

Testbed for Studying the Capture of a Small, Free-flying Asteroid in Space

Brian Wilcox¹, Miguel San Martin², Louis Giersch³, Scott Howe⁴, Håvard Fjær Grip⁵, Reza Nayeri⁶,
Todd Litwin⁷, Jason Carlson⁸, Matthew Shekels⁹, Abhinandan Jain¹⁰, Christopher Lim¹¹,
Steven Myint¹², Jack Dunkle¹³, Allen Sirota¹⁴, Christine Fuller¹⁵
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive, Pasadena, California U.S.A.

A scaled deployable device has been built and tested for the purpose of evaluating the feasibility of capturing an entire small asteroid in free space. The target asteroid was presumed to have a mass <1000 metric tons, with a longest dimension of <13 meters. It could be spinning and tumbling. It could be a "rubble pile" – a collection of loosely-bound particles whose cohesion is barely more than the minimum required by the hoop strength defined by the spin rate. It was decided that the only way to confine a rubble pile was to put it in a bag – a fabric or membrane enclosure which completely encapsulated the asteroid, preventing contamination of the solar arrays, radiators, and other optical surfaces of the spacecraft. Clearly this bag had to be deployed, since the largest dimension of the asteroid is significantly larger than the launch shroud of any present launch vehicle. It was decided that a hardware-in-the-loop testbed would be needed, since the physics of physical contact between the asteroid and the deployed capture bag is too complex to credibly model entirely within computer simulation. This testbed was built at 1/5th-scale for a capture bag assumed 15 meters in diameter (the largest dimension of the asteroid plus a meter on either side). The asteroid mockup was mounted on a robotic arm and force-torque sensors were used to measure the interactions between the spacecraft and the asteroid through the soft material of the capture system. The force-torque measurements were fed into a zero-g simulation of the spacecraft and asteroid, which in turn prescribed the motion of the asteroid relative to the spacecraft.

This paper describes the construction and operation of the testbed, including the selection of the bag materials, the configuration of the capture mechanism, the actuators required to deploy, control, and retract the bag, the hardware-in-the-loop simulation and the sensors used to drive it, as well as results from the system.

Nomenclature

ADAMS = High-Fidelity Multibody Simulation Software distributed by MSC Corporation
ARM = NASA Asteroid Redirect Mission
ARCM = NASA Asteroid Redirect Crewed Mission

¹ Asteroid Redirect Mission "Option A" capture lead, principal engineer, brian.h.wilcox@jpl.nasa.gov

² Asteroid Redirect Mission guidance, navigation and control lead, JPL fellow, alejandro.m.sanmartin@jpl.nasa.gov

³ Asteroid Redirect Mission "Option A" soft-goods lead, louis.r.giersch@jpl.nasa.gov

⁴ Senior Systems Engineer, a.scott.howe@jpl.nasa.gov

⁵ Simulation Engineer, havard.f.grip@jpl.nasa.gov

⁶ Simulation Engineer, reza.d.nayeri@jpl.nasa.gov

⁷ Robotics Software Engineer, telitwin@jpl.nasa.gov

⁸ Robotics Hardware Engineer, jason.a.carlton@jpl.nasa.gov

⁹ Robotics Hardware Engineer, matthew.p.shekels@jpl.nasa.gov

¹⁰ Simulation Engineer, jain@jpl.nasa.gov

¹¹ Simulation Engineer, christopher.s.lim@jpl.nasa.gov

¹² Simulation Engineer, steven.myint@jpl.nasa.gov

¹³ Robotics hardware fab and assembly, john.m.dunkle@jpl.nasa.gov

¹⁴ Supervisor, Robotic Actuation and Sensing Group, allen.r.sirota@jpl.nasa.gov

¹⁵ Robotics Engineer, christine.l.fuller@jpl.nasa.gov

<i>ARRM</i>	=	NASA Asteroid Redirect Robotic Mission
<i>C&DH</i>	=	Command and Data Handling
<i>DOF</i>	=	Degrees Of Freedom
<i>FY</i>	=	Fiscal Year
<i>HEOMD</i>	=	NASA Human Exploration Mission Directorate
<i>IR</i>	=	Infrared
<i>ISRU</i>	=	In-Situ Resource Utilization
<i>JPL</i>	=	Jet Propulsion Laboratory
<i>KISS</i>	=	Keck Institute for Space Studies
<i>NASA</i>	=	National Aeronautics and Space Administration
<i>NASTRAN</i>	=	A very high fidelity dynamic model
<i>NIAC</i>	=	NASA Innovative Aerospace Concept
<i>Orion</i>	=	Multi-Purpose Crew Vehicle
<i>RCS</i>	=	Reaction Control System
<i>RPM</i>	=	Revolutions Per Minute
<i>SADA</i>	=	Solar Array Drive Assembly
<i>SEP</i>	=	Solar Electric Propulsion
<i>SLS</i>	=	Space Launch System
<i>TCP</i>	=	Transmission Control Protocol
<i>V&V</i>	=	Verification and Validation

I. Introduction

THE Asteroid Redirect Mission (ARM) is an outgrowth of a NASA Innovative Aerospace Concept (NIAC) award to John Brophy in 2010. Workshops conducted by the Keck Institute for Space Studies (KISS) were held on the topic in September 2011 and February 2012, led by John Brophy of JPL, Lou Friedman of The Planetary Society, and Fred Culick of Caltech.¹ One of us (Wilcox) led the "asteroid capture" sub-team of the KISS study. During the study it was shown that some asteroids were in orbits sufficiently close to that of the Earth and that, with minimal deflection, they could undergo a lunar gravity assist which would kill-off some 2 km/s of relative velocity, thereby capturing them into the Earth-moon system. A Solar Electric Propulsion Spacecraft (SEP spacecraft) having ~50 kW of solar array and ~10 tons of Xenon propellant could impart as little as 200 m/s of ΔV to an asteroid with a mass up to ~1000 tons and achieve capture into a lunar "Distant Retrograde Orbit". This orbit was known to be very stable (>100 years, and probably indefinitely) and yet reachable by an Orion crew capsule as lofted by the Space Launch System (SLS) so that a human crew could explore this asteroid and return safely to Earth within the endurance constraints of the initial SLS/Orion system. The NASA Human Exploration Mission Directorate (HEOMD) recommended that the mission concept be incorporated into the Administration's budget proposal for FY'14. In the President's budget proposal released in the spring of 2013, the administration announced that NASA would attempt to capture a small asteroid and redirect it into the Earth-moon system where it could be studied by human astronauts.

Eventually the focus of development was reduced to two options: Option A, where an entire 7-10 meter (equivalent spherical diameter) asteroid moving through free space would be captured and returned into the Earth-moon system, and Option B, where a boulder of perhaps 2-4 meters diameter would be captured off the surface of a larger (~100 m) asteroid and returned into the Earth-moon system. One advantage of Option A was that a larger total mass (up to ~1000 tons) could be returned because there are so many small asteroids that one could be selected whose orbit was sufficiently similar to that of Earth that the V-infinity on arriving into the Earth-moon system would be small enough (<~2 km/s) that a lunar gravity assist could "kill off" that excess energy and perform the capture with little extra effort. The advantage of Option B was that a larger host body would be selected that was of known Carbonaceous Chondrite (Type-C) spectral class (and preferably also known to be volatile-rich), which is generally agreed by the asteroid science and engineering community to be of greatest scientific and engineering value (e.g. for future in-situ resources). The small asteroid targets associated with Option A generally have not been characterized as to spectral class or volatile content because they are too faint during the brief period they are close enough to Earth to have been discovered. Another advantage of Option B is the perceived similarity of the surface operations required on the ~100 m host body to acquire the boulder to other future surface operations such as astronaut operations on Phobos. Another advantage of Option A is the perceived similarity of associated operations to a long-term program of asteroid In-Situ Resource Utilization (ISRU), since Option A is able to return into the

Earth-moon system up to ~100 times as much asteroidal mass as is consumed in propellant, whereas for Option B that ratio is close to 1:1 because known Type-C asteroids are not in orbits with low V-infinity with respect to Earth.

The focus of this paper is the work performed in evaluating the feasibility of Option A, leading up to a downselect decision by NASA management. On March 25, 2015, NASA management announced that Option B had been selected as the mission plan for the Asteroid Redirect Mission.

II. Study Guidelines and Methodology

The results of the aforementioned study by the Keck Institute for Space Studies (KISS) were that a spacecraft delivering about 40 kW electrical into the solar-electric propulsion (SEP) system would be able to return a <1000 ton asteroid (nominally 500 tons) into a high orbit around the moon. The requirements set for Option A are that the capture system must accommodate a target asteroid up to 1000 tons with a maximum linear dimension of 13 meters. Although the lowest plausible density for an asteroid of this mass might well imply a larger maximum dimension than 13 meters, the way that candidate asteroids are selected and validated as targets precludes such a possibility. Candidate asteroid targets are discovered by optical imaging, for which an approximate orbit can be plotted after 3 or more images are acquired against the starfield. Given the orbit, the distance from Earth and the illumination geometry by the sun is determined, the absolute magnitude can be estimated. No asteroid would be selected as an Option A target with only this information, however. In addition, either radar or thermal IR imaging must be available, which together with the visual magnitude tightly constrain both the cross-section of the asteroid and the albedo. Because the maximum mass that can be returned by the spacecraft from the given orbit is tightly constrained, this measured cross-section is applied to the maximum plausible density to test if the asteroid mass is confidently below the threshold. If so, the asteroid becomes a valid candidate target for Option A. Note that the size of the asteroid is actually better known than the mass in this process, so that there is little risk that the spacecraft will arrive at the asteroid to discover that the mass is indeed below the threshold but the asteroid doesn't fit into the capture mechanism.

As was done in the KISS study, it is further assumed that the capture mechanism incorporates a bag made of competent fabric or membrane material such that, if the asteroid turns out to be a "rubble pile", then breakup of the asteroid to any degree following first contact will not result in loss of asteroid material nor risk contamination of the spacecraft optical surfaces, solar arrays, thermal radiators, etc. Many if not most somewhat larger asteroids than those considered as Option A targets are thought to be rubble piles because the distribution of spin rates is clustered just below the "rubble pile limit" spin barrier, where the inertial forces are just balanced by the gravitational forces. This spin barrier is at about 2-hour spin period for any sized asteroid, assuming densities associated with low-to-medium porosity. For smaller asteroids, many are observed spinning faster than this spin barrier, but this can be

explained by very weak levels of cohesion similar to or less than that observed at the surface of lunar regolith.²

Because the maximum assumed asteroid dimension is 13 meters, while the maximum diameter of the launch shroud of present-day launch vehicles is 5 meters, it is required that the capture mechanism deploy from a compact stowed configuration. Even next-generation launch vehicles such as the Space Launch System (SLS) will have launch shrouds no greater than 10 meters in diameter, so deployment will continue to be needed throughout at least the next decade. To accomplish this deployment, it is required to have some sort of compressive members that can create tension in the fabric bag to pull it out into the fully deployed configuration. These compressive members can be rigid links, like fingers, that fold up into a stowed "fist", or they can be inflatable beams, themselves composed of fabric, which are inflated to endow them with compressive strength.

The first KISS workshop brainstormed many possible configurations, and within a day or so settled on an inflatable exoskeleton for the capture bag. The concept was that the bag would have sufficient tubes affixed to the bag fabric such that, when the tubes were inflated, the bag would deploy to the shape of a cylinder 15 meters in diameter and ~10 meters long (Figure 1). The capture concept that emerged from that first workshop was that the bag would be deployed from the end of the spacecraft that is opposite the electric

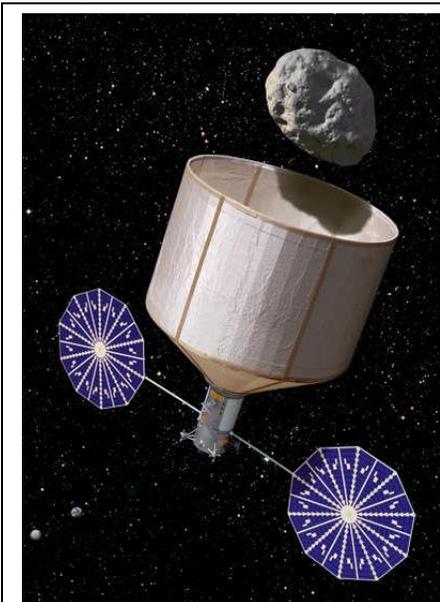


Figure 1: KISS study capture concept utilizing inflatable exoskeleton for capture bag

propulsion thrusters, on an axis of symmetry such that the spacecraft can be spun to match the angular momentum vector of the asteroid. The large solar panels which provide the power for the SEP system extend at right angles to this axis of symmetry, and so are well away from the asteroid at the time of capture. Because it is expected that many, but not all, asteroids will have damped-down to be simple-spinners around their angular momentum vector, once the spacecraft aligns its symmetry axis with this vector and spins to the same rate, there is no relative motion between the asteroid and the spacecraft. At that point the spacecraft Reaction Control System (RCS) thrusters can advance the spacecraft as slowly as desired until the capture bag is centered over the asteroid. Because the relaxed simple spin state of any object is about its principal axis of maximum moment of inertia, we must expect that the longest axis of the asteroid will be approximately at right angles to the spin axis. Thus the required diameter of the bag is greater than the length, because the asteroid enters the bag in the least-favorable attitude in terms of reducing the required size of the "mouth". Since there is no particular reason to believe that the longest dimension will be significantly larger than the second-longest dimension, the mouth of the bag is circular, and the bag is cylindrical. Also this simplifies alignment for capture. Drawstrings would close the opening of the bag and collapse the bag tightly over the asteroid.

Part of the capture concept is that the control system of the spacecraft will be able to successfully guide the bag over the asteroid without hitting it. Since the assumed maximum dimension of the asteroid is 13 meters and the bag diameter is 15 meters, that means there is at least 1 meter clearance between the asteroid and the bag all the way around. During the first KISS workshop, no analysis was done to establish that it is possible to accomplish this maneuver with only 1 meter of clearance, other than the fact that many experienced aerospace engineers were

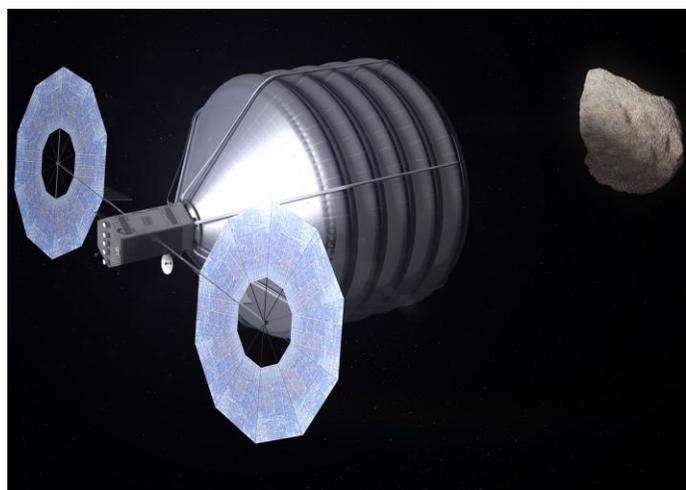


Figure 2: Early inflatable studies for deploying capture bag, based on the KISS study



Figure 3: Early feasibility capture study using inflatable testbed

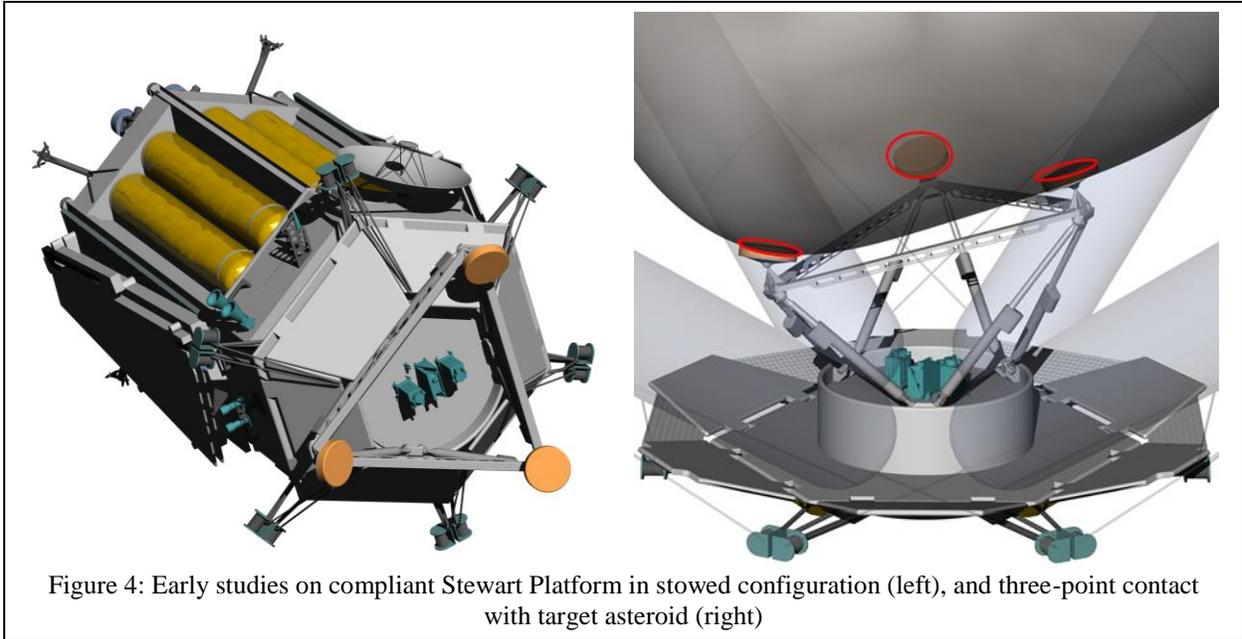


Figure 4: Early studies on compliant Stewart Platform in stowed configuration (left), and three-point contact with target asteroid (right)

present and felt that 1 meter was "doable". However, all were uncomfortable with reducing this clearance to any significant degree. It was felt that the increased mass and cost of making the bag a bit larger than necessary was a small penalty compared to the added risk of trying to fly the bag over the asteroid with reduced clearance.

As the Asteroid Redirect Mission was being considered as part of the proposed NASA budget for FY'14, all of these issues were revisited. An inflatable version of the concept was designed (Figure 2), and an inflatable testbed was used to demonstrate the feasibility of the overall stiffness and force feedback through force-torque sensors (Figure 3). One option for precision capture and stabilization of the asteroid included a Stewart Platform with three-point contact that could be adjusted to optimize the location of the center of gravity (Figure 4). It was determined that although a Stewart Platform may perform well on hard rock monolithic asteroids, it may not work as well on rubble or dust piles, which may be quite likely among the candidate asteroids.

Perhaps the greatest concern with the original Option A approach was the non-deterministic nature of inflatable deployment. Prior inflatable systems such as the Inflatable Antenna Experiment (conducted from the Space Shuttle in May 1996), despite being nominally successful, had not given the broader NASA management community strong confidence because it exhibited alarming gyrations during deployment. The possibility that a cinch cord could

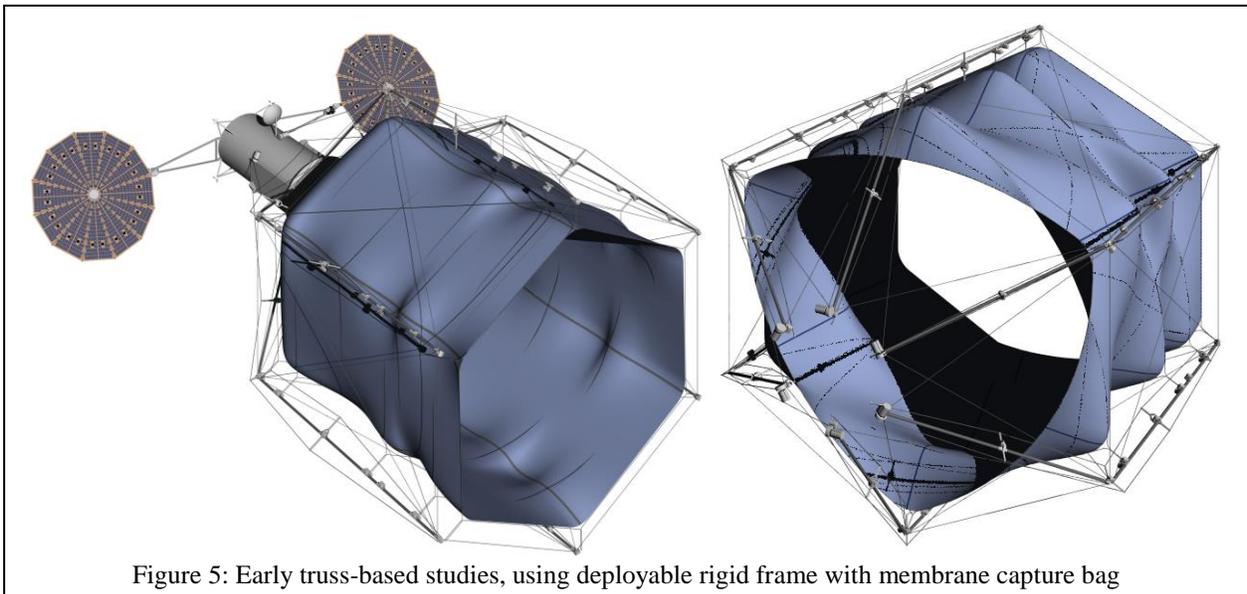
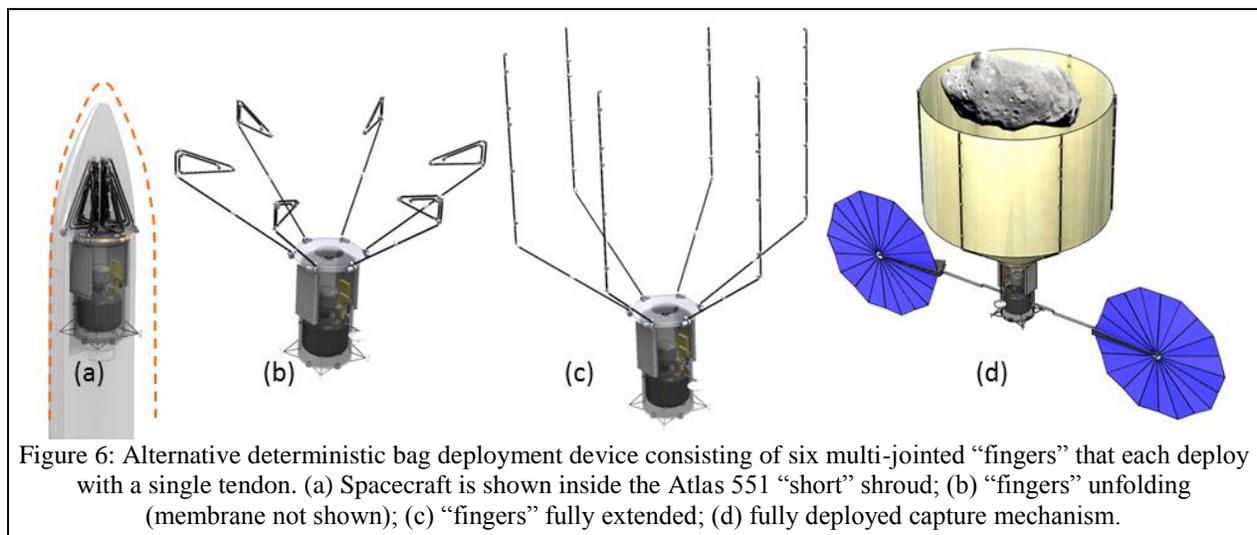


Figure 5: Early truss-based studies, using deployable rigid frame with membrane capture bag

entangle some part of the inflatable structure was also a major concern.

Early studies included a truss-and-membrane concept (Figure 5) that unfolded a space frame, upon which a membrane could be deployed and supported. Figure 6 shows a fully-deterministic all-mechanical deployment approach that was considered during FY'13 as an alternative to the inflatable approach. A key constraint on this design was the desire to fit into the shortest launch shroud of the smallest credible launch vehicle for the mission, which in this case was the Atlas 551 "short" shroud. Since the body of the spacecraft itself consumes the barrel section of the shroud, the capture mechanism needed to fit up into the tapered portion of the shroud. To achieve the required deployed dimensions, this necessitated folding each of the mechanical "fingers" that pulled the bag into the deployed configuration into a highly constrained volume, requiring many "knuckles" per finger. This approach was discarded for several reasons, including the obvious overall complexity, but also the problem of how to restrain the top knuckles of the fingers during launch considering that the successive layers of the bag prevented direct access to each loop of the folded fingers.

A hybrid mechanical/inflatable approach was ultimately adopted after discarding the requirement that the mechanism fit into the shortest shroud. The mechanical part is to have rigid two-link mechanical "petals" that deploy the bag radially to a sufficient size to completely surround the asteroid. The first link of each of six petals is a rectangular sandwich panel that protects the soft bag material from micrometeorite and radiation damage as well as



thermal extremes. The second link of each petal is a trapezoidal panel that folds into the center of the hexagonal cylinder formed by the six first links to form a hexagonal cone, further protecting the soft bag from micrometeorites, radiation, and heat loss along the axis of the cylinder (see Figure 7 and Figure 8). Linear actuators for each petal push the closed, hexagonal stowed package (Figure 8, upper left) open, unfurling both petal and membrane. The first links deploy initially, opening to a star shape. Then the second links deploy, extending so that the hexagonal bag encloses the full 15-m inside radius. At the end of each finger is a "pinch-roller winch" which has a membrane cylinder folded flat and wound on a winch drum, with one or more pinch-rollers to hold it pinched flat until inflated. Inflation pressure comes from a gas source at the end of each membrane cylinder, such as a small helical tube from a tank of pressurized gas. When inflated, each membrane tube grows to a circular cross-section and becomes a rigid boom. The ends of the six inflatable booms deployed by the six pinch-roller winches are themselves connected by an inflatable hexagon of similar inflated membrane booms, so that all of the inflatable booms can be inflated from a single source. Alternatively, baffles can partition the hexagon and axial booms so that there are up to six separately-inflated compartments.

The mechanical petals and the pinch-roller winches allow the deployment of the bag to be "deterministic" in the sense that, from the time the six petals are deployed, the bag fabric is held taught in at least one direction (circumferentially), and then the axial deployment is determined by the rotation angle of each of the pinch-roller winch drums. Once pressure is applied to the membrane tubes emanating from the pinch-roller winches, those booms become rigid and the structure holds the bag open in the circumferential direction and taught axially once the pinch-rollers have completely deployed their respective booms. During the axial deployment, spring-loaded lanyards confine the excess bag fabric at the distal end of the bag near the opening, so that it cannot wander any significant distance and thus interfere with the operations. The deployment mechanism is not only deterministic but

also reversible, in the sense that all of these processes can be reversed. To capture the asteroid, a circumferential drawstring can close the open end of the bag, collapsing the inflated hexagon. Pressure relief valves vent the gas at

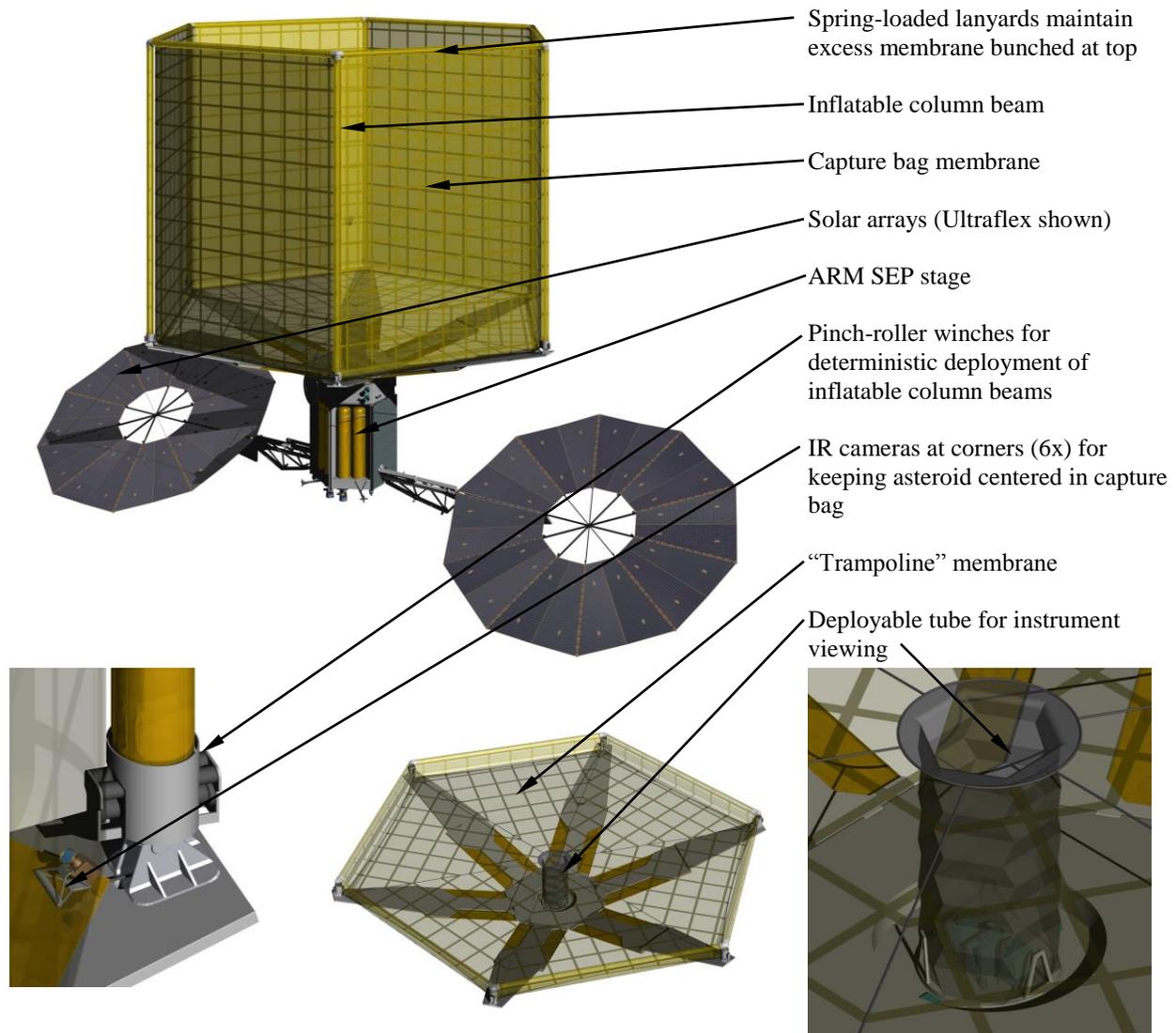


Figure 7: Final design: Hybrid Mechanical/Inflatable capture mechanism approach adopted for Option A

a safe pressure. Then the pinch-roller winches can retract the axial booms, drawing the bag tight to the asteroid and pulling the asteroid down toward the spacecraft. The six retracted axial booms act like "cinch cords" to hold the asteroid tight to the spacecraft while the whole system is despun and subsequent forces are applied by the SEP thrusters to maneuver the asteroid toward its encounter with the Earth-moon system.

A problem is how to protect the spacecraft from damage during the capture process, and to facilitate the capture as much as possible, with the least mass, cost, and risk as possible. The adopted solution to this problem is to have a strong membrane stretched-taut between the tips of the mechanical petals, forming a "trampoline". To increase the deflection distance between the trampoline and the spacecraft, pylons can be put at the end of the petals that extend the trampoline above the plane of the tips of the petals. The petals can open at an angle such that the distance between the center of the trampoline and the spacecraft is especially large, providing further protection to the spacecraft. The primary method for contacting the asteroid would be to push the trampoline into the asteroid (using the RCS thrusters), after the spacecraft had matched the approximate spin of the asteroid about a common angular momentum vector. By continuing to push the trampoline into the asteroid under this condition of minimal relative surface velocity, the trampoline would effectively reach an equivalent "3-point contact", where the asteroid would

gradually damp-out any residual relative motion without the need for the spacecraft to actively modulate its thrust magnitude or direction. Rather, if the asteroid begins to rotate out of its "minimum energy" configuration in the

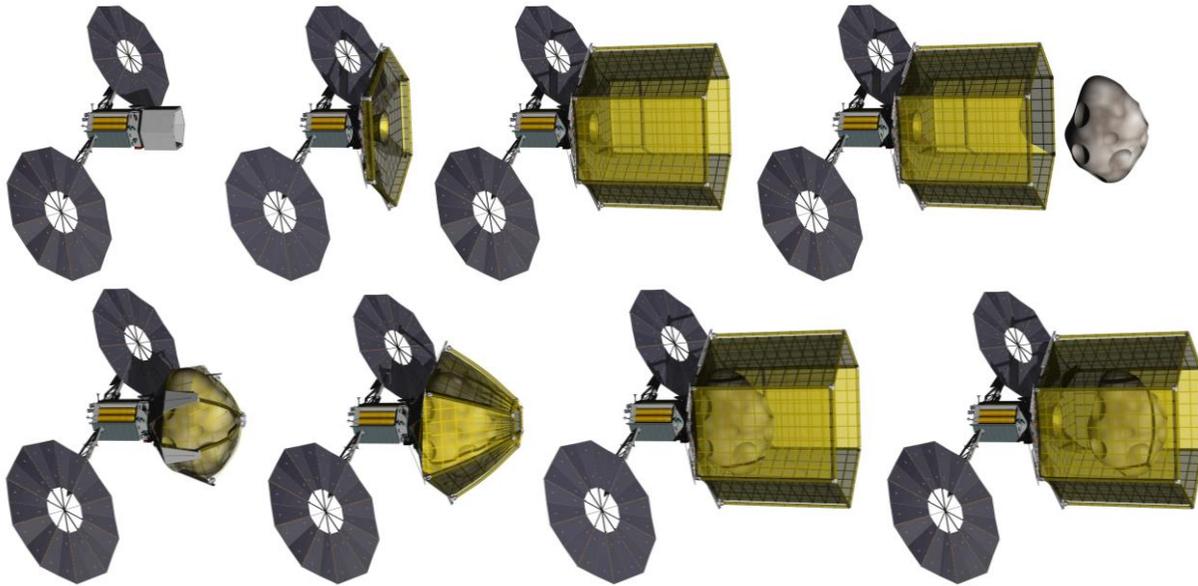


Figure 8: Asteroid capture sequence (clockwise from upper left)

trampoline (as accelerated by a small uniform thrust from the spacecraft along the trampoline nominal surface normal), then the forces will increase on one side of the trampoline and drop on the other, causing the trampoline and spacecraft to accelerate rotationally to match the spin of the asteroid, even if that spin is not that of a simple-spinner, but rather is the complex motion of a tumbling body. Spring-dampers at the corners of the trampoline ensure that the relative motion of the asteroid is damped-out quickly.

The actuators for the trampoline are direct-drive (e.g. without gearing) so that they can emulate any desired spring-damping properties without excessive inertia or friction. A spindle was fabricated so that a Vectran cord to the corner of the trampoline can wrap around this small-diameter spindle to give adequate tensioning force even without gears. 200 Watt brushless DC motors were used to drive these spindles. In the flight system it may be possible to use smaller motors with low-ratio gearheads (~10:1) to accomplish the same function. Redundant cinch winches at the top of the bag ensure that a circumferential cinch cord is able to close the "drawstring bag". These winch motors have low-ratio gears so that, if desired, re-inflation of the inflatable beams can pull open the bag so that all aspects of the capture process are reversible, in addition to be deterministic and repeatable.

Because the sensors used to acquire and characterize the asteroid, initially from long range, are boresighted along the symmetry axis of the spacecraft along the centerline of the capture bag, a hole is needed in the center of the trampoline for these sensors to look through. A launch deployment restraint holds a ring affixed at this hole against the spacecraft bulkhead until the asteroid capture bag is deployed, so that the sensors have a completely unobstructed view. Once the trampoline is deployed and held taught by the spring-dampers, a tube of fabric extending from the trampoline down to the sensor array protects the spacecraft from contamination by asteroid debris released during the capture process, as shown in Figure 7. During the capture process itself, none of these sensors is used for closed-loop control. Rather, the cameras, laser scanner, and science instruments (having previously been used to determine the precise shape, spin-state, and other properties of the asteroid) will be used subsequently only for post-capture analysis. Note that, in the stowed configuration, all the sensors have a clear and relatively wide field of view of the sky along the symmetry axis of the spacecraft, looking out through the inside of the hexagonal cone of the stowed bag deployment device. This allows the deployment of the bag to be deferred as late as possible in the mission, to maximally protect the soft goods of the bag, cinch cords, etc. from radiation, micrometeorites, and thermal extremes. After the asteroid has been fully captured, despun, and cinched tight against the spacecraft, the soft goods are relatively immune to such damage because there is no continuing requirement to hold inflation pressure or to take any significant mechanical loads.

Once the asteroid angular momentum vector and spacecraft are brought into alignment, and the spacecraft flown forward so that the asteroid is "inside the bag", it is desired to send a message to Earth controllers for them to

validate that the autonomous capture process can proceed. Since the round-trip speed-of-light delay between the spacecraft and Earth can be 30 minutes or more, it is required that the relative positions of the spacecraft and the asteroid be maintained both safely and effectively indefinitely while Earth operators evaluate the situation and make the decision to proceed. This problem is exacerbated by the fact that, while rate gyros can exquisitely sense angular excursions of the spacecraft in inertial space, the translational rate of the spacecraft with respect to the asteroid can only be measured approximately, such that propagating the uncertainty over many minutes results in an unacceptable degree of uncertainty with respect to the relative position of the asteroid and the spacecraft.

The solution to this problem is to put thermal infrared (IR) cameras inside the corners of the capture bag at the base nearest the spacecraft. The thermal IR cameras image both the side of the bag and the asteroid, giving a clear band representing the cold sky, which is the gap between the asteroid and the bag. Both the bag and the asteroid will radiate strongly in the IR, and the sky will be very cold and dark at this wavelength. (The capture will always be conducted from the pole of the angular momentum vector on the sunlit-side of the asteroid, so that dark sky will be in the background.) Very simple threshold processing of images from these cameras will allow maintaining the spacecraft centered over the asteroid with the spacecraft symmetry axis aligned through the asteroid center-of-mass and aligned with the angular momentum vector of the asteroid. A simple algorithm will be able to keep the asteroid in a stable relative position with respect to the spacecraft essentially indefinitely while waiting for Earth operators to command either the autonomous capture sequence or an abort (whereby the spacecraft would back away from the asteroid). This is true even if there is a significant offset between the center-of-mass location and the centerpoint of the longest chord across the asteroid.

III. Asteroid Capture Simulation

In the course of the Option A feasibility study, the dynamics of the capture event were studied extensively through analysis and simulation. A simulation model was built in *Darts/Dshell*, a multibody simulation framework developed at JPL and in use both at JPL and at the Johnson Space Center Mission Operations Directorate. In this simulation model, the spacecraft bus was modeled as a single rigid body, and the solar panels were modeled as rigid, solid cylinders on mass-less booms connected to the spacecraft bus via ball joints. Spring-dampers at the ball joints were configured to match the stiffness and damping properties of the baseline solar arrays. The asteroid was modeled as a rigid body with arbitrary inertial properties and with a geometry described by an arbitrary triangular mesh. Connecting the spacecraft bus and the asteroid was the model of the capture device itself.

As the design progressed, several different models were used for the capture device, representing the mechanical designs with varying degrees of fidelity. Early in the process, prior to the invention of the trampoline capture mechanism, various designs were represented in a largely abstract manner through the use of hinged mechanisms and webs of spring-dampers, which could be tuned to achieve system-level compliance properties consistent with a physical capture device. The work was focused on determining the feasibility of capturing a tumbling asteroid spinning up to 2 RPM without exceeding the load limits on the solar array drive assemblies (SADAs), represented in this case by the spring-loaded ball joints connecting the solar panels and the spacecraft bus. Results indicated that a capture device with the proper level of compliance could provide sufficient level of isolation to allow the dynamics to settle without exceeding the SADA load limits. Nevertheless, the margins were small for certain types of rotational patterns, and the results were predicated on an idealized approach strategy in which the asteroid's instantaneous angular velocity was projected into the future and the matched by the spacecraft at a particular epoch and the grab occurred quickly.³ The upper bound on the asteroid rotation rate was later lowered to 0.5 RPM at the request of the ARM study lead and agreed-to by NASA management. This is not expected to significantly reduce the population of acceptable target asteroids in the size range of interest.²

The eventual trampoline capture design was modeled in *Darts/Dshell* through the use of a novel technique based on estimating the instantaneous trampoline shape by a convex hull and deriving forces and torques through energy and moment balances, based on a certain potential energy and viscoelastic damping profile as a function of trampoline deflection.⁴ The results showed that the spacecraft tended to settle against the asteroid and catch up with

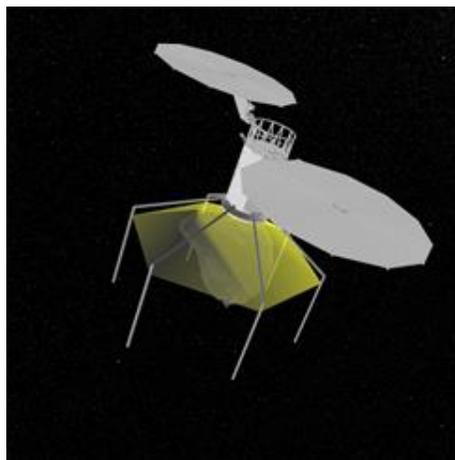


Figure 9: Visualization of the “trampoline” capture from *Darts/Dshell*

its rotational motion after some initial transient. Due to the constant thrust applied throughout the capture, the spacecraft would orient itself toward a stable configuration, typically resting on a flatter area of the asteroid. Figure 9 shows a visualization of the trampoline capture from a *Darts/Dshell* simulation.

To better understand the dynamic interactions between the asteroid and the capture system, specifically the trampoline dynamics, a higher fidelity model was developed in MSC ADAMS. In this model the trampoline was modeled via finite element techniques and its dynamic contact with the asteroid modeled using Hertzian contact mechanics. The finite discretization steps for the trampoline as a tension-only membrane is illustrated in Figure 10.

In order to minimize the number of DOFs for the trampoline, we constrained the 3 rotational DOFs of the elements, so each element only has 3 translational DOFs. It is worth noting that this modeling concept retains the geometric nonlinearity of the membrane (element force direction changes as the system deforms).

In the ADAMS model, each solar array wing is modeled as a rigid element with two DOF discrete springs representing its bending and torsional stiffness. The six sandwich-panel petals are modeled as rigid elements with discrete stiffness at the root to capture their compliance. The solar array and petal stiffness values in the model are tuned based on the corresponding higher fidelity finite element models in NASTRAN. At the six tie-down points, the trampoline connected to the petals' tip through winch forces that could be designed as active or passive.

The objective of the modeling effort is to assess the following system parameters during the asteroid interactions with the capture mechanism:

- Solar array peak loads
- Petals max stroke, driven by its stiffness
 - It is desired to have a very stiff petal in order to decouple the trampoline dynamics from the petal dynamics, although it is possible that this requirement could be reduced with sophisticated control of active spring-dampers implemented with electric motors.
- Trampoline Max stroke:
 - The trampoline should not bottom out during the contact with asteroid
 - The trampoline stroke is driven by the six winch forces at the attachment points with petals
 - It also driven by the level of the spacecraft RCS thrust
- Level of thrust to maintain the contact
 - Capture system should be able to maintain the contact with asteroid during the cinch process (relative velocity should converge to zero at steady state)

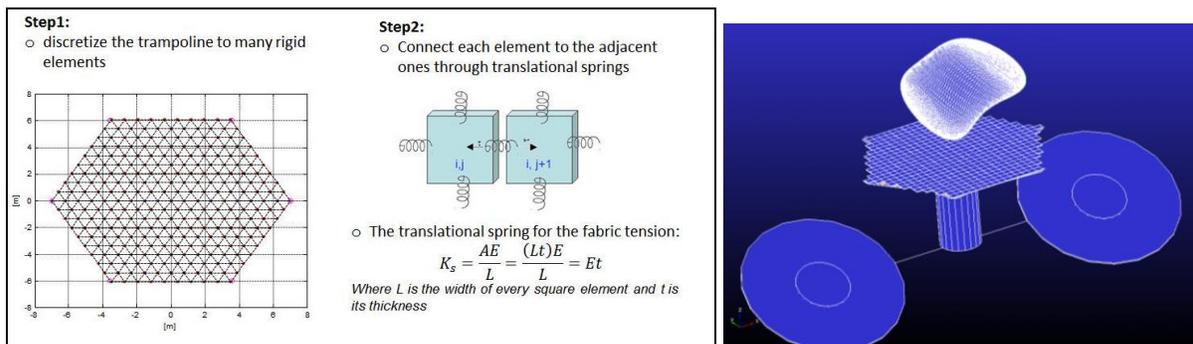


Figure 10: Trampoline discretization in ADAMS

Extensive sensitivity studies were conducted to assess the impact of various input parameters on the above mentioned output parameters. Here we just show a representative case in which we used a constant spring winch force along with ratchet (force is only applied in one direction, no cable re-wind) at the trampoline tie-down points with the petals. In this case we assumed a 1000 metric-tons asteroid spinning at 0.25 rpm and approach velocity of 0.05 m/sec. The initial contact between the asteroid and trampoline is detected though gyro rate data, which triggers thrusters firing to maintain the contact afterwards. As observed in the Figure 11, with a 400 N thrust after the initial contact, the capture system is able to maintain the contact (the relative velocity converges to zero), while the resulting trampoline stroke and solar array (SA) loads stayed within an acceptable threshold.

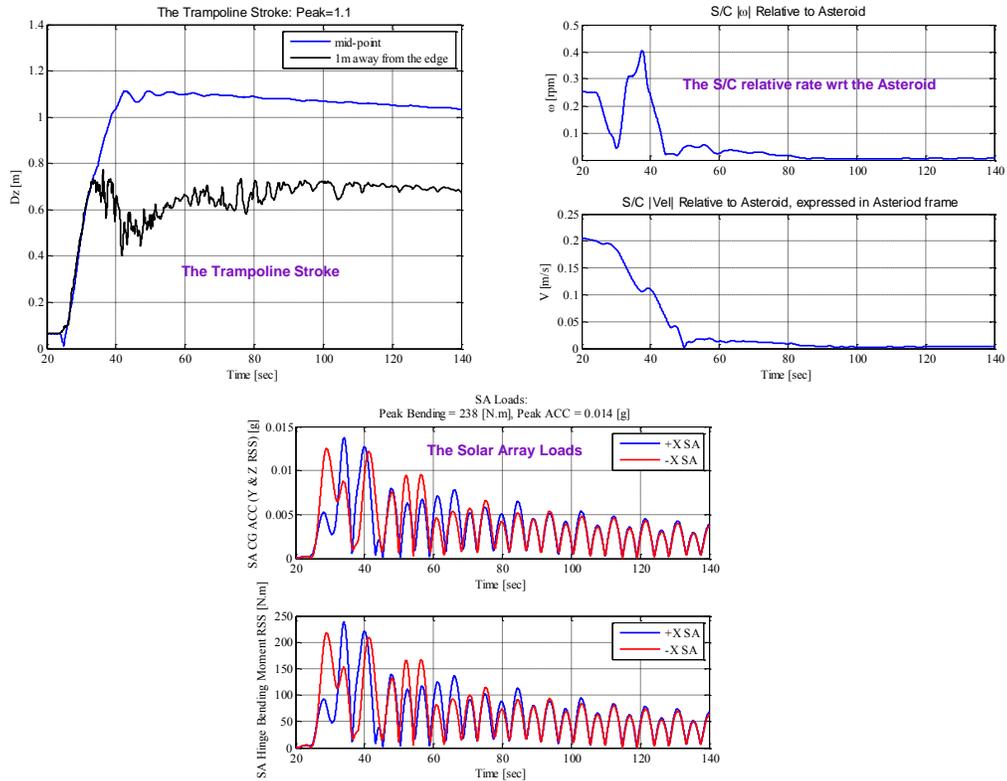


Figure 11: Representative ADAMS time history results for a 1000 metric-tons asteroid spinning at 0.25 rpm and approaching the capture system at 0.05 m/sec

IV. Option A Capture Testbed

A hardware-in-the-loop testbed was constructed to facilitate a deeper understanding of the issues. This 1/5th-scale testbed (Figures 12, 13, and 14) has been implemented with the deployable petals, trampoline with hole and fabric tube, pinch-roller winches, inflatable booms, and spring lanyards, along with redundant cinch winches to close the bag opening once the simulated asteroid is inside the bag and the autonomous capture sequence has been triggered. The spring-dampers at the corners of the trampoline are implemented as direct-drive (e.g. without gearing) brushless motors so that it is easy to change either the spring or the damping characteristics as part of the development process. At a future time it can be decided whether to implement the spring-dampers mechanically or as software-controlled motors in the actual flight system. One advantage of software control is that the details of the spring-damper characteristics can be modified once the actual mass and inertial properties of the asteroid are known upon spacecraft arrival.

The capture mechanism is mounted on a large frame that is rigidly connected to a robot arm that has an asteroid mockup on the end. This robot arm has 7 degrees-of-freedom (DOF), in addition to the ability to spin the asteroid mockup about an axis through its center and nominally at right-angles to a long post to the wrist of the robot. The asteroid mockup is split into two halves so that the long post can pass through a gap between the two halves, so that the rotation of the asteroid around this last spin axis is as free from interference with the capture bag as possible. The concept is that the bag can close over the asteroid while the long post passes through the small bag closure that remains after the cinch cord has drawn the fabric as bunched as possible. Even in this configuration, the robot can spin the asteroid inside the bag, around the axis orthogonal to the long post, and also maneuver the post a modest amount in pitch, roll, and yaw without putting undue forces on the bag. Multiple experiments have also been performed without raising the bag, so that only the asteroid and trampoline interact, without interference between the bag and the long post. This improves the fidelity of the simulation because the long post is free to move as needed to simulate proper asteroid motion. Having the asteroid spin about an axis roughly at right angles to the angular momentum vector approximates the common situation for a tumbling asteroid. The residual motion of the asteroid, as seen in the rotating reference frame, is often a slow spin about an orthogonal axis to the angular

momentum vector (essentially the residual of the instantaneous spin vector as projected onto the plane orthogonal to the angular momentum vector in the time-averaged uniform rotating reference frame).

The overall concept of the capture testbed is that a force-torque sensor at the base of the capture mechanism will measure any forces and torques of interaction between the bag (including trampoline) and the asteroid. Because the capture mechanism is fixed in the laboratory reference frame, a "physics engine" is needed to translate these measured forces and torques into what would actually happen to a free-floating spacecraft and asteroid. This is especially true since the asteroid is expected to be vastly more massive than the spacecraft, and so the forces of interaction will mostly cause the spacecraft to accelerate, as opposed to the asteroid. However, in the testbed, this

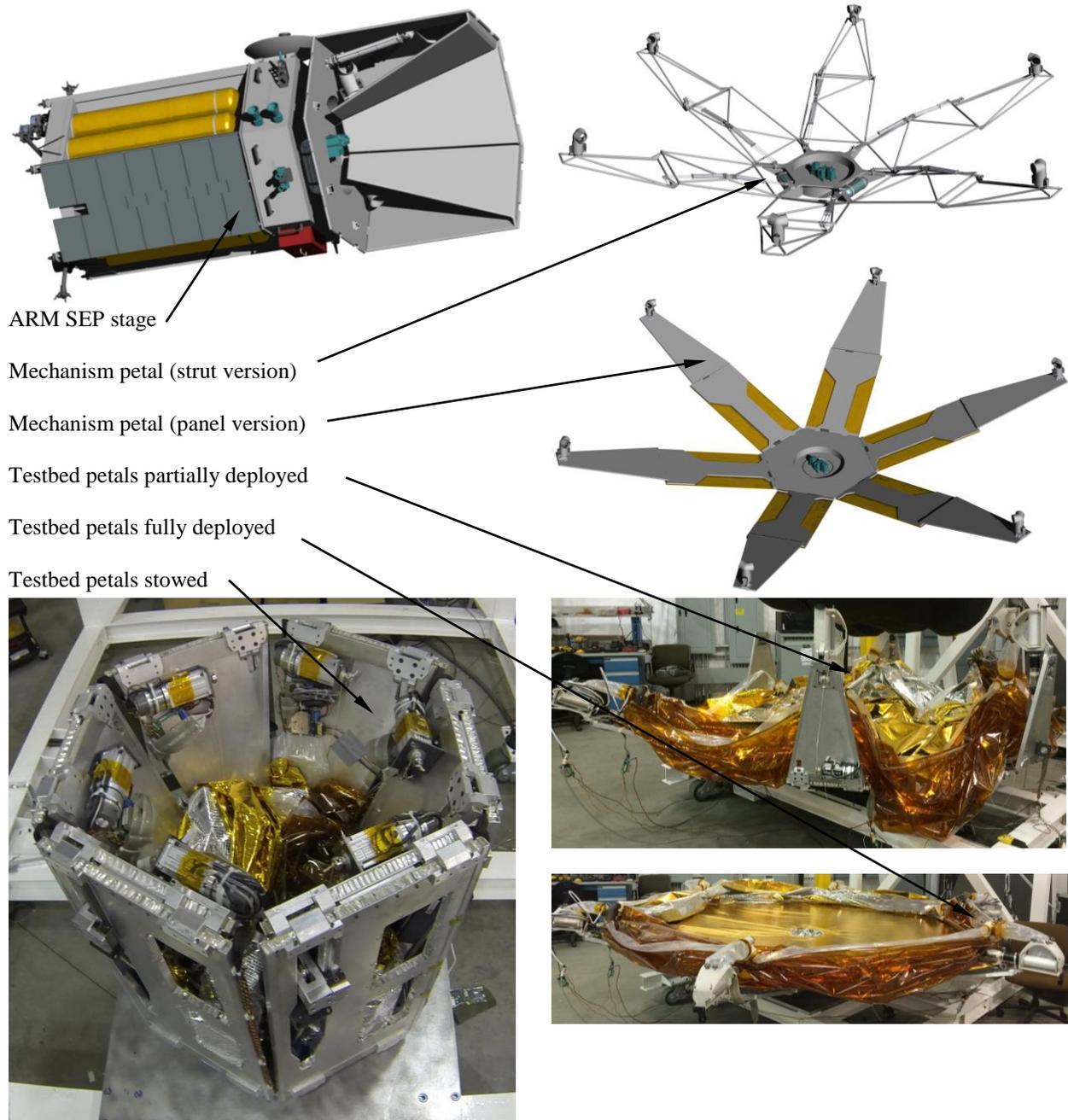


Figure 12: Proposed Option A asteroid capture mechanism flight version (top), and robotic testbed (bottom)

physics engine calculates the commands to the robot arm so that the state of the asteroid evolves correctly as seen by a body-fixed observer on the spacecraft, despite the fact that the spacecraft is not an inertial reference frame.

After the asteroid has been characterized, the compact hexagonal stowed package (Figure 8, upper left) opens up and readies the capture mechanism for asteroid capture. The testbed simulates a hexagonal stowed configuration (Figure 10, lower left). Linear actuators with force-feedback open the rectangular petal sections and then the trapezoidal sections to a full star shape. The star shape is maintained open while feedback-controlled winches at each petal tip keep the trampoline at a specified tension.

A display in the testbed area shows what an external observer would see from a nearby inertial reference frame, with both the asteroid and the spacecraft moving according to the laws of physics. Once the capture is initiated (e.g. following approval by Earth operators), the RCS thrusters of the spacecraft are pulsed-on momentarily to start advancing the spacecraft at ~ 5 cm/s along the angular momentum vector of the asteroid. It is assumed that the spacecraft has already spun-up so that the rotation around the spacecraft symmetry axis matches that of the asteroid. Of course this is all invisible in the testbed, because the spacecraft frame is the same as the laboratory frame. Only the physics engine "knows" that the whole laboratory is spinning, so that it can correctly calculate all the "fictitious forces" such as centrifugal and Coriolis.

Once contact is made between the asteroid and the trampoline, the simulated RCS thrusters (which again exist only in the "mind" of the physics engine) are commanded to apply a continuous thrust of a few hundred Newtons between the trampoline and the asteroid, always aligned with the symmetry axis of the spacecraft. This simple algorithm avoids the need for any sort of closed-loop sensor feedback in the control of the spacecraft during the capture process. By maintaining the thrust along the symmetry axis, the asteroid effectively "feels" a small equivalent gravity force as if it were "falling" into the trampoline. The spring-dampers cause any relative motion to quickly damp out. This causes the spacecraft to undergo rotational acceleration as needed to match any tumbling motion that the asteroid might have. Even though the angular momentum vector of the asteroid is constant in space, if the asteroid is tumbling then the instantaneous angular velocity vector is not constant in space. The asteroid will "roll around" in the damped trampoline until it comes to rest, as seen in the spacecraft reference frame. If the center-of-mass of the asteroid gets off of the spacecraft symmetry axis in one direction, then the continuous RCS thrust will cause the spacecraft to start to rotate so as to roll the asteroid over the trampoline in such a way as to bring the center-of-mass of the asteroid back to the centerline.

The physics engine is programmed with the inertial properties of the spacecraft and the asteroid, which allows the full-scale capture event to be studied. As with most hardware-in-the-loop simulations, the benefit of this system is that the forces and torques of interaction between the asteroid and the capture mechanism are measured – not simulated. So whatever complex physics might occur between the surface of the asteroid and the bag/trampoline material are automatically incorporated, despite the fact that such physics might be incredibly difficult to model. Had Option A continued development, it was assumed that different asteroid surfaces and bag materials would be tested to evaluate issues such as "snagging" of the fabric by the surface of the asteroid. Also complications in the asteroid motion caused by the hole in the middle of the trampoline would be evaluated.

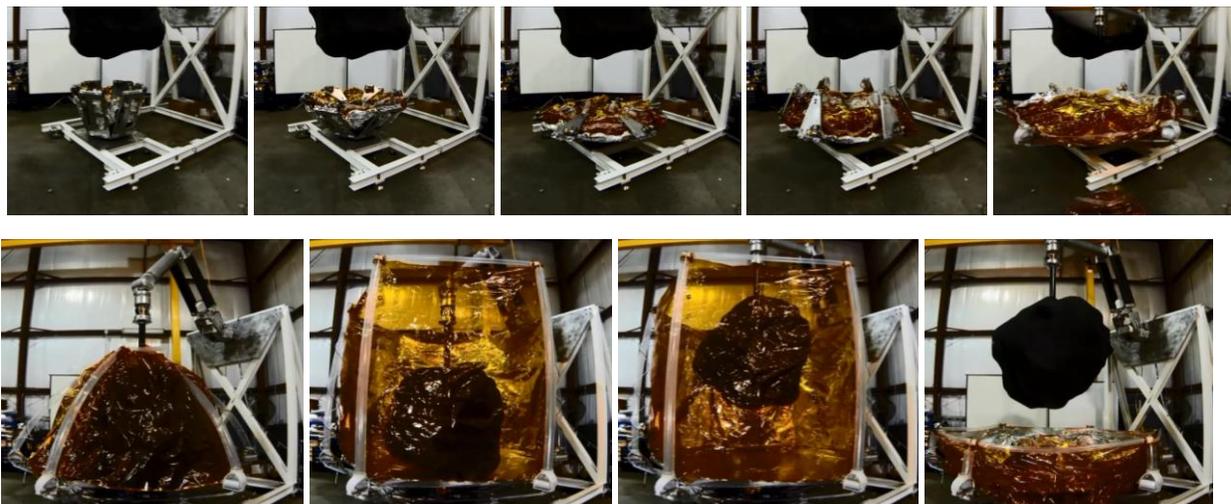


Figure 13: Hardware-in-the-loop Option A capture testbed sequence (clockwise from upper left)

V. Asteroid Testbed Physics Engine

The *Darts/Dshell* simulation described earlier is used as an intrinsic part of the asteroid capture testbed, as a “physics engine” allowing the dynamics to evolve in a virtual zero-g environment. When used as part of the testbed, the modeled trampoline is removed from the simulation, leaving the spacecraft and the asteroid as nominally unconnected components. The forces acting between the spacecraft and the asteroid are instead fed to the simulation from a force-torque sensor in the testbed, which is used to evolve the simulated trajectories of the spacecraft and the asteroid and in turn command the robotic arm holding the testbed asteroid. With this approach, the software simulation includes only those aspects that are well-understood – primarily rigid-body dynamics in a zero-g environment – while the difficult-to-model forces and torques arising due to contact via the compliant capture mechanism are measured from the physical testbed.

It is informative to consider the sequence of events occurring within a single timestep of the simulation:

1. At time t_n , current force-torque measurements from the base of the capture mechanism are gathered by the testbed control software and passed to the simulation software.
2. The force-torque measurement is translated into equivalent forces and torques at the spacecraft center of mass. The negative of the force-torque measurement is translated into forces and torques at the asteroid center of mass.
3. Applying the computed forces and torques, the simulation advances time to t_{n+1} , evolving the trajectories of the spacecraft and the asteroid.
4. The visualization of the asteroid and the spacecraft, as seen from the inertial frame, is updated.
5. Based on the updated state of the simulation, the asteroid’s position, attitude, velocity, angular velocity, acceleration, and angular acceleration, as seen from the spacecraft-fixed reference frame are computed and passed to the testbed control software.
6. The testbed control software updates the robotic arm actuator inputs to track the trajectory specified by the simulation software.

Physically, the simulation software resides on a separate computer, with communication taking place over a custom TCP protocol. It is the responsibility of the testbed control software to maintain time; the simulation software will block until it is told to advance time using a new force-torque reading. In this way, the simulation clock stays synchronized with real time to within one time step.

VI. Other Considerations

An implicit assumption in this approach is that the forces and torques felt by the asteroid are precisely equal to and opposite of those felt by the spacecraft. This assumption ignores those transient forces needed to accelerate the fabric material of the capture device itself. However, because the mass of the capture fabric is small both compared to the asteroid and the spacecraft, the neglected forces will necessarily be small. If available, a second force-torque sensor mounted on the robotic arm could be used to differentiate between the forces on either side of the capture device. A related issue is the 1-g weight of the capture device, a proportion of which is supported at any point in time by the testbed spacecraft and by the asteroid. The resulting forces and torques cannot be precisely compensated, either with one or two force-torque sensors; however, it can be approximately compensated, at least prior to the closing of the bag, by subtracting the static weight of the capture device from that measured by the spacecraft force-torque sensor. Because the capture mechanism is axially-symmetric and aligned with the vertical, with only the light bag fabric ever getting somewhat out-of-symmetry, this effect is minimized.

The bag material selected for the Option A capture testbed is kapton laminated with a rip-stop scrim. It was assumed that this material would be suitable for the flight system, since previous simulations had shown that, if the spacecraft matches the spin around the asteroid angular momentum vector, then the forces on the bag fabric are quite modest. During the KISS study and into the pre-phase-A work, it had been assumed that some very robust fabric such as a heavy-weave of Vectran would be required for the bag, but these subsequent simulations showed that the forces are not great so that this substantial mass penalty was not required.

One of the considerations for the bag material is thermal control of the asteroid after capture. Since the asteroid initially is in an orbit very similar to that of Earth (causing the low V-infinity), radiative-equilibrium will cause the average interior temperature of the asteroid to be near room temperature. If the asteroid is spinning at all, then large

parts of the surface are alternately exposed to the sun and to cold sky, further equilibrating most of the interior of the asteroid at moderate temperatures. One of the functions of the bag material is to try to maintain this moderate temperature during the return cruise and throughout operations in high lunar orbit so as to preserve the asteroid in a pristine state.

When the asteroid is in the bag, but the bag is not closed, then the bag forms a thermal cavity with clear lines-of-sight for thermal radiation to bathe the entire surface of the asteroid and the entire interior surface of the bag in approximately uniform IR radiation. Some combination of the trampoline and one side of the bag will be illuminated by sunlight, which will heat the bag fabric so that it radiates strongly in the thermal IR spectrum. Appropriate coatings of the bag material, such as the aluminized or gold-coated kapton used for similar purposes on many spacecraft, will ensure that the radiative temperature inside the bag is moderate, or perhaps slightly cooler than room temperature if desired. Note in Figure 13 that, in the testbed, the back-side of the capture bag is aluminized, while the front side is not coated so that visitors can observe the motion of the asteroid inside the capture bag.

Once the bag closes, and the spacecraft despins the asteroid using the RCS thrusters, then the thermal situation could be completely different. One side of the bag and asteroid will be constantly facing the sun, and the other side will face cold sky, with possibly little heat transport to equilibrate between the two. However, in our design, there is the possibility that the petals of the mechanical deployment for the trampoline can remain fully extended, while the pinch-roller winches can retract the inflatable booms such that they form straps over the top of the asteroid to "hug" it against the trampoline (second-to-last image of Figure 8, and last image of Figure 13). In this configuration, the trampoline and retracted inflatable straps form a "lens" which contacts the asteroid mostly at the top and bottom on the centerline, but with fairly large open voids on the sides. If the asteroid doesn't break-up, then this configuration would allow sufficient forces to be applied to the asteroid to fly it to the Earth-moon system (the thrust of the SEP engines is ~ 1.5 Newtons), and yet these voids around the beltline of the asteroid will allow radiative equilibrium to be established around most of the asteroid. Assuming the required thrust vector of the SEP system is roughly at right angles to the sun direction (a common situation in orbital dynamics), then the sunlight will shine on one side of the asteroid, the cavity will allow this energy to equilibrate around the beltline, and there is no large "arctic circle" which fails to see any sunlight for long periods. Again, with proper surface coatings on the bag material, it should be possible to ensure that most of the asteroid is maintained at a moderate or cool temperature by passive means. If the asteroid does break up, it may not be possible to maintain this desired thermal control, since it will likely be necessary to fold the fingers to tightly grasp the asteroid on all sides, as shown in the lower-left of Figure 8. But if the integrity of the asteroid is retained, then it may be possible to fly the asteroid back using the configuration shown just to the right of the Figure 8 lower left tight-grip illustration, maintaining the desired thermal control.



Figure 14: Detail of pinch-roller winch on Option A capture testbed

Several methods for de-spinning the asteroid were considered, including "yo-yo" masses on the end of cords that would be released to carry away the angular momentum. However, since the inertial properties and spin state of the asteroid will be unknown until the spacecraft arrives, it is difficult to design a yo-yo that "lets go" at the right time. Also, there was concern about risk of the yo-yo cords becoming entangled with the solar arrays, antennas, or other protrusions. So ultimately it was decided to despin the asteroid less than 200 kg of extra RCS propellant (the maximum needed for a ~ 2 RPM spinner). One result of this decision is that there is no physical manifestation of the despin system in the Option A testbed, because for our purposes the RCS system exists only inside the physics engine. All that is needed is that the Option A capture testbed show that the asteroid can be restrained sufficiently that the torques from the RCS thrusters be adequately transmitted to the asteroid. It is planned that the spacecraft use 22 Newton thrusters which are ~ 2 meters from the symmetry axis, so the maximum torque applied to the asteroid during despin, even with combinations of thrusters firing, is ~ 100 Nm. Since the surface of the asteroid is several meters from the center-of-mass, that requires a few tens of Newtons of force be distributed over the contact area of the bag, which is expected to be many square meters. So if each of the pinch-roller winches are retracted to squeeze the asteroid with at several least tens of Newtons, then any reasonable degree of friction between the bag and the asteroid will adequately transmit the RCS thrust to the asteroid. The pinch-roller winches can easily be designed to meet this requirement. If the asteroid is a rubble-pile that completely dis-assembles during the capture process, then the pinch-roller winches will be drawn tight to compress the loose material into the smallest possible

volume, including folding the mechanical fingers to reduce this volume, as seen in the last image of Figure 8. Also for this case, a back-of-the-envelope calculation shows that the instantaneous delivery of any residual angular momentum (beyond that already matched by the spacecraft spin around the asteroid angular momentum vector) to the bag fabric is easily absorbed by the compliance of the bag attachment to the spacecraft. This compliance comes from the spring-dampers at corners of the trampoline and the flexure of the inflatable booms attached to the top of the bag. Note that the bag fabric itself cannot load the inflatable booms in tension, which would be the only "stiff" way for forces from the capture mechanism to be applied to the spacecraft during the despin process.

Verification and validation (V&V) is an important consideration in the end-to-end Option A capture system design process. Ideally, it would be possible to V&V the completed full-scale system on Earth in 1-g. In any event it is crucial that whatever capture approach is selected not require a flight experiment in space to validate system performance and effectiveness, because there is neither time nor money in the ARM plan for such an experiment. The selected design appears to satisfy this "desirement", in the sense that it is possible to design the selected capture system (as depicted in Figure 7) so that it can deploy either vertically-upwards or vertically-downwards in 1-g (e.g. in a large vacuum chamber such as Plum Brook) and all functions can be exercised (as depicted in Figure 8). This same system would be used in flight, although the inflation pressure would be much higher than the minimum needed for microgravity. However, in the spirit of "test as you fly and fly as you test", it is preferable to use the same high pressure inflation system for flight as is used in 1-g testing.

Table 1 has the current-best estimated masses for each of the hardware elements of the Option A capture system.

Element	CBE
Capture Module	970.3
C&DH/Power	45.4
Structural/Mechanical	84.7
Petal assemblies	350.2
Actuators	170.9
Soft Goods	162.8
Inflation system	10.8
Thermal	44.9
Harness	25.6
Sensors	68.4

Table 1: Current-best-estimate masses (kg) for hardware elements.

VII. Conclusions / Discussion

Analysis and hardware testing indicates that it is feasible to capture a ~1000 ton asteroid from an Earth-like orbit and secure it tightly to a solar-electric propulsion spacecraft. This is evidently true even for tumbling asteroids by matching the spacecraft spin to the asteroid angular momentum vector, at least for spin rates of <0.5 RPM, without taking special hardware measures to protect the solar arrays from damage by transient inertial forces as the asteroid and capture mechanism interact. A hardware-in-the-loop testbed has shown that a hybrid mechanical-inflatable capture mechanism is able to deploy into a ~15 meter capture system composed of soft goods whose deployment is deterministic, repeatable, and reversible. The soft goods include a capture bag that is able to completely enclose the asteroid to prevent spacecraft contamination in the event that the asteroid breaks up. A "trampoline" cushions the spacecraft from asteroid contact using a relatively small mass, with active direct-drive motors performing the needed spring-damper function by tensioning cords connected to the corners of the hexagonal trampoline. Continuous unmodulated and uniformly-directed thrust by the spacecraft RCS system allows the asteroid to "settle" into the trampoline as its relative motion damps out with respect to the spacecraft. Once the asteroid is completely enclosed by the capture bag and secured by cinch cords, the RCS system can despin the entire spacecraft/asteroid system using a modest RCS propellant mass.

Had Option A been selected as the ARM mission plan, work would have continued with the testbed to establish the range of bag and trampoline fabric types are sufficiently robust for this application, despite a variety of plausible asteroid surface properties. For example, it was planned to emplace temporary hooks into the surface of the asteroid mockup so that snagging of the bag at first contact was virtually assured. Other variations amenable to study using the testbed include the degree of tumbling of the asteroid (e.g. angle between the instantaneous spin vector and angular momentum vector), different inertial properties (e.g. highly oblate to highly prolate), and capture timing strategies (e.g. keeping the bag open until the asteroid has settled into the trampoline).

In summary, it is believed that the capture of an entire small asteroid by a SEP spacecraft is feasible with low mass penalty both in terms of the capture mechanism and in terms of RCS propellant use.

VIII. Acknowledgments

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