Boulder Capture System Design Options for the Asteroid Robotic Redirect Mission Alternate Approach Trade Study

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This paper presents a boulder acquisition and asteroid surface interaction electro-mechanical concept developed for the Asteroid Robotic Redirect Mission (ARRM) option to capture a free standing boulder on the surface of a 100 m or larger Near Earth Asteroid (NEA). It details the down select process and ranking of potential boulder capture methods, the evolution of a simple yet elegant articulating spaceframe, and ongoing risk reduction and concept refinement efforts. The capture system configuration leverages the spaceframe, heritage manipulators, and a new microspine technology to enable the ARRM boulder capture. While at the NEA it enables attenuation of terminal descent velocity, ascent to escape velocity, boulder collection and restraint. After departure from the NEA it enables, robotic inspection, sample caching, and crew Extra Vehicular Activities (EVA).

I. Introduction

A key component of NASA's asteroid initiative is the Asteroid Robotic Redirect Mission (ARRM). Initially NASA requested a study of the feasibility of a mission to capture an entire four to ten meter diameter asteroid and redirect it to trans-lunar space[2] (Option A). An alternate ARRM concept (Option B) also being studied by NASA is to capture a two to four meter boulder from the surface of a larger 100 + meter diameter Near Earth Asteroid (NEA) and redirect it to trans-lunar space.[3] Option B provides NASA the option to trade potential return mass for centimeter level characterization of an entire large NEA, greater certainty of target NEA composition, ability to select the boulder captured, additional experience operating in a microgravity environment including extended surface contact, and the ability to perform one or more Planetary Defense (PD) demonstrations on a large NEA. In the ARRM Alternate Approach Trade Study (AATS) the Option B concept was investigated to determine feasibility and identify potential differences from the ARRM Option A. A major difference between the options is the system to either capture a small free floating NEA or capture a free standing boulder from the surface of a large NEA. The operations and capabilities of each are vastly different; however after acquisition of NEA material these systems both must restrain it for return and exploration by astronauts in cis-lunar space. The purpose of the AATS was to develop a boulder capture system and concept of operations to the level of detail sufficient for a cost assessment to be completed.

II. Design Considerations

The design process began with a discussion of functions that the system would have to accommodate. A reference mission to Itokawa set the gravity field the system would have to accommodate as well as the design parameters for boulders. Boulder sizes of 1 m to 4 m were set as upper and lower bounds with a mass as much as 70,000 kg based on the results of early mission design analysis. Preliminary design work was focused on spherical boulder shape with these parameters, but oblate and prolate aspect ratios were added later to accommodate the variety of boulder shapes anticipated.

Being a study, a set of requirement did not exist. Instead, a set of design considerations were assembled to use in developing the Capture System. Assuming that only capture and restraint of the target boulder was required, and that no site preparation work was required prior to a crew visit, the design team focused on defining the simplest system to meet the requirement. Because sample preparation during the transit to cis-lunar space was not deemed

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necessary, highly dexterous robotic arms and changeable tools are not needed. Another key assumption was that the target boulder would be of sufficient strength to withstand being captured without the need to encapsulate it in a containment bag or vessel. This was based on the theory that the freestanding boulders on asteroids have survived the collisional processes that created them as well as the accretion process that resulted in their location on the surface of an asteroid.

III. Methods of Capture Considered

A wide variety of capture method concepts were compiled from team brainstorming sessions and a list of candidate methods was formed. Each method was then evaluated against a set of weighted functional considerations and the results were used to inform the design team as to the best capture method to pursue. Table 1 is a list of the methods evaluated with a brief description of their functionality.

Table 1. Capture Methods Considered with Descriptions

Cable Driven Manipulator(s) with End Effectors: Multi-link arm actuated by winch-driven cables that are paired in an antagonistic manner. Each link has two winches and two spreader beams. Accommodates end effectors for grasping boulder.
Clamshell System: Rigidly mounted to S/C; incorporates fixed volume jaw systems that capture and contains the boulder.
Free Flyers deploying a Net: Daughter S/C deployed from mother S/C carrying a net to the surface and snaring the boulder.
Gripper System: Rigidly mounted to the S/C; grips the boulder's surface without fully wrapping around it.
Harpoon System: Deploys a tethered harpoon that retracts to pull the boulder and S/C together.
Inflatable Capture Bag: Smaller version of the free-floating asteroid capture system.
Legs with jacking screws and loose net: 4 pusher legs each with actuated paddle that restrains the boulder and incorporates a detritus net.
Mesh Barrel w/ Collapsing Lid: Deployable fixed diameter mesh barrel; lid rotates to separate boulder from surface then retracts to pull boulder against the S/C.
Multi-Limb End Effector on Payload Module, no manipulator (Spaceframes): Three long multi-DOF digits the act as fingers to grasp boulder and restrain it.
Robot Arm(s) (7-DOF) with End Effectors: Conventional robotic arm with Microspine Gripper or other end effector.
S/C deployed Net System: Throwable net concept, either tethered of free. S/C retracts/grapples net.
S/C deployed Snare System: Boom deployed snare that tightens around boulder for restraint.
Single-DOF Claw System: Multi-digit claw with 1 actuator driving all digits; digits either rigid or under-actuated

A set of functional considerations based on known relevant engineering factors and the best engineering assumptions and judgments of the team were applied against these methods. These considerations, their assigned weights, team member inputs and the results of the evaluation are listed the matrix in Fig. 1 arranged in ascending order of resultant score.

Capture Methods Evaluated

Evaluation Scoring: Scale 0 to 3 (Worst to Best)	Weighting Factor (1 to 3, matters least to matters most)	Free Flyers deploying a Net	S/C deployed Net System	S/C deployed Snare System	Inflatable Capture Bag	Cable Driven Manipulator(s) with End Effectors	Legs with jacking screws and loose net	Gripper System	Clamshell System	Harpoon System	Mesh Barrel w/ Collapsing Lid	Single-DOF Claw System	Articulated Spaceframe System	7-DOF Arm with Gripper System
Assumptions		*n Number of reels*	*Deployed by S/C rigid extendables*	*Deployed by S/C rigid extendables*	*Multiple bag jettsonable design*	*Multiple EEs for various boulder sizes*	*≥6 DOF per leg*	*Post Mounted, multiple heads due to Boulder Sizes*	*Post mounted, single DOF actuation*	*n Number of Harpoons with Reels*	*Lid Loads for constraint and containment*	*n Number of fingers, fixed shape or spring*	*Fully actuated*	*n Number of arms, multiple EEs and hovering*
Accommodates Easily Fractured Boulder	3	3	3	1	3	2	1	1	3	0	3	2	2	1
Accommodates Boulder Volume Variability	3	1	1	2	1	1	2	1	3	2	3	1	3	3
Accommodates Boulder Mass Variability	1	1	1	2	1	3	3	2	3	1	3	3	3	3
Offers Least S/C Disturbance during Ops	2	3	2	1	1	3	2	2	2	3	1	1	3	3
Constrains Boulder for Crew Ops	3	2	3	3	3	2	2	3	1	3	1	3	3	1
Low Residual Strain Energy for Crew Ops	3	1	1	1	1	0	3	2	3	1	2	3	3	2
Crew Access Ease to Boulder	3	2	2	3	1	3	1	3	1	3	1	2	2	3
High Flight Heritage/TRL/Similarity	3	0	0	0	1	1	2	1	2	1	3	3	2	3
Reversible System (Boulder Release)	2	0	0	1	0	3	3	3	3	0	3	3	3	3
Multiple Attempts Possible	2	0	0	1	3	3	3	3	3	3	3	3	3	3
Low DOF/Complexity of Operation	3	0	1	1	3	1	2	3	3	3	3	3	1	2
Low Development and Test Time	3	0	0	1	1	1	1	2	3	2	3	2	2	3
Low Capture System Mass	2	0	1	3	2	2	3	3	1	3	3	3	1	2
Low Capture System Volume	2	3	3	3	2	1	3	1	1	3	3	3	2	3
Low Polymer degradation	2	1	1	1	1	1	2	2	3	2	2	3	3	3
Avoids Pluming Asteroid	3	1	1	1	1	3	3	2	2	3	1	2	3	1
Accommodates Site Topography	1	3	3	2	2	3	3	3	2	3	2	1	3	3
Unaffected by Adjacent Boulders	3	1	1	1	1	3	3	3	1	3	1	1	3	3
	Scores	51	57	66	69	86	92	93	91	95	95	96	102	103

Figure 1. Evaluation Matrix and Results

The trade study resulted in a near-tie for the two highest scored methods with both having a good degree of separation in their scores from the third highest scoring method. This indicated a clear advantage for the two highest scoring methods and gave the team the confidence to move forward with concept development.

IV. Capture Method Development

The natural way of thinking of how to capture a boulder is to apply the anthropomorphic analogy of a hand grasping a round object. This can be accomplished with manipulator arm and end effector and has been demonstrated repeatedly in various spaceflight missions. The space shuttle's robot arm is a good example of a manipulator capable of handling masses in microgravity of this scale. A less complex approach for the ARRM is to replace the manipulator arm with a large scale end effector. The spacecraft would position the digits over the boulder and control its position rather than having the spacecraft hold station and moving the manipulator. This is advantageous because the boulder will potentially be many times the mass of the ARRM spacecraft. Minimizing the number of digits required to provide six degree of freedom restraint yields three finger-like digits set 120° apart from each other. The initial design was based on this rational and was dubbed the Spaceframe Capture Arms.

Each limb consisted of two vee-cross section segments with two coplanar joints for two degrees of freedom per limb. Each segment was of welded tube frame construction. Being an open frame, or space frame, design, it was assumed that irregular protuberances of the boulder would aid in restraining the boulder. This is opposed to a closed frame, or web frame, design where protuberances contacting webs would slide and would not promote 6 Degree of Freedom (DOF) restraint. The Spaceframe also minimizes the obstruction of the boulder's surface for examination and site work. To facilitated being able to reach under the boulder while still on the surface of the asteroid, the distal segment included a spade-like component set nearly normal to the frame and oriented toward the centerline of the vehicle as shown in Fig. 2.

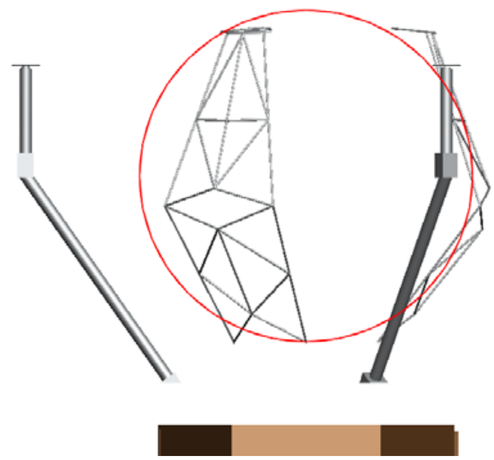

Figure 2. Two-Segment Capture Arm Concept

Actuation of the joints was provided by linear actuators using ball screw drive. This method of actuation was selected due to its' ability to generate high forces with relatively low mass. The length of the segments and short moment arm from the depth of the vee-shaped segments make for high forces at the line of actuation. Heritage rotary actuators were considered as well but were dismissed as they would increase joint complexity and weight significantly. While widely used in spacecraft design, rotary actuators rise in mass at a greater rate for a given force than a linear actuator. Given that the time to capture the boulder was not particularly short (time allowed was set at 30 minutes due to asteroid rotation rate), flight heritage actuators from the Mars Exploration Rover (MER) were selected, providing up to 3692 N (830 lbf) of force, at a mass of 1.63 kg (3.60 lbs)[4]. Limb poses were developed and illustrated for spherical boulders ranging from 1- to 4-meters with some success. However, when non-spherical aspect ratios were attempted adequate 6 DOF restraint was not possible for all cases.

The next iteration of the three-limbed system included an additional segment added to each limb and the lengths of each segment was iterated until a configuration was found that provided 6 DOF boulder restraint in all cases. Fig. 3 shows this configuration in two different poses with two different sized boulders.

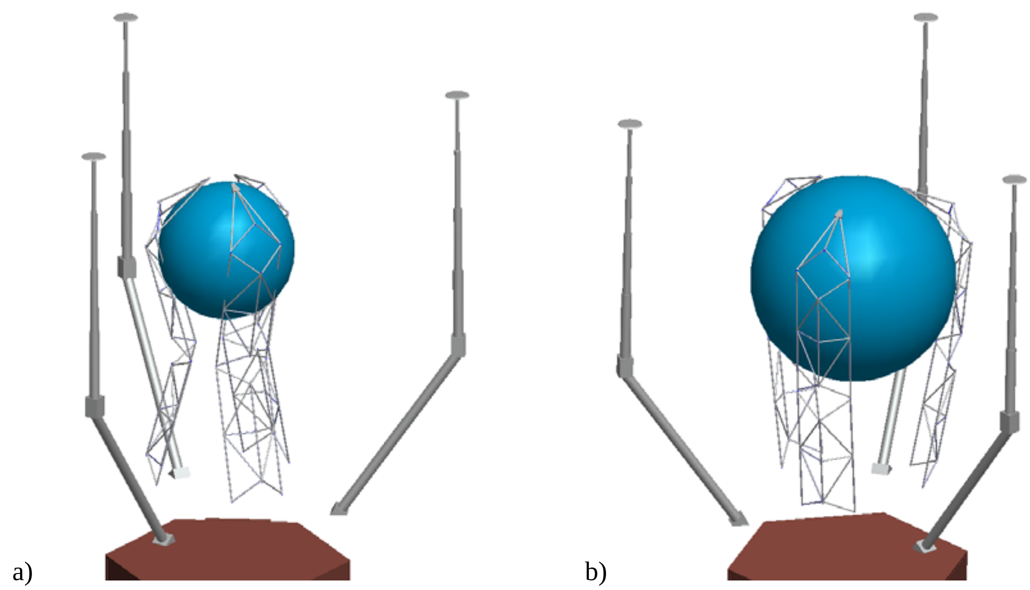

Figure 3. Three 3-Segment Limbs with a) 2-meter boulder and b) 4-meter boulder

This iteration retained the MER heritage actuators. With the restraint issue resolved it was decided that this configuration would be further developed for cost analysis.

V. Evolved Requirements

As the development began the team interviewed representatives for the crew training team at Johnson Spaceflight Center (JSC). Inputs were gathered to help inform the design so as to provide the crew with the adequate restraint points and translation aids. Since EVA durations are limited to four hours per day and two days total, it became apparent that crew operations would need to be streamlined as much as possible. Pre-EVA boulder examination, while possible in a limited manner due to fixed camera positions, is possible with the Spaceframe Arms but sample preparation is not. To best inform Headquarters it was agreed that a parallel costing effort would be performed using conventional robotic arms with end effectors. With Goddard Space Flight Center (GSFC) providing their optical navigation system for proximity operations from their proposed Restore Satellite Servicing program, the team included the robotic arms GSFC is developing for Restore for cost analysis as a comparison with the Spaceframe Arms. JPL developed Microspine Grippers[5] were included as a baseline boulder grasping end effector and were included in the cost estimate as well.

VI. Surface Contact Method Development

From the onset of the study the AATS team debated whether it was necessary to “land” on the asteroid to capture the asteroid or to simply hover over the boulder while capturing it. Interacting and landing on a microgravity body is unlike landing on the Earth, moon or Mars where the vehicle descends to the surface, cuts thrust, then the landing gear absorbs the remaining momentum and brings the vehicle to rest. The act of landing on a microgravity body is more appropriately described as rendezvous and docking. The asteroid retrieval spacecraft is roughly 8000 kg at the NEA, however it is nearly weightless with only 0.8 N of force due to gravity. In addition the force of gravity is not necessarily perpendicular to the surface of the asteroid given its potentially irregular shape. This renders conventional landing systems, which uses springs and dampers, unusable as there is practically no weight to compress springs. Likewise, the dampers would have to have so little damping that design would be impractical. Yet the need to absorb the vehicle’s low momentum due to its extremely low contact velocity must be addressed otherwise the vehicle may bounce off the surface.

An additional complicating factor was the desire not to plume the asteroid’s surface with Reaction Control System (RCS) jets to prevent regolith and dust from being disturbed and settling on the solar arrays, optics, and other sensitive equipment. This held for ascent as well as descent. Additionally, loiter time while hovering would require RCS firing toward the surface to react the microgravity and the loads imparted on the spacecraft during the capture event. The addition of a surface contact and interaction system allowed for using the RCS to apply additional downward force to help stabilize the spacecraft during capture operations, effectively rigidizing the spacecraft-asteroid system, thereby simplifying the Guidance Navigation and Control (GNC) requirements. It was decided the most prudent course was to carry forward a surface contact subsystem for mass and cost estimating purposes until such time that it is proven that contacting the NEA wasn’t necessary. The debate continued and the contact subsystem was included in the cost estimate submitted to Headquarters.

An early concept for surface contact gear included motor and vehicle thrust compressed springs that imparted the initial ascent velocity. Another concept used Storable Tubular Extendible Member (STEM) drives to absorb the momentum of contact, position the spacecraft at the requisite height above the boulder, then provide the push off acceleration to reach initial ascent velocity. Conceptual versions of the STEM driven contact limbs are shown in Figs. 2 and 3 above and included spring-loaded bases that opened up to the deployed position (as shown) after launch. Developing these contact limbs would have to be in parallel with the Spaceframe arms, in order to minimize cost and schedule it was decided to develop a set of contact arms that shared the design of the capture arms. The result was a set of limbs which were identical in joint design and frame layout with only segment length increases. For surface interaction a contact pad was added at the tips of each of the newly designed contact arms. This allowed for minimizing Non-Recurring Engineering (NRE) costs between the Capture and Contact Subsystems. The final iteration used for cost estimation is shown in Fig. 4.

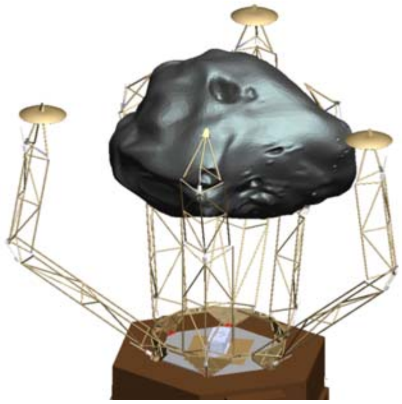

Figure 4. Spaceframe Capture and Contact Arm Final Iteration

The required speeds of the two subsystems differed significantly so another design cycle would be needed to replace the MER actuator with a high-speed, high-force actuator for Contact Arm use. However, time expired and the cost estimate went forward with the MER actuators used throughout both subsystems with the assumption actuators with the different specifications and flight heritage would be available at a similar cost. This was based on discussions with multiple vendors who confirmed that not only the estimated rate and force requirements could be met but at a cost similar to that of the MER actuator due to the NRE being amortized across the number required.

VII. Multiple Configurations for Costing Purposes

To fully inform Headquarters of the state of design at the end of the study the team explored hovering versus landing. Four configurations were developed and are listed here in order of increasing mass and complexity:

1) Hovering Spaceframe Capture Arms
2) Landing with Contact and Capture Spaceframe Arms
3) Hovering with two 7-DOF robot arms
4) Landing and capture with 7-DOF robot arms (3 for contact, 2 for capture)

For costing purposes fully developed part counts were tallied for configurations 2 and 3 and were used in the cost estimates prepared by the study team members. A hybrid configuration using three Spaceframe Contact Arms and two 7 DOF arms was added to the list as well for Headquarters consideration. The five configurations described are illustrated in Fig. 5.

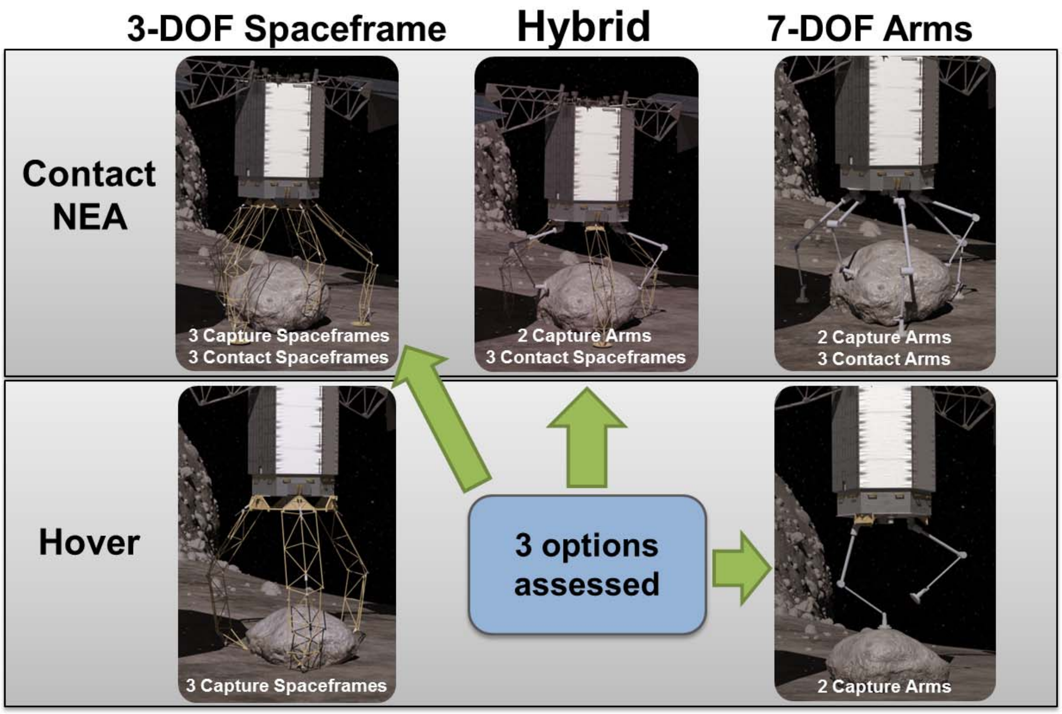

Figure 5. Configurations Evaluated by Study Team (Image Credit: NASA/AMA, Inc.)

With all but the smallest boulder mass, analysis showed that the 7 DOF arms do not have sufficient stiffness to avoid low frequency vibration which could possible induce coupling with the lengthy solar arrays. This eliminates the possibility of the 7 DOF arms from being the sole means of restraining the boulder so the hybrid configuration was been selected for further study with the contact arms providing restraint of the boulder. This allows both 7 DOF arms to be used for examination and sample preparation over a much large area of the boulder's surface and puts the contact arms against the boulder after ascent from the NEA. The Spaceframe also acts as a ladder or gangway and provides a translation path for the crew during an EVA and is aligned with the side hatch on Orion as the crew will have to work in sunlight and will not be allowed in shadows for any significant amount of time. The next iteration will include a tube cross section change from round to square or rectangular to accommodate existing EVA assist devises which clamp to structure members to react crew and tool loads. In the hybrid configuration the Spaceframe Contact Arms will be known as the Contact and Restraint System, or CRS, and their individual arms will be designated limbs from this point forward. This is to delineate them from the robot arms.

VIII. Hybrid Configuration Concept of Operations

As the operation of the Spaceframe Capture Arms and Contact Arms are so similar, their operation will be described herein for the hybrid configuration only.

In preparation for launch, the three CRS limbs are restrained at their tips to form a three legged tower or pyramid for maximum stability and stiffness during launch. The launch restraints consist of flight heritage pin pullers which are electrically actuated[6]. The possible location of contingency sample collection devices on the contact pads where the launch restraints are located makes pyrotechnic separation devices less desirable due to the shock they introduce when they fire. Even though the electrically actuated pin pullers function considerably slower than pyrotechnics, the release of the launch restraints is not required to happen rapidly or with synchronicity or simultaneity between the three restraints.

During outbound travel the CRS launch locks are released and the system is exercised. This allows for any post launch issues to be resolved and puts the S/C into the pose required for proximity operations. As this will be the first zero-gravity experience with the system, the outbound trip to the NEA allows for learning the zero-gravity behavior of the system and to make software modifications and uploads. This is a key difference in the operation of the inflatable free-floating asteroid capture system proposed for ARRM Option A. Deployment of the CRS is also required to clear the view of the boresight sensors and instruments. Once the system has been tuned it enters a quiescent mode and remains dormant through asteroid and boulder characterization. Likewise, the robot arm's launch locks are released during the outbound transit and the system is exercised. Launch robot arm launch restraints are similar to the CRS restraints and are electrically actuated for the same reasons. The Microspine Gripper end effectors are also attached to the arms and removed from their berths and exercised. Again, once the subsystem is tuned it enters a quiescent mode and remains dormant through asteroid and boulder characterization. Both the CRS and robot arm system are equipped with heaters and insulation to warm drives and joints as necessary prior to and during operations in which they are used.

Once a boulder has been selected for collection, the CRS is reactivated and pre-positioned to eliminate excess travel to reduce the operation time on the surface. Likewise, the first robot arm is prepositioned for boulder capture with some predetermined clearance. The second arm is positioned in a standby position ready to be called into action if necessary.

Due to the distance from Earth while at the NEA, tele-operation is not possible, so there is no human in-the-loop during the terminal descent, capture and ascent phases. The vehicle's optical-navigation system will be able to bring the vehicle to the surface with a high degree of precision. Having fully characterized the boulder and the surrounding terrain during the characterization phase, ground controllers will program the vehicle to perform a descent profile, capture profile, and ascent profile, with respect to the CRS, robot arms and end effectors. If the vehicle departs from the programmed routine beyond allowable extents, an abort will be initiated and the vehicle will depart for a planned safe point some distance from the asteroid.

The vehicle descends in attitude-controlled freefall starting from a predetermined altitude and initial velocity (possibly zero). When the CRS contacts the surface the programmed deceleration sequence begins and the actuators absorb the energy from momentum of the vehicle until the vehicle comes to rest. This begins by driving the actuators to make the CRS limbs match the contact velocity of the spacecraft and then quickly ramp down the actuator velocities to zero, bringing the vehicle to rest. Meanwhile, the RCS thrusts away from the NEA's surface pushing the spacecraft against the surface of the asteroid. The RCS thrust is then ramped down to a predetermined level of thrust to maintain surface contact for the remainder of surface operations. After the flight computer determines the spacecraft is stable, the boulder capture event begins. If spacecraft stability cannot be attained, the flight computer commands the vehicle to abort and the CRS pushes the spacecraft off the surface and the vehicle is moved to a safe point for ground control to reset for another attempt.

After landing when the capture event is initiated, the robot arm drives the Microspine Gripper into contact with the boulder. Contact is determined by the magnitude of force registered by the arm's force sensor. The Microspine Gripper then engages and grips the boulder. Positive grip is indicated by forces building in the drive with diminishing stepper progress. The robot arm joint's brakes then engage to rigidize the arm and the ascent sequence starts. Using a preprogrammed ascent profile, the CRS drives and imparts the requisite initial velocity, which can exceed escape velocity for Itokawa (11 m/s).

Once a safe altitude is attained, the CRS begins the preprogrammed restraint sequence. The restraint routine is programmed for the captured boulder's shape and may involve having the robot arm adjust the boulder's orientation or location with respect to the spacecraft. The restraint routine can be programmed and uploaded prior to descending to the surface based on shape models developed during the previously accomplished characterization phase or after examining the captured boulder after departing the surface. Restraint may happen in hours or days after departing the surface after ground control determines restraint may begin.

Each joint is monitored by the flight computer for current flow (force) and displacement (motor revolution count) during the restraint routine. After the boulder is moved to its restraint location relative to the spacecraft, the preprogrammed restraint routine begins by driving the appropriate segment of Limb 1 to contact the boulder. Motions are allowed to dampen and the appropriate segment of Limb 2 is brought into contact with the boulder. Again, motions are allowed to dampen and the appropriate segment of Limb 3 is brought into contact with the boulder. "Appropriate segment" refers to the segment that is the first that should be used to restrain a given boulder. Due to its irregular shape, it may be necessary for a hypothetical boulder to be restrained with, for instance, the second segment of Limb 1, followed by the first segment of Limb 2, and the third segment of Limb 3. Each boulder will have its own, unique restraint configuration.

The operation repeats with the next set of appropriate segments contacting the boulder in sequence until all required segments are in contact. The system then determines if the requisite amount of preload is applied and, if not, drives all required segment actuators simultaneously to the required preload levels. Preload is defined as some sufficient load to restrain the boulder during the highest anticipated accelerations. As time is not a factor, the whole process can take from an hour to days. Lastly, the actuators' power-off brakes are engaged for transit to cis-lunar space and the remainder of the mission. If during high acceleration operations slippage is indicated either visually or by mass property changes, the CRS can be reenergized to restore preload.

With the boulder restrained, the robot arms are free to perform examination and sample gathering operations while in transit after releasing the Microspine Grippers and stowing them. Prior to Microspine Gripper release the robot are joint brakes are disengaged, releasing any residual strain energy in the arm, and the new joint positions are incorporated in the operating routine. This will prevent the arm from springing violently when the Microspine Gripper releases the boulder. The robot arms then return the Microspine Grippers to their berths in preparation for tool or examination devise selection and use by ground control.

IX. Forward Work

Having successfully developed a Capture System that is feasible and can be developed and tested for approximately the same cost as capturing a whole asteroid, Headquarters extended the study, allowing the CRS, robot arm, and end effector concepts to be further developed. This is to better inform Headquarters as to the true expected cost of performing the proposed asteroidal material redirect mission. As part of the ongoing study, certain risk reduction tasks have been identified to be performed in the interim between the conclusion of the initial study and the planned Mission Concept Review (MCR). For the CRS, a two arm full scale mockup will be built and demonstrated on the LaRC flat floor facility using air bearings to simulate microgravity. Using sheet metal analog structures and low-cost, off the shelf actuators, the mockup can be quickly assembled and made operational. Preliminary design of the mockup is shown in Fig. 6.

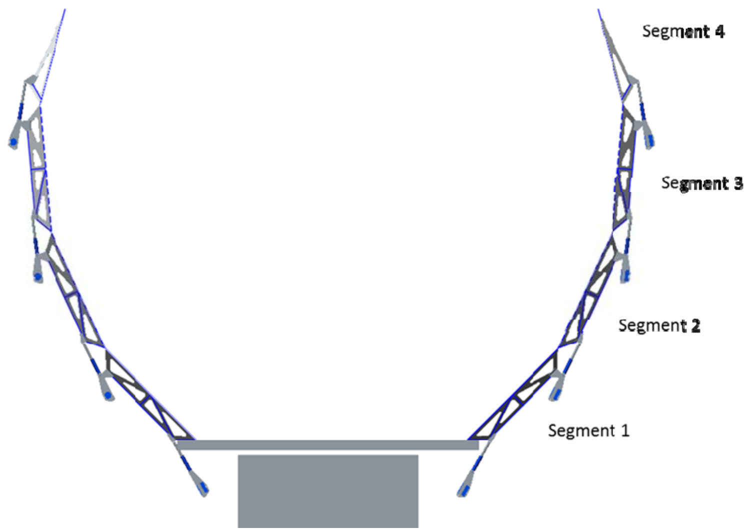

Figure 6. Sheet Metal Mockup with Low-Cost Actuators

It will inform the flight design by showing that the multiple actuators can be operated simultaneously to control contacting an asteroid's surface, provide initial ascent velocity, and restrain boulders of different shapes, sizes and masses. A mock boulder set will provide physical representations of the different sizes and aspect ratios. Dead weight will mimic the S/C mass and boulder mass. Sheet metal structure allows for rapid alterations to geometry if needed. If, for instance, segment dimensions need to be altered, new sheet metal panels can be water sawn and bent and installed much faster than with welded tubing. As it will be a concept demonstrator only and not an EDU, the mockup will approximate the geometry of the flight design but will not fully meet the load capability of the flight design.

Robot arm development continues in the Restore Program and this concept continues to benefit from it, additionally risk reduction directly related to this proposed mission is being worked. Operational environments are being applied and the existing robot arm design is being analyzed for resonant frequency modes and forces. Likewise, the end effector is being further developed to advance it level to TRL 5. During the study, a plastic prototype Microspine Gripper was installed on a robot arm and successfully demonstrated on various sized rocks. A more flight-like design is being developed with flight-like materials and configurations. Boulder material analogs are being developed and tested with the existing plastic prototype in preparation for the upcoming newer version.

X. Summary

The concept CRS design was evolved over the course of the AATS from a set of 13 capture methods that were assessed over 18 weighted engineering considerations to a detailed design that is currently undergoing full scale testing and risk reduction. Five potential variants were matured to the level of fidelity required for cost and schedule development. The Spaceframe concept that began as an analog for fingers gripping a boulder is now the NEA contact system that attenuates descent velocity, provides push-off for ascent, and restrains the captured boulder after the robotic arms and Microspine Gripper extract it from the surface. A detailed concept of operations has been developed for the system's operations and specific geometry and actuator choices are being refined based on selected target NEA and results of ongoing risk reduction.

Acknowledgments

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