Orientation Mechanism for the Mars Sample Return Mission Capture and Containment Return System

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Abstract

NASA established the Mars Sample Return mission (MSR)[1,2] with the goal of returning samples collected by the Mars Perseverance rover. 30 sample tubes are placed in a container known as the Orbiting Sample (OS), which is launched into orbit by the Mars Ascent Vehicle (MAV) aboard the Sample Retrieval Lander (SRL). In orbit, the OS is intercepted and ingested by the return phase of the mission known as the Capture, Containment and Return System (CCRS). Once captured by CCRS, the OS is prepared for Earth entry via several specialized mechanisms such as the Orientation Mechanism (OM). The OM is a six degree of freedom device that positions and orients the OS for a precise transfer to a capsule, known as the Earth Entry Vehicle (EEV). The EEV provides atmospheric entry, descent and landing at Earth. This paper describes the development of the OM using test results from various test apparatus including a Neutral Buoyancy Tank (NBT).

Mission Overview

The CCRS spacecraft is a joint effort between NASA and ESA to return Martian soil samples to Earth. The European Space Agency (ESA) supplies the launch vehicle (Ariane 64) and the spacecraft bus known as the Earth Return Orbiter (ERO). NASA is developing the specialized payload onboard ERO to process the OS for the return trip to Earth. NASA's Goddard Space Flight Center (GSFC) in Greenbelt, Maryland is responsible for managing the overall mission with support from the Jet Propulsion Lab (JPL) in Pasadena, California. The image below contextualizes CCRS within MSR. [3]

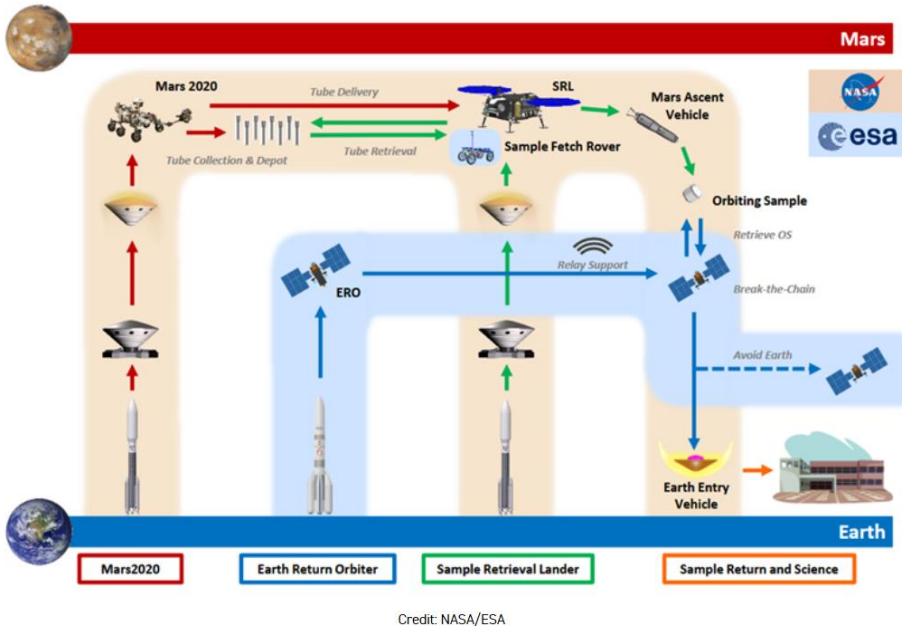


Figure 1 Mars Sample Return Architecture

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System Architecture

The architecture of CCRS includes subsystems that handle the OS at various stages. The Capture and Configuration System (CCS) on CCRS, as shown in figure 2, is designed to sequentially capture and position the OS within the spacecraft. The last stage of CCS is the OM which stations the OS precisely so a robotic manipulator can grasp and withdraw the OS from the OM.

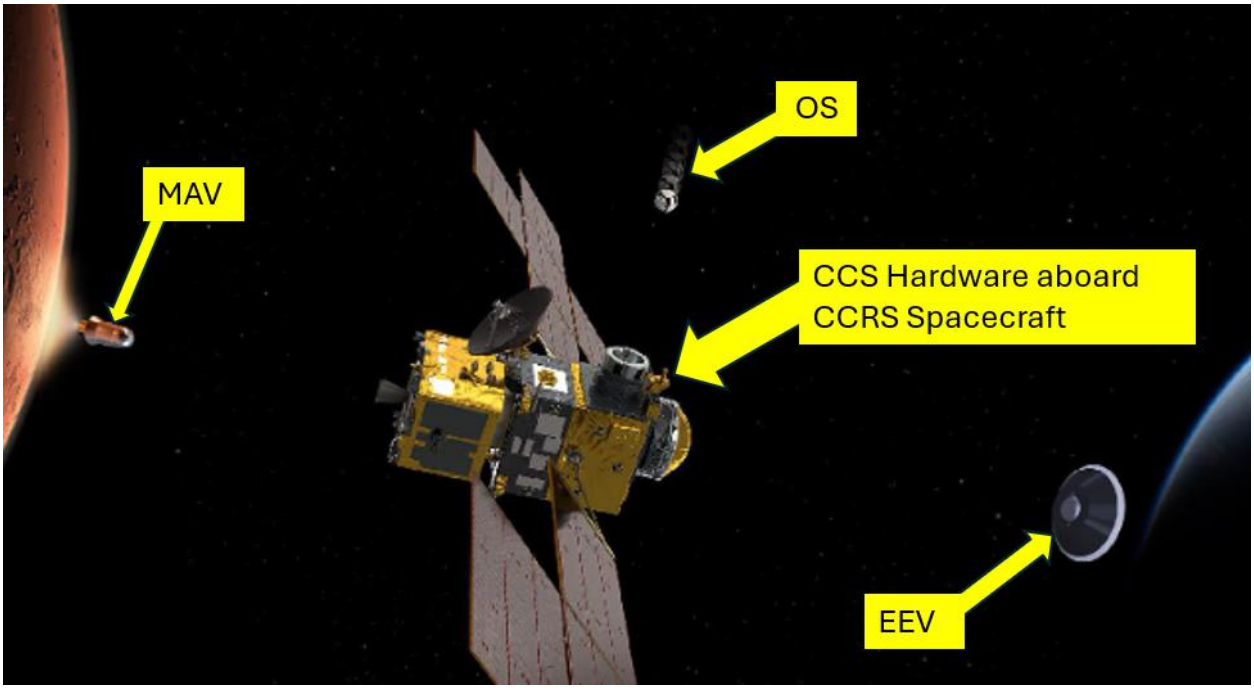


Figure 2 CCS Aboard ERO Spacecraft

The CCS is shown highlighted in figure 3 as part of the CCRS assembly.

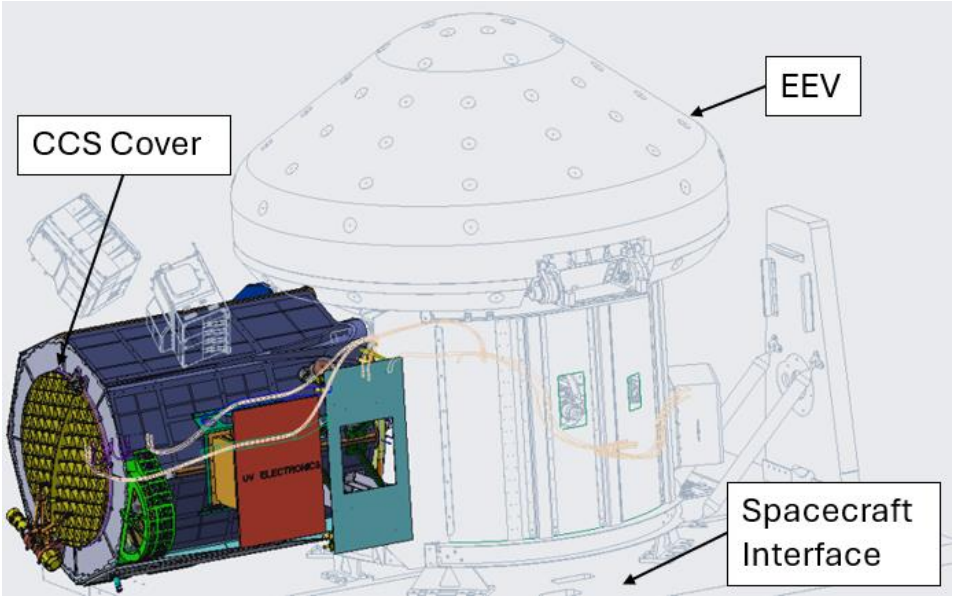


Figure 3 CCS Relative to CCRS Assembly

The OM is positioned at the mid-point of the CCRS equipment and is the final stage of securing the OS in the CCS. The image below shows the position of the OM within the CCS assembly.

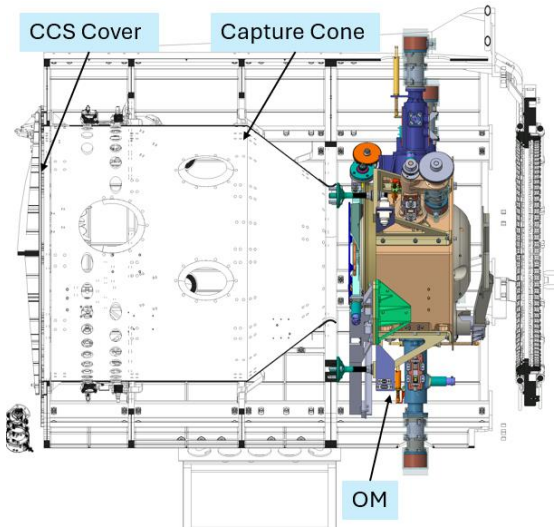


Figure 4 OM Inside of CCS

OM Description

Hardware Subsystems

The OM assembly, as shown in figure 5, consists of a cylindrical liner with two operational covers. The liner constrains the movement of the OS to a known volume with 2 openings allowing independent paddles to enter the internal volume of the OM. An upper lid, the Orientation Mechanism Guard (OMG), and a lower lid, the Restraining Door (RD), have independent functional requirements but are similar in that both can move out of the way to permit the OS to pass through.

The OM mechanisms are independently actuated by a standardized DC brushless motor with a planetary gearhead. The gearhead drives either a gear or a lead screw to get the corresponding motion. The Flat Paddle (FP) has one linear degree of freedom that applies preload through the OS into the Saddle Paddle (SP). The SP has 2 independent degrees of freedom, 1 linear and 1 rotary. The SP manipulates the OS into position and then stations itself against hard stops.



Figure 5 Subsystems within OM

Concept of Operations

The OM starts in a configuration with the OMG retracted, the RD blocking the exit, and the 2 paddles retracted. The OS is directed into the OM by a system known as the Linear Transfer Mechanism (LTM). The LTM signals the OM controller that the OS has been trapped inside the OM liner and the internal control scheme to the OM can take over.

Once triggered to close, the OMG traps the OS inside of the liner. The paddles now extend to grasp the OS within the internal volume of the OM. Depending on the position and orientation of the OS, the paddles follow an algorithm to align the OS long axis with the axis of the OM liner. The OS may present itself in manners captured in the graphic below. The first stage of operation in the OM closes the paddles to establish this initial case of the OS.

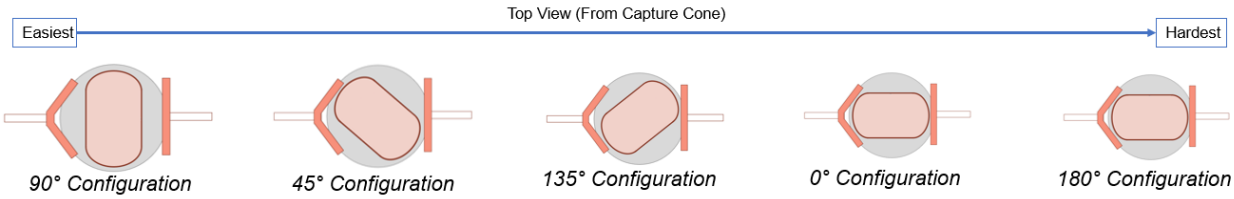


Figure 6 Possible Key Challenge Poses of OS Inside of OM

The information from the paddle positions gives a means to estimate the pose of the OM and is illustrated below. The numbers listed are the distances between the paddles as the process moves the OS into alignment.

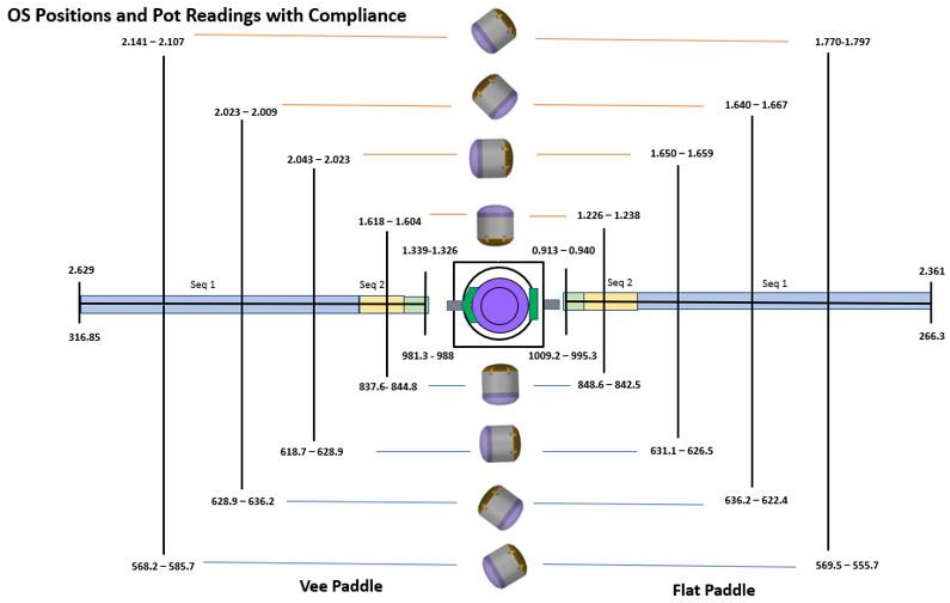


Figure 7 Paddle Separation as OS is Aligned

Once the OS is captured between the paddles and aligned to the liner, the paddles relax slightly, and the RD pushes up to seat the OS against the bottom surface of the OMG. The paddles then firmly regrasp the OS and the OMG is opened. Cameras located above the OMG take pictures of the OS to determine orientation by passing an image through a pattern recognition algorithm [4]. The image is transmitted to Earth to confirm the OS orientation. Once orientation is confirmed, either the OS is flipped (in the case the OS is upside down) or the OMG is closed again.

At this stage the OS is ready for processing downstream of the OM. A system of ultra-violet (UV) lights irradiates the OS to remove the risk posed by external contaminants. After the necessary duration of exposure of UV onto the OS has elapsed, the RD is retracted, and the manipulator moves into position to grasp the OS. A grasping mechanism on the manipulator, known as the SOLAR, cages the OS and fingers latch on. The OM paddles are then retracted to a known distance to create a controlled volume for the OS to move inside of. The fingers on the SOLAR mechanism close the grasp on the OS feature and increase the holding preload. Once SOLAR has a tight grip of the OS, the OM paddles are fully retracted, and the OS is removed from the OM.

The sequence described above gives a simplified order of how the OS starts from an unknown pose in a bounded volume to a state where the position and orientation are well understood.

Maturation and Confluences

In a most basic sense, the OS is a cylinder with round ends. The concept of operations for the OM is based on a right-angle cylinder assumption and uses custom design elements to accommodate deviations from nominal.

The contours of the OS changed over the design cycle and were shaped by tradeoffs internal to the OS team. Below is an image detailing some of the changes to the profile during this phase.

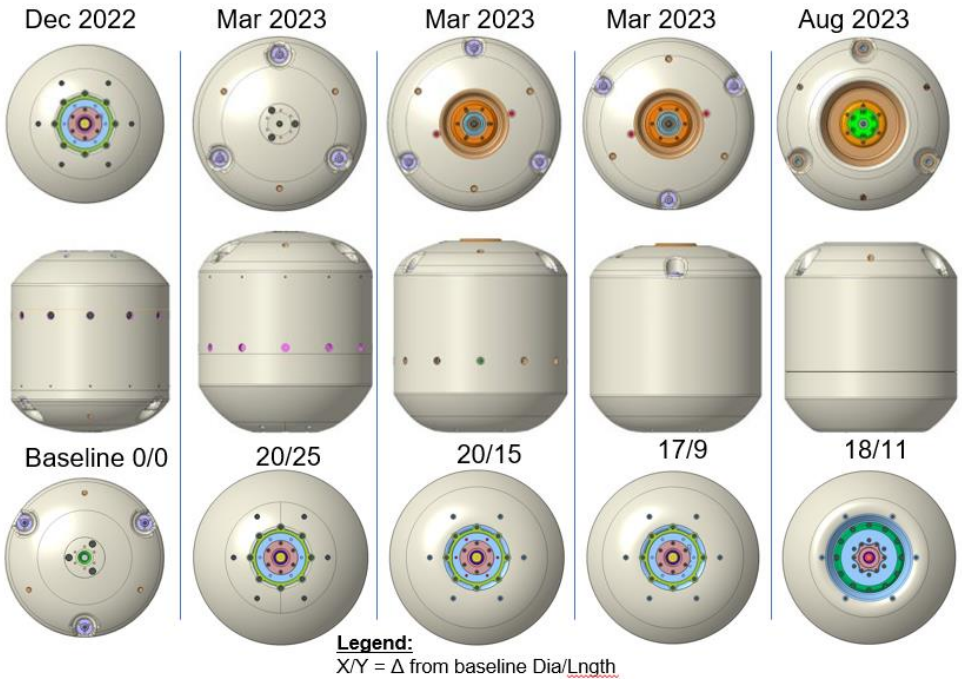


Figure 8 Timeline of Outer Shape of OS

The Interface Control Document (ICD) for the OS contains a graph, shown below, that defines load limits for hardware that touches the OS. This graph determines the curvature of contact points built into the OM based on material. The OM components that make direct contact with the OS conform to this graph. The design of these touch points intends to minimize risk of damage while still providing the means to constrain the OS.

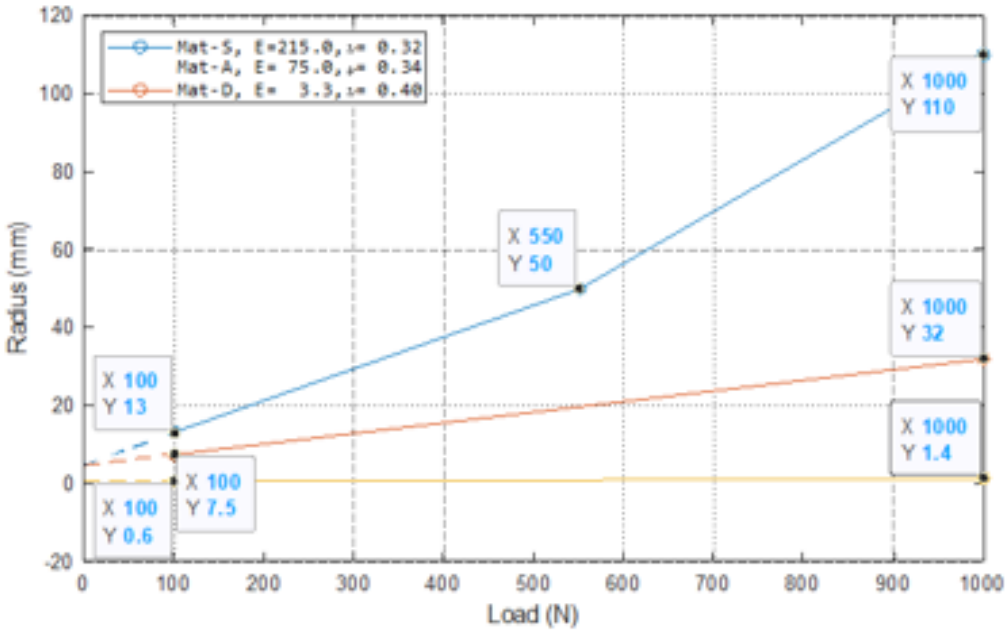


Figure 9 Graph from OS ICD Limiting Forces on OS

Subsystem components

Paddles

Early paddle designs used the V shaped approach but later evolved to use only contact points. A point contact design avoids bending stresses that are induced due to being over constrained. The OM paddle design developed towards not requiring high precision and closer to an accurate kinematic arrangement. [6]

Instead of a V shape, the paddles include five contact points, as shown in figure 10, to accurately constrain the OS. Four of the points are on the saddle paddle and positioned to create the most stable arrangement while not interfering with nearby components.

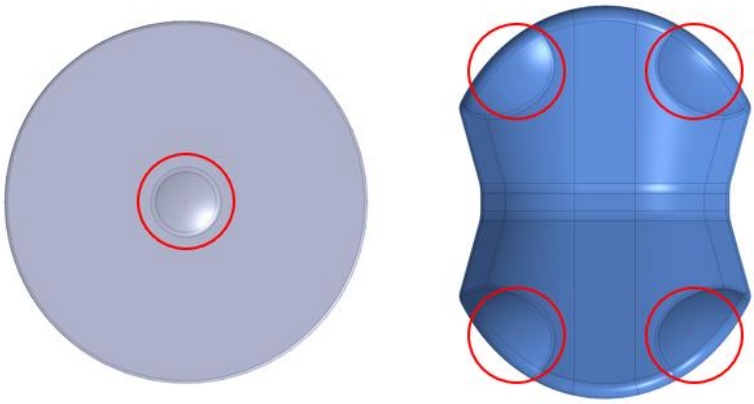


Figure 10 Flat and Saddle Paddle Touch Point Geometries

The paddle designs have an additional constraint to stay within that cylindrical portion of the OS as highlighted in figure 11. This continuous surface does not bridge across joints in the assembly and

provides a target region for the saddle paddle to seat against in the final stage of alignment. The image below highlights this region.

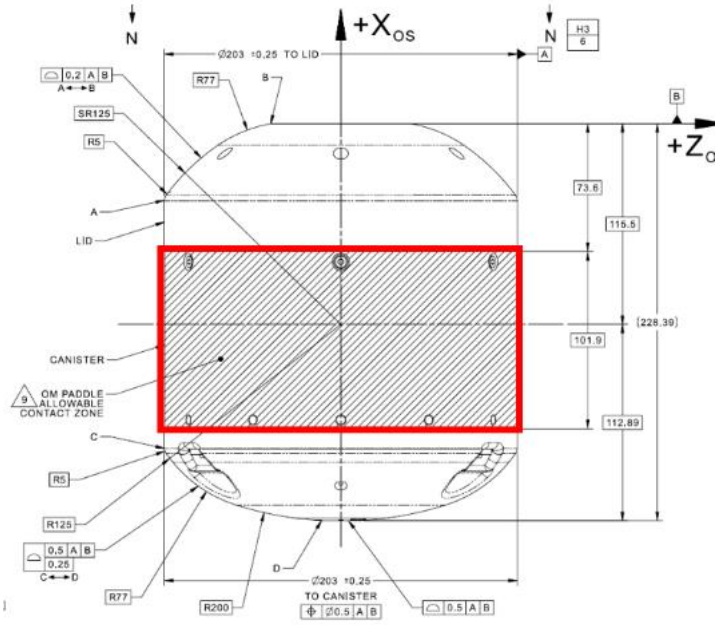


Figure 11 Region of OS for Final Seating

Restraining Door (RD)

The RD, shown in figure 12, blocks the exit of the OM and sets the bottom boundary for the OS to move within. During the OS alignment, the RD provides a seating force to push the OS against the OMG. The RD must translate along the axis of the OM and must rotate out of the way for the OS to be extracted. This motion is achieved with a linear drive along a shaped cam groove that allows for motion in both directions.



Figure 12 Registration Door

Orientation Mechanism Guard (OMG)

The OMG, shown in figure 13, is a 1 DOF device that initially blocks the opening into the OM to prevent damage during the capture phase of the OS. The OMG must withstand high energy impacts during capture without binding. The device uses a linear drive that moves the guard along a straight guide. Once the OMG permits the OS to pass into the OM, the bottom surface must provide a repeatable datum surface that the OS is positioned against for final seating.

Protruding and Retracting OS Disruptor (PROD)

The PROD, shown in figure 14, is a 1 DOF device added late in the development cycle due to late changes to the OS outer shape. The PROD provided protection against the OS falling into a pose the paddles could not resolve. In the case the paddles could not put the OS into a pose so the alignment could continue, the PROD would knock the OS out of that case so the paddles could try again.



Figure 13 Orientation Mechanism Guard

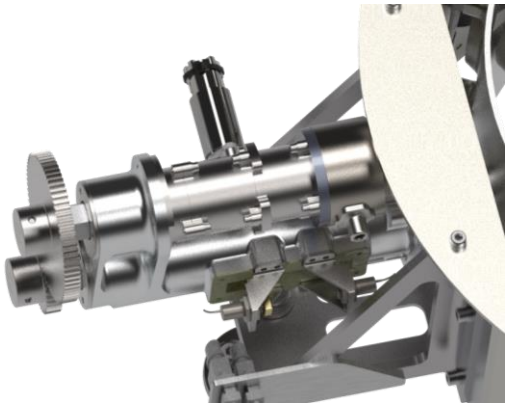


Figure 14 Protruding and Retracting OS Disruptor

OM Flight Design

The flight design was an ongoing effort up to the project's stop work order. An underwater model of the OM was built, the Neutral Buoyancy Tank OM (NBT OM), to inform the flight design. The NBT OM constraints varied from the flight version, but the test platform gave valuable insights into the problem. There are numerous requirements levied on the flight OM (74 requirements in Level 5 document) but for the purposes of this paper the functional requirements are presented. The OM design seeks to

1. Position and orient the OS within the precision needed for a successful handoff to the manipulator
2. Provide adequate clearance for neighboring hardware necessary for processing. This includes around the OS and the OM itself.
3. Present the OS in a mechanically stable fashion that can withstand loads imposed at the handoff
4. Allow clear line of sight on the OS end facing outwards for cameras to verify proper orientation
5. Actuations shall be accomplished with a standardized DC blushless motorized actuator known as the Work Horse Actuator (WHA)
6. OM is to be unpowered when sustaining the OS pose for handoff.
7. Position and orient the OS within 60 minutes
8. OM assembly to have a first mode natural frequency no less than 60 Hz
9. Provide telemetry that indicates OM status regardless of actuator feedback
10. Provide power fault tolerant means to operate OM with OS inside
11. Provide control strategies that can recover if primary sensors fail
12. Provide motion hard stops for actuators that provide repeatable indexing

The design of the OM had to meet constraints for the surrounding hardware as well as the OS itself. Much of the neighboring sub-system evolution progressed simultaneously in the CCS forcing the OM

design to be robust against changing requirements. The outer shape of the OS proved to be very influential on the design of the OM as well as strategies implied within.

Nearby sub-systems in CCRS imposed constraints on the design of the OM also. Packaging, assembly and access were just some of the concerns when adjusting solutions to accommodate mission objectives. The complexity of the requirements exchanged between the neighboring systems is beyond the scope of this paper. Suffice to conclude that design teams that cross international and intranational borders need to cooperate in a compassionate manner to meet system requirements in a sensible manner.

Testing

Testbed to facilitate development

During maturation of the OM concept, a few scale models were built that operated in a shirt sleeve environment. It became clear that dynamics of the OS in a 0 G environment within the OM would be difficult to simulate. The option of a 0 G flight was determined to be too costly and not useful as a development platform. The design team needed a test environment that was easier to access and cheap to modify. Simulating the 0 G Mars orbital environment became a focus during the development cycle.

The choice was made to use a neutral buoyancy tank for several reasons

1. The test setup is cheap to set up and operate
2. The OS is allowed to freely float in all 6 degrees of freedom when entering the OM
3. The test hardware is easily accessible for engineers and technicians to implement new designs and processes
4. The fidelity of the OM hardware could be easily upgraded as the designs matured
5. The setup allowed easy viewing of the OS during operation. This allows viewers to better understand the OS dynamics as well as permitted cameras to capture the motion.

The Neutral Buoyancy Testbed (NBT) used for development is shown in figure 15. The actuators are sealed and pressurized with compressed air to ensure the safe implementation of electrical components. As a general design rule, commercial items were used when possible. DC brushless motors with drivers coupled with planetary gearheads from Maxon were used to actuate all the devices. The potentiometers chosen for position sensing were supplied by P3 America. Custom enclosures were manufactured out of 6061 Aluminum by local machine shops. Fasteners are typical commercial varieties albeit corrosion resistant for underwater application.

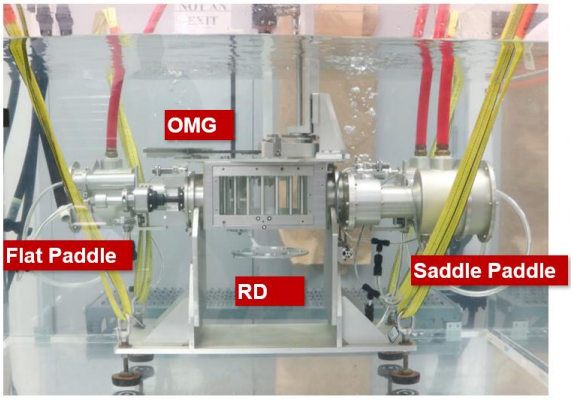


Figure 15 Neutral Buoyancy Air and Electrical Services Shown

As the design requirements matured, the need arose for position sensing of the actuators that are independent of the mechanism drive. To meet this requirement, a solution using commercial linear potentiometers that were encased in pressurized enclosures were added as shown in figure16.

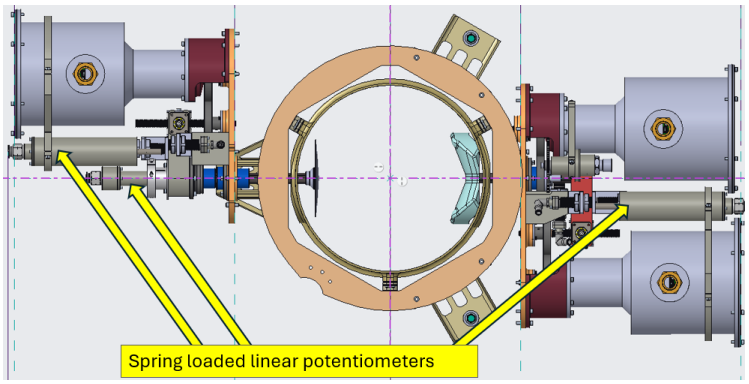


Figure 16 NBT Position Sensing and Compliance

A compliance device is integrated into the flat paddle. A spring and potentiometer give feedback as to the amount of force being reacted across the OS. This feedback allows for consistent seating in the paddles as well as protects from overloading the OS.

Facility Support

Facilities at the Goddard location for the NBT had to include services for overhead crane, compressed air, 120 VAC power and the ability to supply and drain water for intermittent use. A dedicated tank was procured fabricated from 50mm thick acrylic plate. The tank was placed on a custom frame to facilitate access and viewing. An interface box, as shown in figure 17, was constructed to isolate building power from the tank via DC power supplies. The interface box also provided a transition stage to send down regulated shop air to the actuator housings. Connections from the actuator drivers in the housings were routed up to the transition box where penetrations allowed serial connections to a control computer. A schematic of the test layout is shown below.

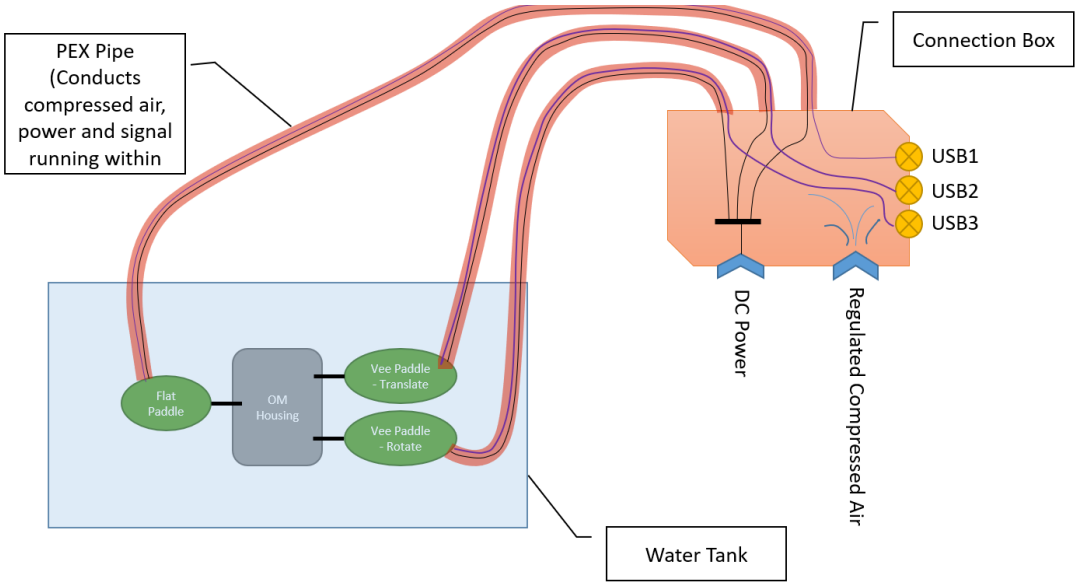


Figure 17 NBT Schematic from Interface Box

OS development for NBT

A version of the OS was developed using the outer profile that was concurrent with the flight design at that time. To make the OS buoyant, tubes sealed with air were included in the interior of the OS. Final

balancing of the OS was accomplished with internal hardware. The exterior surface of the OS was tagged with uniquely patterned markers, as shown in figure 18, that allowed for tracking the position and



Figure 18 NBT version of OS with DIC Tags

Dynamic models used to quantify the possibilities for OS orientation and position were developed in ADAMS. This model was correlated with a method of data collection known as Digital Image Correlation (DIC) [5]. The position and orientation of the OS is tracked, as shown in figure 19, while moving inside of the OM using high speed cameras. This information is correlated with the Adams model to tune contact parameters. The properties of fluid drag on the OS are used to tune the simulation properties and then later removed to approximate how the OS moves in vacuum.

Running a Monte Carlo analysis on the OS dynamics within the OM was the goal. The data from the NBT is used to gain confidence in the simulation as well as create a more accurate simulation of the OM performance.

A test assembly like the NBT OM could be flown to the ISS to operate in a true gravity-free environment. The complexity, cost and schedule required for such a series of tests was deemed unacceptable by project management at GSFC.

Concept of Operations in NBT

The OS is introduced to the OM with no predetermined position or orientation. The RD is set closed and the OMG closes behind the OS capturing the OS inside of the liner. The paddles then move towards the center contacting the free-floating OS until the paddles reach a preset force monitored by the compliance device. Once the OS stops moving, the position sensors send the paddle locations back to the control algorithm. The distance between the paddles is calculated to estimate the pose of the OS. Depending on the configuration, the SP retracts and rotates to encourage the OS into a pose that is closer to the desired final alignment pose. Once the OM has advanced past a more difficult pose it does not allow the OS to fall back into that pose in a manner akin to a ratchet.

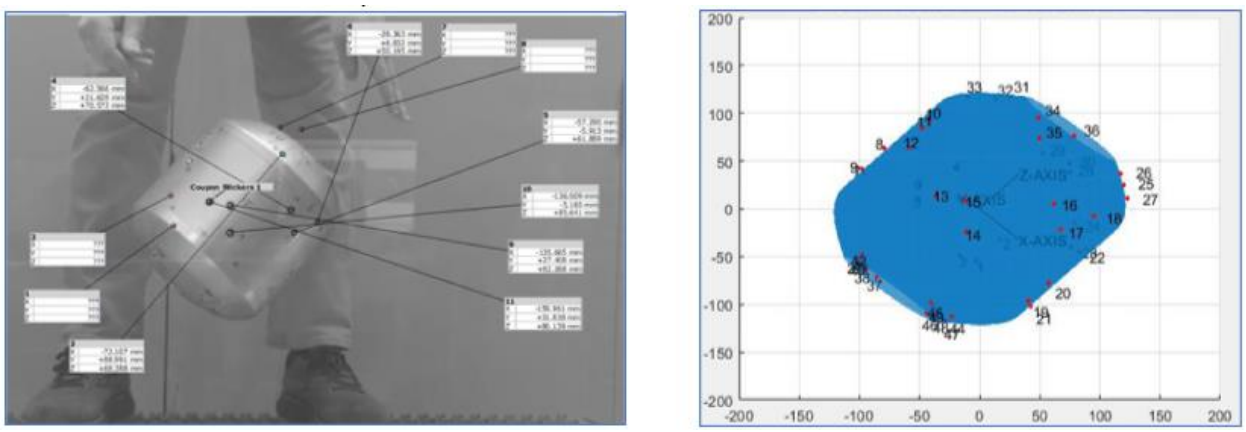


Figure 19 OS in NBT with Camera Tracking Tags

The study of the OS dynamics with the latest geometry in ADAMS revealed a case where the OS could not get out of a specific position. Although the test team never saw this case in the NBT, this special case required adding the PROD, as shown in figure 20, to knock the OS out of this pose. An analysis of 55 cases, as shown in figure 21, shows the likelihood of the OS landing in this location with this orientation.

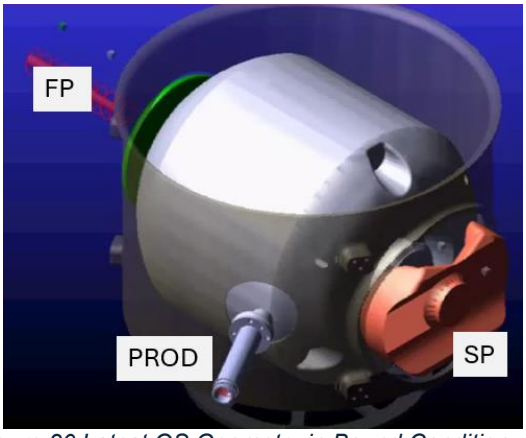


Figure 20 Latest OS Geometry in Bound Condition

Final State	#Runs	%
Final	26	47.27%
90 Deg	7	12.73%
180 Deg	7	12.73%
0 Deg	6	10.91%
45 Deg	9	16.36%
Total	55	

Figure 21 Probability of Latest OS Not Solving

Stability of the OS in the OM

In the final configuration, the OS is suspended between the OM paddles on preloaded contact points. Although this configuration is statically determinant, the stability of the OS is limited by the extent of preload applied. Analysis revealed that the preload to hold the OS in the paddles determines how much load could be applied before the OS shifted. A test setup was built to measure this force shown in figure 22.

The manipulator interface to the OS, SOLAR, imparts loads while trying to grasp the OS. The stability of the OS in this pose is crucial to SOLAR functioning. Figure 23 shows the data collected for 2 different spring rates as various preloads.

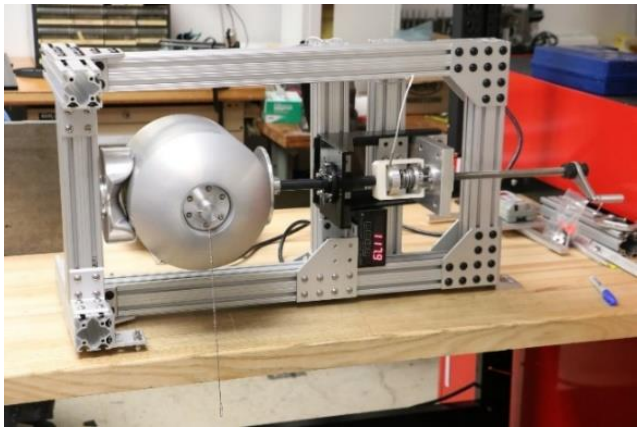


Figure 22 OS in Static Rig to Measure Stability

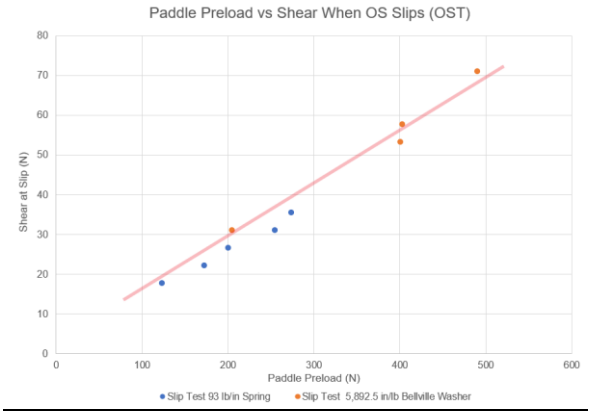


Figure 23 Plot of Load on OS at Slip

Repeatability of the OS in the Saddle Paddle

The OS needed to be stationed repeatably in the OM assembly. A means to measure how well the OS repeated a pose in the SP was built. This setup, shown in figure 24, uses a laser to measure how repeatably the OS settles in a static SP. The results shown in figure 25 imply the OS would repeatably settle into the position within an error of 0.07mm. This term is small compared to the OS position error budget of 5 mm.

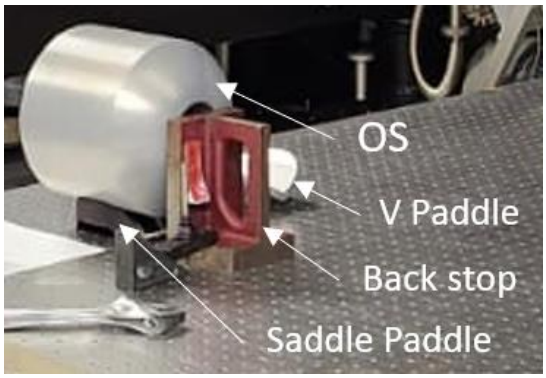


Figure 24 Measuring OS Repeatability

Saddle Repeatability			
	X (mm)	Y (mm)	Z (mm)
P1	-37.570	1533.320	-522.670
P2	-37.590	1533.310	-522.670
P3	-37.350	1533.320	-522.830
P4	-37.500	1533.320	-522.700
P5	-37.580	1533.320	-522.660
P6	-37.550	1533.330	-522.680
P7	-37.520	1533.320	-522.690
P8	-37.540	1533.320	-522.690
P9	-37.480	1533.330	-522.720
P10	-37.540	1533.320	-522.720
STDEV	0.070	0.006	0.049

Figure 25 Data from 10 Trials

Conclusions

The development phase of the OM for MSR CCRS includes many unconventional solutions that require convenient test setups. The MSR CCRS mission is highly constrained and requires teams develop complex machinery in a very short timeframe [7]. The structure of the teams working on CCRS meant discussions cross temporal, geographical and cultural boundaries were routine. The onset of virtual meeting spaces both helped and hindered the very human experience of creative work. For the work of maturing CCRS to continue, the contributions from various teams had to evolve regardless of the members truly knowing each other or each other's perspective. Building a team that collaborates effectively in this organization is difficult and no broad plan was established to build this cohesiveness [7].

This paper summarizes the maturation of the OM for several key aspects including the role testing played in shaping the designs. There are many detail lessons learned but here are some that might have helped speed up the development of the OM.

1. Define boundary conditions for the OS as early as possible. The OS was one system that reached across several systems and was not fully matured until late in the project. This hindered many sub systems such as the OM [7]. The OM has an intimate relationship with the extremal

geometry of the OS and had to adapt to all those changes. It is impossible to design an OM that would work with any shape the OS might take.

2. Establish a system where tradeoffs can be negotiated in a cooperative environment. Virtual platforms such a MS Teams should not replace forums where face to face human contact can happen [7].
3. Solidify a schedule friendly to design evolution for a complex design problem. The design of the OM had to respond to all the systems surrounding it. None of these systems were mature and therefore their requirements on the OM were in constant flux. Teams need a schedule that can buffer disruptions due to conflicts.
4. Hydrodynamic drag in the NBT slowed the OS down during free floating phases. This delay made input from the OM less influential. Paradoxically, the NBT environment is harder to get the OS aligned in the OM. NBT testing mostly resolved within 5 minutes so the team developed confidence the OM would perform on Mars orbit.
5. DIC is a great tool for capturing dynamic behavior but planning for line-of-sight viewing would allow for better data collection. Transparent view windows were added to the OM in the NBT to permit more data collection of the OS inside of the mechanism. If the design had included more transparent parts or more cameras the data should be more comprehensive. The amount of data gathered is also to be considered. External data storage is necessary.
6. A shift in the center of mass of the OS created another variable to study within ADAMS. The distribution of mass within the OS is hard to predict as the sample tube masses are not the same. Some early ADAMS runs indicate further study is necessary to understand if there is an added risk of the OM not solving.

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