Concepts for Mars On-Orbit Robotic Sample Capture and Transfer

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***Abstract*—A potential Mars Sample Return (MSR) mission would require robotic autonomous capture and manipulation of an Orbital Sample (OS) toward returning the samples to Earth. An orbiter would capture the OS, manipulate to a preferential orientation for the samples, transition it through the steps required to break-the-chain with Mars, stowing it in a containment vessel or an Earth Entry Vehicle (EEV) and providing redundant containment to the OS (for example by closing and sealing the lid of the EEV). In this paper, we discuss the trade-space of concepts generated for both the individual aspects of capture and manipulation of the OS as well as concepts for the end-to-end system. Notably, we discuss concepts for OS capture, manipulation of the OS to orient it to a preferred configuration, and steps for transitioning the OS between different stages of manipulation, ultimately securing it in a containment vessel or Earth Entry Vehicle.**

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1. INTRODUCTION

A potential Mars Sample Return (MSR) architecture consists of a multiphase mission which would incorporate several critical technologies, see [1-4]. The fundamental objective would be to return samples of Martian rock, regolith, and atmosphere for analysis in a terrestrial laboratory. JPL's Mars 2020 Rover will obtain samples and insert them into sample tubes. These tubes will be left on or just beneath the surface of Mars. A future mission could collect the sample tubes on the Martian surface and load them into a Mars Ascent Vehicle (MAV), a small two or three stage solid rocket booster. The MAV would ascend into low Martian orbit (LMO). Once in orbit, the MAV would eject the sample canister as an orbiting sample (OS). The OS would be captured in LMO by the conceptual Next Mars Orbiter (NEMO), and reoriented from an unknown orientation to a known orientation. The OS would then be sealed in a redundant fashion by a break-the-chain (BTC) process in order to comply with planetary protection requirements. After that, the OS would be inserted into an Earth Entry Vehicle (EEV) to bring it back to Earth. This paper specifically addresses the capture, reorientation, and retention of the OS.

2. ORBITING SAMPLE (OS) CONCEPT PARAMETERS

The OS would be captured with an incoming relative speed of up to 10 cm/s, and a rotational speed of up to 10 RPM. The OS would be equipped with a beacon to track its relative location to within 10 cm (including the positional and attitudinal uncertainty of the spacecraft).

The OS would have a mass of 12 kilograms and a major diameter of 28 centimeters, and would be roughly spherical in shape. Because the OS serves as the nose cone of the MAV, on hemisphere of the OS would feature Thermal Protective Shielding (TPS). This hemisphere may not be modified with positive features, but may have negative features e.g. a groove or blind hole. The opposite hemisphere may have either positive or negative features, but would require negative features for the ejection mount on the conceptual MAV. Henceforth the plane dividing these hemispheres will be referred to as the equatorial plane.

The OS would be loaded with the sample tubes such that the tubes are oriented at a 45-degree angle with respect to the equatorial plane.

3. SYSTEM GOALS

As the distance between the OS and the spacecraft narrows to one meter, the OS would fill the entire field of view of the onboard camera and no new data would be taken. As such, the capture of the OS would have to be completed entirely autonomously, and failure could result in an uncontrolled collision between the OS and the spacecraft. The goal of the capture, therefore, would be to autonomously accommodate the full spectrum of position error and nonzero incident angle of the incoming OS, and constrain the OS about all three translational degrees of freedom. Ensuring a successful capture would require an evaluation of contact dynamics between the OS and the capturing mechanism, e.g. a capture cone.

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The OS would be captured with an unknown orientation; the OS would have to be re-oriented to a specific orientation to prepare for a landing event. Note that in a special case where the required orientation of the tubes is orthogonal to the gravity vector at landing, only 1 degree of freedom must be reoriented. In all other cases, 2 DOF of rotation must be reoriented. In all cases the sample tubes could rotate about their cylindrical axis. Because the nominal landing orientation is not finalized, an optimal design will constrain the OS in 2 rotational DOF.

Once the OS is captured and oriented, it would have to be retained such that its 5DOF positional and attitudinal constraints are maintained throughout the EEV's crash landing on the Earth's surface. The OS would be retained within the BTC seals, and the OS that would return to earth should not include any vestiges of a capture or reorientation process, e.g. actuators.

4. Approaches and Performance Metrics

In this section we show system criteria adapted as figures of merit in order to more quantitatively assess the feasibility of each proposed architecture. Each merit/criterion is assigned a weight from 1-3 to reflect how critical it is for a successful mission. 1 represents is a low weight; this figure of merit is useful to be considered, but not fundamental to the ultimate goal. 2 represents an intermediate weight for features that dramatically increase feasibility but are not essential to mission success. 3 represents a high weight. These are bounding criteria of the system architecture.

The system shall:

(1) Have as few actuators as possible (≤ 3); weight 3.

(2) Not rely on a particular coefficient of friction between the OS and any component. Because the OS will be dirty when it is captured, this coefficient of friction is indeterminate. A form closure approach is preferred; weight 3.

(3) Minimize the components that will remain inside the OS container through the earth re-entry and landing phases. All such components must be rigid bodies with fixed attachments; weight 3.

(4) Retain the orientation of the OS during the entire landing event, during which the OS will experience ~3000 g's; weight 2.

(5) Behave in a deterministic way, i.e. a pre-determined time-dependent / limited action set will lead to capture, reorient and retain the OS (defined time window is related to power resources); weight 2.

(6) Make as few modifications as possible to the non-TPS hemisphere of the OS; weight 1.

(7) Minimize the volume of the OS container used to retain the OS; weight 2.

(8) Retain the OS with a different mechanical component than the one used to capture the OS (Planetary Protection requirements); weight 3.

(9) Ensure that as few components as possible could interact with the OS, and each of them can be ejected after interaction (Planetary Protection requirements); weight 3.

(10) Be compatible with the MAV system, BTC system, and EEV system; weight 3.

5. OS Capture Dynamics

Monte-Carlo style analyses of an OS being captured over the full range of potential OS trajectories were performed in M3TK, an in-house dynamic simulation software. For a given cone and OS geometry, we can evaluate the range of conditions for which the OS is successfully captured. This quantification informs the specifications that a proposed flight system must meet in order to ensure capture, e.g. the cone geometry and the speed at which the lid closes. The capture cone paradigm is dramatically more successful if there is an intermediary stage in which the OS is enclosed before it is constrained. If the OS is surrounded by an enclosed volume prior to any collision event, the system does not rely on contact dynamics for a successful capture.

Two zero-g contact dynamics testbeds were built to supplement the dynamic simulation. The first is a 3-axis gantry with a rotating OS end effector and an integrated force-torque sensor. The three translational axes are active, and are driven entirely by data from the force-torque sensor. By calibrating out the gravity vector, the OS will respond to external forces as if it were floating in zero-g. It is important to note that this is merely an approximation since the bandwidth of the gantry is of a smaller order than the bandwidth of the metal-on-metal collisions we seek to evaluate. There is a single active rotation axis on the OS, which is controlled by a thin-gap motor. The thin-gap motor can work like a clutch; the OS can be actively spun to an initial velocity and then allowed to rotate passively. There is a second entirely passive axis of rotation on the OS.

A full-scale cone was built from aluminum to test the contact dynamics of an OS entering a capture cone. The capture cone was fabricated from two waterjet rings connected by aluminum tubing. The tubing is mounted on revolute joints, enabling the height of the cone to be reconfigured in-situ. Aluminum sheet metal was bent along to the interior of the cone so that the OS interacts with a solid metal surface instead of intermittent struts.

Figure 1. The Gantry and Capture Cone testbed

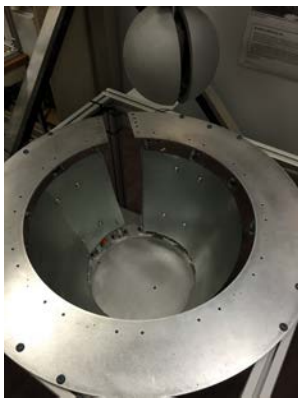

Figure 2. Testbed OS and Cone Detail

The second zero-g analog is a rigid OS mounted as the end effector of a Kuka robotic arm. By mounting an OS to the end of the 6 DOF, the OS can be moved to any position and orientation within the Kuka's workspace. A force-torque sensor was also mounted on the Kuka arm so that the OS will respond to contact forces in real-time in a similar fashion to the gantry.

6. INITIAL REORIENTATION CONCEPTS

The first reorientation concepts we surveyed were extremely general in nature and did not focus on actuation, mechanisms, or system-level integration. This type of trade-space analysis was useful for identifying various distinct methodologies for reorienting a spherical object. Some initial concepts are briefly summarized below:

Omni drive wheel: The OS is preloaded against omni drive wheels, which rotate the OS until a sprung-loaded retention feature seats into a potential well in the OS. The BallIP features [6] a similar usage of multi-axis reorientation from omni drive wheels to balance a counterweight atop a ball.

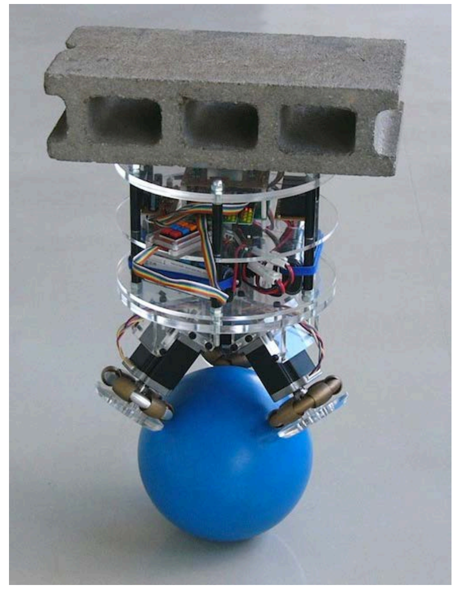

Figure 3. BallIP using omni wheels to balance on a ball

This design uses a gravitational preload to constrain the omni wheels to the sphere; the omni wheels can be constrained to the sphere in a zero g environment by a sprung loaded ball transfer.

This design is particularly attractive because it allows the OS to remain fully translationally constrained during reorientation. However, it cannot be considered deterministic because the omni wheels rely on friction to apply a moment to the OS. Because the OS will be dirty when it is reoriented, the coefficient of friction cannot be easily characterized. It is therefore very difficult to determine the required preload to ensure a no-slip condition is met.

Head scratcher: This design utilizes an OS with an equatorial flange. Three "fingers" would start at a single point on the OS (shown in figure 4), and trace three equally-spaced hemispherical paths (shown in figure 5). When the fingers reach a plane, they will each coincide with the equatorial flange.

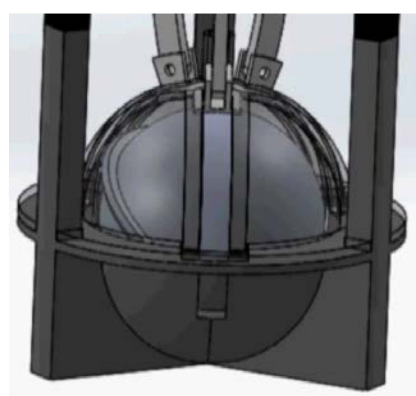

Figure 4. CAD rendering of the head scratcher at initial position

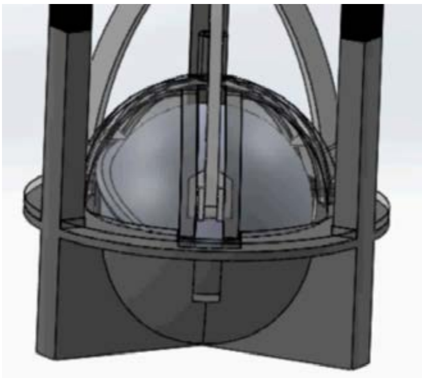

Figure 5. CAD rendering of the headscratcher mid operation

This design is highly deterministic, as there is a very small singularity region in which there is a binding potential. By chamfering both the flange and the fingers, the singularity case only exists between a point and a line (the case in which the fingers start exactly on the equatorial plan and never engage with the flange). However, two roadblocks are apparent with this design. The first is that the actually mechanism to move the fingers will be either complicated or bulky. Additionally, the design assumes that the OS will rotate freely but is translationally constrained. Implementing these constraints or accommodating an unconstrained OS adds significant complexity to the design.

Visor: A visor makes a complete sweep around an OS with a pin. The pin is ultimately captured between the visor and a retention feature, with geometric features that directs the pin to a single point. This design will be addressed at length in the ensuing section, *Integrated Engineering Concepts*.

Sense and Constrain: The OS is captured and fully constrained (6DOF) by a body on a 2 DOF gimbal. The orientation of the OS is determined via a sensor suite, and the gimbal is rotated to the proper orientation.

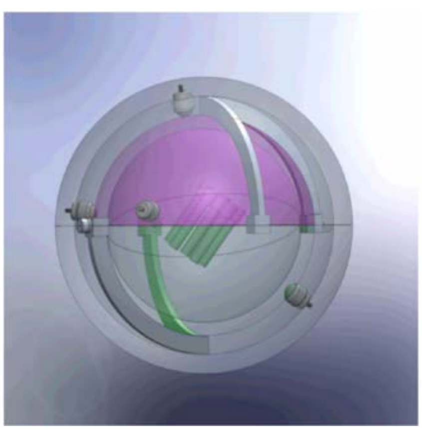

Figure 6. A 2 DOF Gimbal concept

This approach is particularly appealing in the particular case in which the tubes are meant to be oriented perpendicularly to the gravity vector at landing, since the reorientation can be accomplished with a single direct drive actuator. This is especially true since a 2DOF gimbal complicates any further manipulation of the OS to accommodate BTC operations.

Constraining an unoriented spherical OS will rely on friction (i.e. an interference fit) or crushable (i.e. Velcro), unless a retention mechanism can accommodate angular misalignment (e.g. a spring loaded pin engaging against a hole in the OS). Non-frictional retention mechanisms will also require either many parts or many features on the OS so that any OS orientation can engage with the retention mechanism.

Platonic Solid: As a possible solution to the 2 DOF gimbal requiring friction or crushable to retain the OS, we evaluated an OS with a TPS hemisphere and a non-TPS quasi-hemisphere in the form of a platonic solid. Ideally this OS would behave like a sphere during capture, but when the cups, which have mirrored negative features to the platonic solid, fully close they rotate the OS until the faces of the platonic solid seat in the faces of the cups. There are five platonic solids, each with different dihedral angles. This dihedral angle stipulates the maximum reorientation an OS will need to undergo before it seats in the cups. The dihedral angle also determines the moment-arm with which the cup can engage with the OS to reorient it.

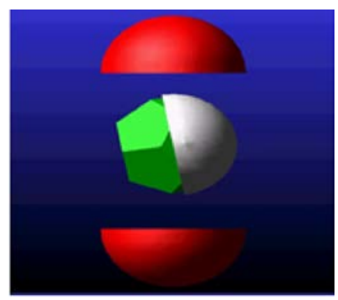

Figure 7. An MSCAdams™ Simulation of the plantoic solid concept

We performed several dynamic simulations with MSCAdams™, and conclude that this working concept presents some problems. While the design works with a low coefficient of friction (~.2), the OS can bind at several initial orientations with a higher coefficient of friction between the OS and the cups. Furthermore, several problems from the 2DOF gimbal concept persist in this variation. Notably, the 2 DOF gimbal paradigm complicates the ejection of reorientation mechanisms in preparation for the sealing of the OS and loading the OS into the EEV (without including vestiges of the reorientation process).

Iris/Grapple: Inspired by the Canadarm end effector [7], this approach entails closing a grapple or iris around a pin feature on the OS.

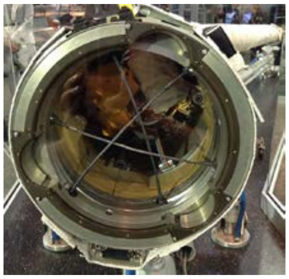

Figure 8. The Canadarm grapple end effector

A grapple would require a free body to have two pins on opposite poles to guarantee a successful reorientation. This poses a problem since requiring pins on both sides of the OS, coincident to the axis of the sample tubes, necessitates a positive feature on the TPS hemisphere of the OS. The need for two pins can be eradicated by spring loading the OS into an opening and closing iris. This, however, features many moving parts. Furthermore, irises are not designed to handle thrust loads.

Trackball: Inspired by a computer mouse, this approach entails actuating a spherical wheel preloaded into the OS until a potential well on the OS aligns with the sphere. This concept is canonically similar to the omni-drive wheel, and therefore faces the same shortcomings.

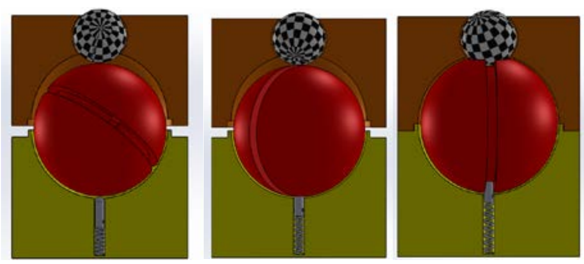

Figure 9. The trackball concept in initial, intermediate, and final states

Nested cone: This design would utilize an OS with pins at both poles. A series of concentric cylinders would engage with the OS, each with a successively larger diameter. Each cylinder would preclude the OS from a new range of orientations via the chamfered features. When all cylinders are engaged with the OS, its polar axis is constrained to a plane.

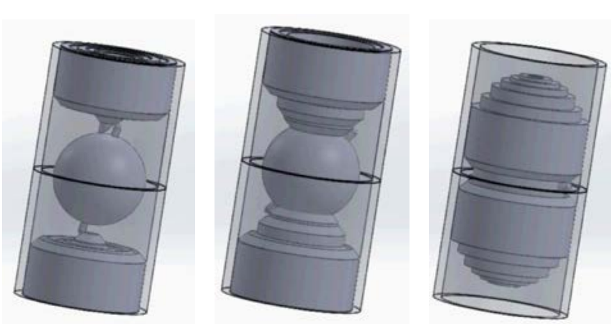

Figure 10. The nested cone concept in initial, intermediate, and final states

This design features many moving parts, and also requires a pin on both hemispheres of the OS. This lead to a possible polarity degeneration issue for what concerns the sample tubes orientation.

Chamfered cylinder: This design utilizes an OS with two hemispheres of different radii (a TPS hemisphere and a smaller non-TPS hemisphere. The OS enters a capture volume of a chamfered cylinder. This chamfering of this cylinder reflects the geometry of the OS such that this is only one OS orientation in which the lid of the cylinder can seat fully. By intermittently applying various torques to the OS via off-center axial loading, the OS should rotate about all 3 attitudinal DOF. To apply these loads, we consider a single degree of freedom linear actuator with a sprung mass system to apply periodic and eccentric torques to the OS.

Figure 11. The nominal operation of the chamfered cylinder concept

In this design, we apply this approach twice: the OS is reoriented the first time (passing from ∞^3 to ∞^2 possible orientations), the OS is reoriented the second time (passing from ∞^2 to ∞^1 possible orientations) and then retained using a form closure approach, passing from ∞^1 to the final orientation.

This design is non deterministic, and there are several identified singularity cases in which the OS will be unable to reorient.

7. Integrated Engineering Concepts

The initial trade space studies for capture and reorientation paradigms yielded several engineering-level designs for end-to-end solutions. Several of these designs are being fabricated for a testbed environment. Moving these concepts to engineering-level designs proves challenging due not only to the growing complexity of the systems, but also due to the inherent difficulty of testing weightless reorientation concepts in a 1g environment. As such, designs often require multiple testbeds or test cases to adequately assess their feasibility. Some designs can only be tested end-to-end in a zero-g flight, which can be achieved by tests on NASA's C-9 parabolic aircraft or onboard the International Space Station (ISS).

The first testbed that was fabricated was the omni drive wheel concept. The first testbed was fabricated to measure the effects of preload, camber angle, and wheel axis on the rotation of the OS. The OS rests on three ball transfers, equally spaced at a 45-degree angle with respect to the OS. Drive wheel assemblies can be easily added to the testbed at adjustable positions and orientations. Integrated load cells in the drive wheel assembly offer a live readout of the adjustable preload for each drive wheel.

The drive wheel concept was further developed for an implementation case, which included an integrated concept for OS capture. The design features a capture cone with four articulated blades that capture the OS. These blades aim to satisfy the aforementioned condition of capturing the OS before a collision event; when the blades have closed beyond a specific angle the OS cannot escape the enclosed volume. Because this angle is obtuse, it can reasonably be reached prior to a collision event. The articulated blades, upon closing fully, preload the OS into a hemisphere of the BTC shell. The drive wheels are positioned at the distal ends of the two blades, such that the preload the blades exert is through the drive wheels. These two drive wheels would then engage in an under-actuated reorientation scheme: the two wheels engage with the OS on different axes, and create a 3DOF periodic motion of the OS in a no-slip case. In order to dramatically reduce the torque the blades need to exert to avoid being backdriven when colliding with the OS, they are series elastic actuated. By incorporating series elastic actuation and allowing 1 degree of deflection during the collision between the OS and the blades, the forces imparted on the blades are reduced by two orders of magnitude.

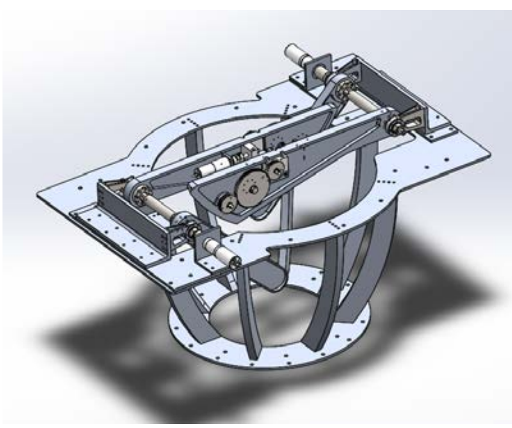

Figure 12. A CAD rendering of the capture cone with integrated series elastic actuated blades, featuring driven omni wheels at the distal end of the blades

Another tested for an integrated capture and reorientation concept was fully designed and is currently being fabricated. This design features an OS with an equatorial flange that is simultaneously captured and constrained by two hemispherical BTC shells. The inner diameter (ID) of the shells is larger than the outer diameter (OD) of the OS, but smaller than the OD of the flange. Thus the only stable configuration of the OS is one in which the equatorial flange of the OS rests between the two BTC hemispheres. The design is based on the premise of approximating the reorientation of the OS as the flip of a coin. To combat the singularity and near singularity cases in which the equatorial flange is jammed between the two shells (akin to a coin landing on edge), the flange of the OS is equipped with rollers to minimize friction between the flange and the BTC shells.

In a nominal operation the bottom BTC shell is static and the top BTC shell is driven by a linear stage. The top BTC shell is mounted to the linear stage by a universal joint, which is sprung to a neutral position. This joint enables the BTC shell to deflect in order to orient an OS that enters off-axis from the center of the cone. Once the OS is fully captured, it can be rotated about its equatorial axis until it engages with a retention feature.

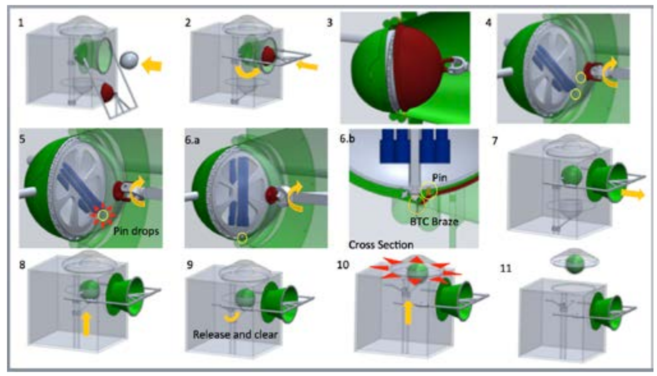

Figure 13. A full storyboard of nominal flight operations concept

The testbed in fabrication, which is designed to test certain identified jamming cases, is reconfigurable to run both in the direction of gravity and in the direction opposite gravity. By running the same tests with and against gravity, the zero-g case is encapsulated within the bounds of the experimentation. The testbed includes upper and lower BTC shells, a capture cone, interchangeable sprung universal joints, and an active linear stage. The BTC shell is attached to the linear stage through a force-torque sensor in order to measure the forces the driven BTC shell must impart to unseat the OS from jam cases.

The cone is form spun from stainless steel. The bottom shell is drawn from stainless steel, and the top shell is drawn with a welded shaft. The equatorial flange is clamped between two spun hemispheres via an internal bolt and nut, which engages on internal flanges welded to the hemispheres. The sprung universal joint is a traditional universal joint through a compression spring. This joint can be easily replaced with machined helical shaft coupling, enabling customizable deflection parameters.

Additionally, The aforementioned visor concept is currently being adapted to an engineering level design. The current design incorporates a visor, just above the bottom BTC hemisphere, on a linear rail. The visor is preloaded against a spring, and fastened into place by frangibolts. The OS, with a pin feature at its pole, enters through the capture cone into the bottom hemisphere, and is encapsulated by the top BTC hemisphere. There is adequate clearance between the ID of the BTC shells and the diameter of the OS and pin such that the OS can rotate freely and is loosely translationally constrained. Geometric constraints of this system resolve into two distinct scenarios: the visor will either engage with the pin, or with the antipole of the OS as the pin drags along the BTC shell. In the latter case, the visor is unable to pass through the antipole and therefore cannot be used to deterministically reorient the OS. To address this dilemma, the wiper features a slot with a compression spring. The wiper, in its initial configuration, sweeps over a radius that is smaller than half of the diameter of the OS and the length of the pin. If the wiper engages with the antipole before engaging with the pin, the wiper's radius will grow as the compression spring in the wiper slot is loaded, enabling the wiper to pass over the antipole of the OS. Thus the wiper will always be able to direct the pin towards the retention feature. Once the pin of the OS locks into the retention feature, the capture cone is ejected and the frangibolts preloading the wiper to the compression spring are fired. The spring pushes the wiper along the linear rail away from the OS, and the BTC hemispheres are preloaded against each other in preparation for BTC operations.

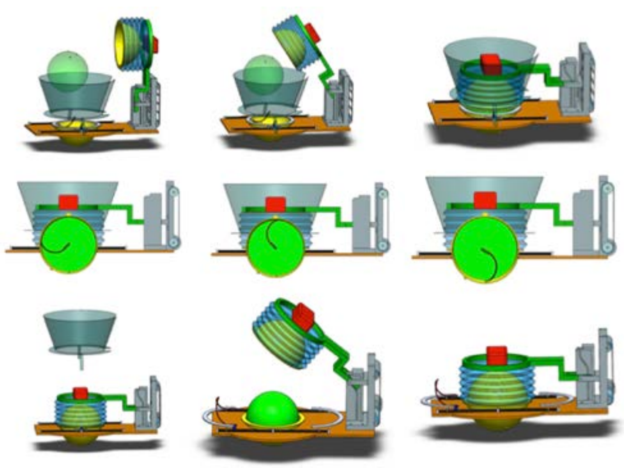

Figure 14. A storyboard for the capture and orientation concept, allowing for ejection of all capture / reorientation mechanisms prior to BTC sealing

8. CONCLUSIONS

In this paper, we have evaluated the current trade-space of concepts generated for both the individual aspects of capture and manipulation of an OS as well as concepts for the end-to-end system. We also present three integrated engineering concepts under development and evaluation through physical testbeds.

This process is an on-going research activity at NASA JPL continues to evolve in accordance with changes in the potential Mars Sample Return requirements.

9. ACKNOWLEDGEMENTS

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11. BIOGRAPHY

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