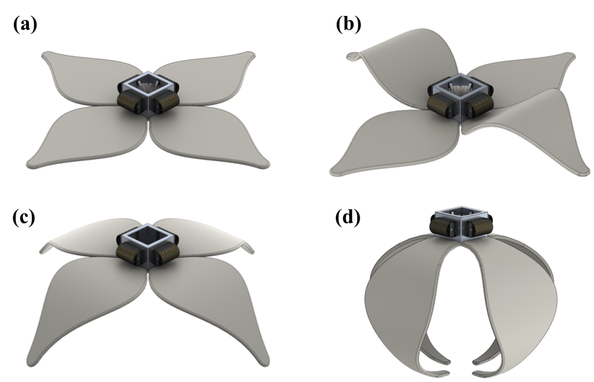

Figure 2 - Images of AoES concept in four modes for a) anchoring or solar sailing, b) crawling, c) hopping, d) landing.

The initial design for AoES are pictured in Fig. 2. The soft-robotic legs are made of a flexible silicone elastomer, which allows for accommodation of rough asteroid surfaces to keep significant surface area in contact. Furthermore, the legs are actuated using HASEL actuators - a necessary component for enabling surface mobility. This is inspired by existing soft robots developed and demonstrated in terrestrial environment.

Recent literature has found that rubble pile asteroids should have cohesion on the order of magnitude of 1-10^2 Pa. If spread over a square meter surface area, an adhesive force roughly four orders of magnitude lower between the AoES and the regolith would suffice to keep the AoES design anchored to the surface. AoES will also incorporate electroadhesion to supplement the van der Waals anchoring and mobility.

AoES are designed to support four main modes of operation, as pictured in Fig. 2. The crawling concept is inspired by nature in how animals which rely on adhesion or large surface areas for locomotion (such as slugs or caterpillars) move.

The high area-to-mass ratio of the AoES design (currently designed to ~0.1 - 0.5 m^2/kg) also provides another important capability - orbit and hopping trajectory control using SRP forces. This method requires no fuel, and is effectively solar sailing. The AoES can also use the legs to absorb landing energy to preclude Philae-like uncontrolled bounces across the asteroid surface. An internal impulse from the material launching system or by quickly slapping all four soft-robotic legs can be used to start the hop, as is picture in Fig. 2c. Then, the hop trajectory can be controlled through similar methods as with the orbit control.

The final major component of the AoES design is the capability for AoES to liberate and loft asteroid material. The initial design of the digging/launching mechanism can be seen in Fig. 3. When the four regolith spades are placed together, they create a bucket that can be accelerated on a track linearly up through the centerline of the bus. When the bucket reaches the end of the track, it will come to a halt but the material inside will escape the open top of the bucket to be lofted from the surface. 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.

In total, this 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 - in many cases using these perceived difficulties to the advantage of the architecture.

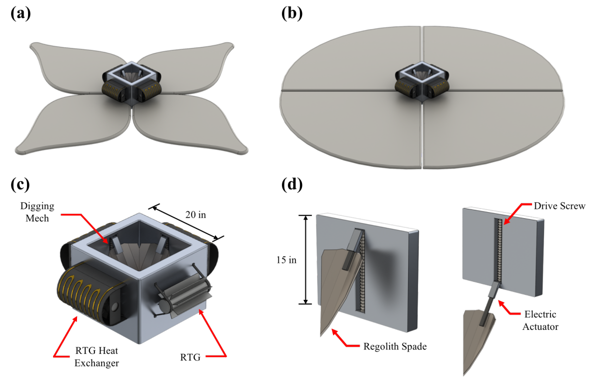

Figure 3 - AoES System design with (a) petal legs - more mobile, (b) circular legs - higher area-to-mass ratio, (c) showing the central bus, and (d) the digging mechanism.