An Orbiting Sample Capture and Orientation System Architecture for Potential Mars Sample Return

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***Abstract*—An orbiting sample capture and orientation system architecture for a Rendezvous and Orbiting Sample Capture System (ROCS) concept was developed to enable spacecraft-based, in-orbit capture, orientation, and transfer of a Mars sample container into a containment vessel as part of a potential Mars Sample Return (MSR) campaign. An analysis of the system functions, requirements, interactions, and constraints was performed. A trade study was carried out on relevant technologies, and a set of evaluation criteria was developed to help determine the most feasible concepts for implementation. The MArs CApture and ReOrientation for the potential NExt Mars Orbiter (MACARONE) concept is proposed as a promising system architecture for the ROCS Capture and Orient Module (COM). The concept uses a sliding trap door for Orbiting Sample (OS) capture, a Motorized Cups Mechanism for OS orientation, and a 2 DOF Turret Arm with a paddle for transferring the OS into a containment vessel. This approach facilitates modularity, development flexibility, testability in a 1G environment, analyzability without the need to simulate or test for 0G contact dynamics, ability to encapsulate potential dust surrounding the OS, and ability to be ejected to reduce the probability of Earth exposure to unsterilized Mars material.**

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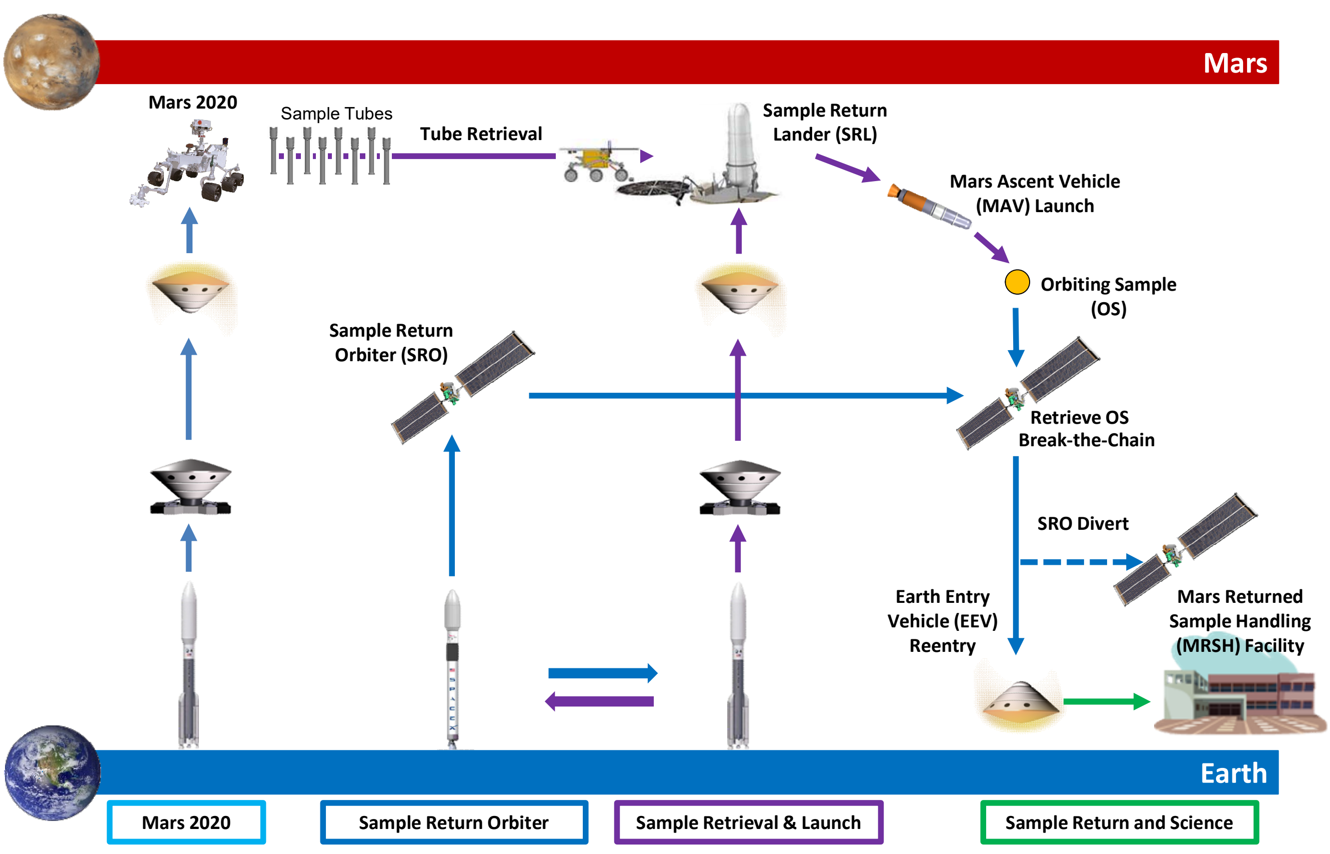

Figure 1: Notional MSR architecture. Note that all elements beyond Mars 2020 are conceptual.

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1. INTRODUCTION

Making significant progress towards Mars Sample Return was recommended as one of the highest-priority goals for the decade 2013-2022 by the 2011 Planetary Decadal Survey [1].

A driving motivation for sample return is the inability to perform definitive life detection tests on Mars with current space-qualified technology and available rover resources. Therefore, there is a desire to bring samples back to Earth to be studied using the most sophisticated laboratory equipment available. A notional architecture for sample return is shown in Fig. 1 [2], [3]. It should be recognized that all studies described here are preliminary results of work in progress and that no decisions on the design or implementation of a Mars Sample Return mission have been made by NASA.

The Mars 2020 rover will acquire, encapsulate, and seal collected regolith and rock core samples. In the future, a Sample Return Lander (SRL) would carry a rover that would recover the samples and a Mars Ascent Vehicle (MAV) to launch the samples into orbit around Mars within an Orbiting Sample (OS) container. The next element would consist of a Sample Return Orbiter (SRO) to retrieve the OS from Mars orbit and deliver it to Earth within an Earth Entry Vehicle (EEV). Once on Earth, the samples could be safely collected and transferred to a notional Mars Returned Sample Handling (MRSH) facility for quarantine and curation.

Sample Return Orbiter

The Sample Return Orbiter (SRO) would detect, rendezvous, and capture the OS in Mars orbit, transfer the OS to an EEV, and then target and release the EEV to Earth for entry. An SRO concept using solar electric propulsion (SEP) is described in [4]. Fig. 2 shows a potential rendezvous sequence carried out by the SRO [2].

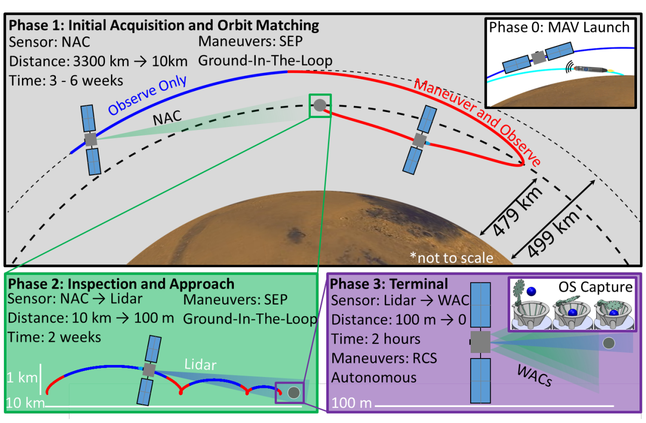


Figure 2: Rendezvous with a conceptual solar electric propulsion (SEP) orbiter [2].

2. RENDEZVOUS AND OS CAPTURE SYSTEM

A Rendezvous and OS Capture System (ROCS) is proposed as a payload for an SRO spacecraft bus to perform OS capture in Mars orbit, transfer of the OS to an EEV, and release of an EEV towards Earth for Earth entry (Fig. 3).

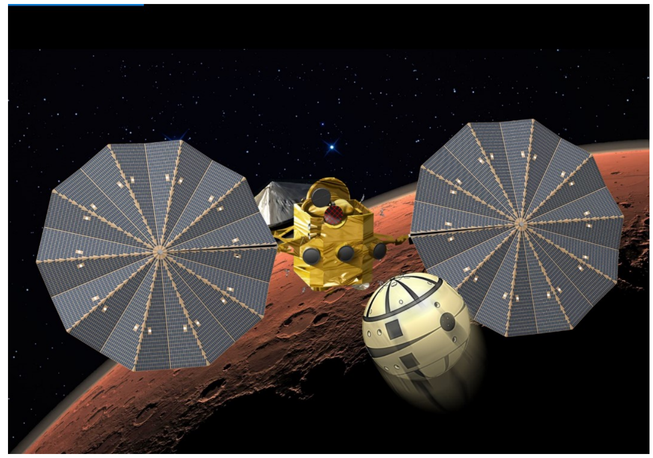


Figure 3. Artist's concept of the Orbiting Sample (OS) capture in Mars orbit (Credit: D. Hinkle).

ROCS Needs, Goals, Objectives, and Functions

A high-level description of the ROCS needs, goals, objectives, and primary system functions is shown in Fig. 4. The overarching need would be for the system to retrieve the OS from Mars orbit. Three distinct goals were specified in order to meet this envisioned need. The first goal would be to capture an OS from Mars Orbit, which would address the physical aspect of retrieving the OS. The second goal would be to "break-the-chain" (BTC) between unsterilized Mars material and Earth (i.e. to prevent exposing the Earth's biosphere to any unsterilized Mars material), which would address planetary protection back contamination concerns. The third goal would be to package the OS in an upright orientation in an EEV to preserve the sample science.

The goals were further decomposed into specific system operational objectives. The first objective would be to cage the OS (i.e. spatially constrain the OS within the system boundaries). The second and third objectives would be to seal off all unsterilized Mars material within both Primary and Secondary (redundant) Containment Vessels (PCV and SCV) to meet potential to-be-defined Planetary Protection Restricted Category V sample return mission containment assurance policies. The fourth objective would be to orient the OS in an upright orientation within ±5 degrees relative to an EEV reference axis to ensure the hermetic seals within the tubes do not see high sample-to-seal impact loads that could potentially cause a failure of the seal, putting the returned sample science at risk of contamination (Fig. 5).

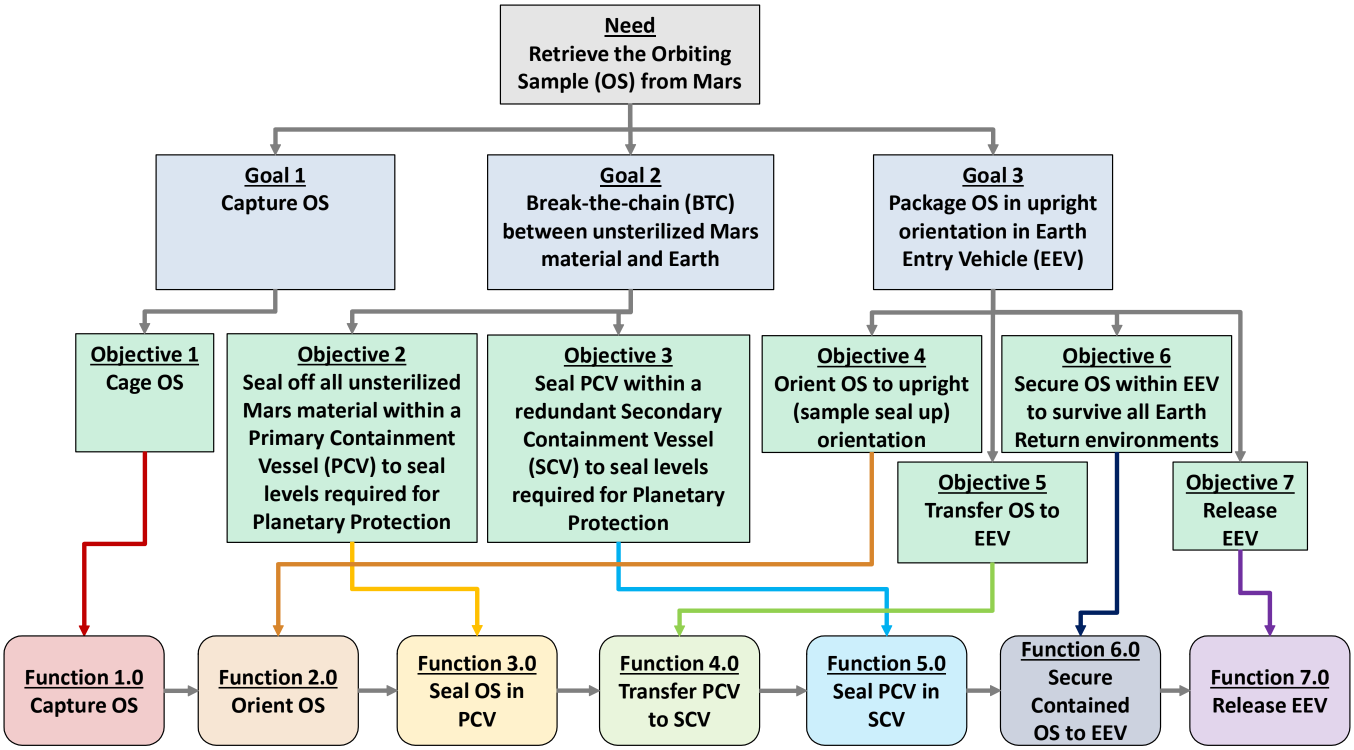


Figure 4: ROCS Needs, Goals, Objectives, and Functions.

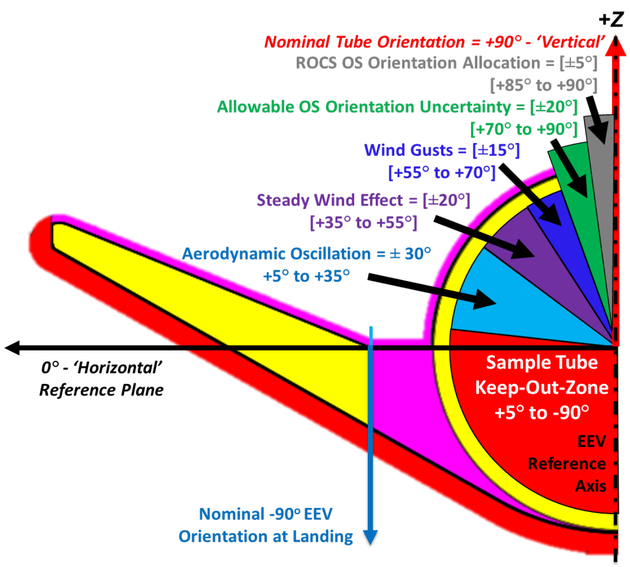


Figure 5: Diagram showing allocations for angular uncertainty of tube orientation during EEV landing (Credit: S. Perino).

The fifth objective would be to transfer the OS to the EEV. The sixth objective would be to mechanically secure the OS within the EEV in order to protect the OS, PCV, and SCV during all subsequent Earth Entry, Decent, and Landing (EDL) environments. The seventh objective would be to release the EEV from ROCS.

Specific system functions were assigned in the concept to accomplish each proposed objective. These were defined as Capture OS, Orient OS, Seal PCV, Transfer PCV to SCV, Seal PCV in SCV, Secure Contained OS to EEV (the Contained OS represents the sealed SCV, sealed PCV, and OS), and Release EEV. The functions were labeled and ordered, as shown in Fig. 4, to reflect a possible logical sequence compatible with a given set of technologies that have adoption potential into the ROCS concept. The Capture OS, Orient OS, and Seal OS in PCV functions incrementally increase OS constraints by imposing limits on translation and by constraining orientation until the OS is fully constrained within the PCV. Transfer PCV to SCV, Seal PCV in SCV, Secure Contained OS to EEV, and Release EEV address the proposed EEV layout where the SCV Base is initially housed in the EEV (Fig. 10). Packaging the OS inside the EEV would entail loading the OS first into the EEV, then applying the SCV Lid to create the secondary seal, and closing off the EEV with the Aeroshell Lid to secure the OS, which would prepare the EEV for release.

Proposed ROCS Requirements

Based on the high-level ROCS Needs, Goals, and Objectives, a proposed set of key and driving requirements were produced, as shown in Tab. 1. Requirements 1, 3, 4, 7, 9, 10, and 11 align with the seven objectives shown in Fig. 4. Due to the criticality of the capture, orientation, and BTC functions, requirements were added to explicitly provide on-orbit confirmation of their successful operation. Requirement 6 was added to ensure that in addition to sealing off Mars material within the PCV and SCV, the exterior of the SCV would be free of unsterilized Mars material.

Table 1: Proposed key and driving ROCS requirements.

ID	Proposed Requirements for the ROCS Concept
1	The ROCS shall **capture the OS** in Mars orbit with characteristics as specified in the Mission to Future Missions ICD.
2	The ROCS shall **provide on-orbit confirmation of OS capture**.
3	The ROCS shall **seal the OS within a Primary Containment Vessel (PCV)** to provide assured containment of the OS and its contents throughout exposure to all loads and environments specified in the Mars Future Missions Environmental Description Document.
4	The ROCS shall **seal the OS within a Secondary Containment Vessel (SCV)** to provide redundant assured containment of the OS and its contents throughout exposure to all loads and environments specified in the Mars Future Missions Environmental Description Document.
5	The ROCS shall **provide on-orbit confirmation of proper operation of the BTC operation** and **containment systems** in telemetry.
6	The ROCS shall **assure**, through a combination of: (i) cleaning, (ii) sterilization, and/or (iii) encapsulation, that **no unsterilized Mars material is present exterior of the OS containment vessels**.
7	The ROCS shall **orient the OS reference axis within ±5 degrees** relative to the EEV reference axis.
8	The ROCS shall **provide on-orbit confirmation of proper OS orientation** relative to the EEV.
9	The ROCS shall **transfer the PCV to the SCV**.
10	The ROCS shall **secure the Contained OS to the EEV**.
11	The ROCS shall **release the EEV** under conditions as specified in the Mission to Future Missions ICD.

ROCS Assumed Interactions

Fig. 6 shows the assumed primary external entities and their key interactions with ROCS. External conceptual entities include the Sample Return Orbiter (SRO) spacecraft that carries ROCS, the OS, ground support equipment (GSE) used for system integration and test, and the Mars Returned Sample Handling (MRSH) element Human-System Interface (HSI) that retrieves the EEV and accesses the OS. The EEV is highlighted within ROCS since it would separate from the rest of the ROCS payload upon Earth return and independently interact with the MRSH HSI.

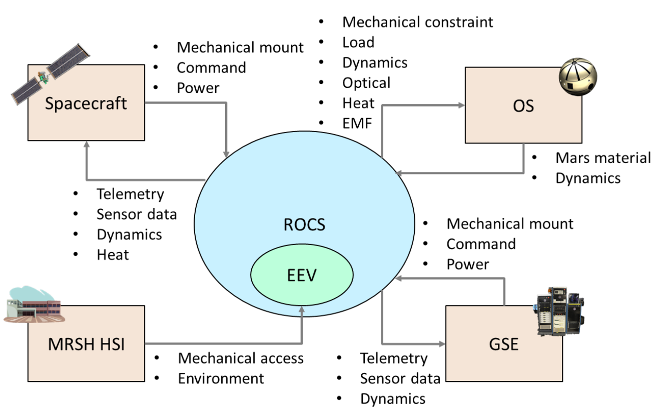


Figure 6: ROCS context diagram.

Both the GSE and Spacecraft provide mechanical mounting, power, and commands for integration, testing, and operations. ROCS feeds back to the spacecraft and GSE telemetry, sensor data, possible heat soak-back from the BTC operation, and dynamics from the capture and manipulation of the OS, as well as release of the EEV. The OS potentially exposes ROCS to Mars material and contact dynamics. ROCS exposes the OS to mechanical constraint, load, and dynamics for manipulation and packaging into the PCV, SCV, and EEV. Additionally, ROCS may perform optical active sensing of the OS for capture and orient operations, as well as introduce heat and electromagnetic fields to the OS during the BTC operation. The MRSH HSI may potentially place the EEV within a controlled environment upon retrieval and disassemble the EEV, SCV, and PCV to access the OS. In this architecture, all motor control, data acquisition, power, computing, and communication with the ground are assumed to be carried out through the Spacecraft.

ROCS Assumptions and Interfaces

The following assumptions were made for the OS, OS rendezvous, BTC, and EEV.

Orbiting Sample (OS)—A diagram of a notional OS for 31 sample tubes is shown in Fig. 7 and described in [5]. Parameters assumed for the OS are:

- **Diameter:** Maximum 28 cm
- **Mass:** Maximum 12.5 kg
- **Center-of-mass Offset:** Maximum 1 cm
- **Moment of Inertia:** Maximum 0.15 kg-m^2
- **Outer Mold Line (OML):** Spherical with potential for negative or positive features
- **Surface Characteristics:** Thermal control coatings consisting of gold platting and black thermal paint with matte finish
- **Relative Spin Rate:** 1 to 3 rpm

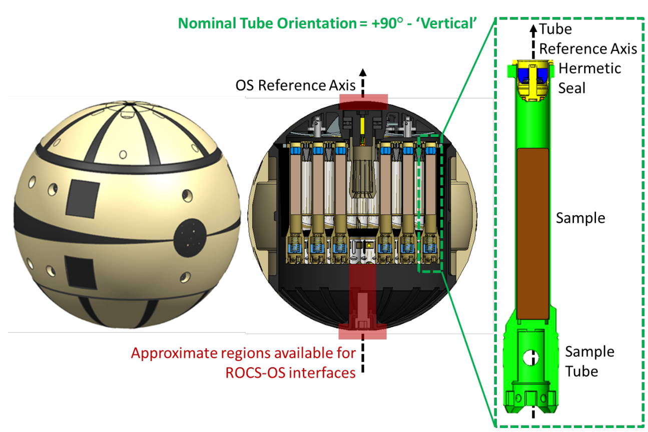


Figure 7: Notional OS with sample tubes. Regions available for ROCS-OS interfaces are shown in red.

OS Rendezvous—Assumed initial conditions of the OS at the onset of capture based on spacecraft Monte Carlo simulations during rendezvous with the OS are described below and shown in Fig. 8:

- Axially symmetric capture scenario

- Capture plane located at physical entrance to ROCS capture interface

- Maximum lateral offset of the OS at the capture plane (L_{off}) is 10 cm in any direction off the capture boresight axis

- Velocity magnitude (V_{OS}) of the OS at the capture plane ranges from 2 to 10 cm/s

- Maximum radial component of velocity results in a max angle θ_V of 5° in any radial direction

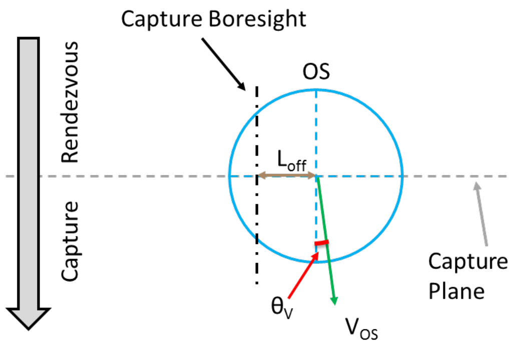


Figure 8: Assumed OS rendezvous initial conditions.

Break-the-Chain (BTC)—Induction brazing is assumed for the break-the-chain primary seal to fulfill ROCS Requirements 3 and 6 pertaining to primary sealing and sterilization. Details of the technology are described in [6] and summarized at a higher level in Fig. 9. The system concept consists of a double-walled PCV Lid brazed together, a PCV Base brazed to the Deck that separates the region exposed to Mars material from the "Earth clean" region isolated from Mars material, and a Coil assembly that performs the brazing. Connecting the PCV Lid to the PCV Base would occur along the OS reference axis and is assumed to require placement accuracy on the order of millimeters and angular accuracy on the order of degrees.

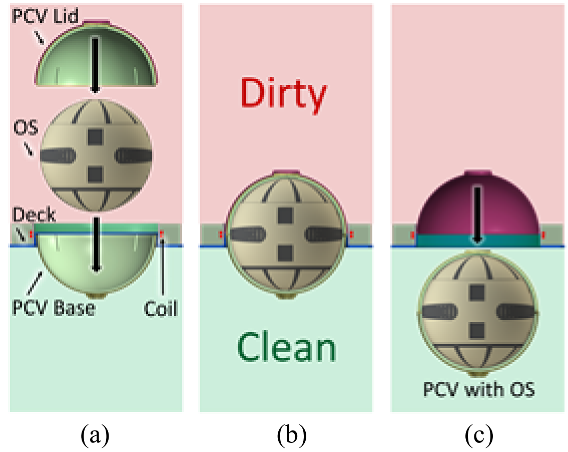


Figure 9: Illustration of an inductive brazing sequence. (a) OS assembled with the PCV Lid to the PCV Base brazed to the Deck. (b) Inductive brazing operation simultaneously brazes together the PCV Lid outer wall to the Deck, brazes together the PCV Lid inner wall to the PCV Base, separates the PCV Lid inner wall from the PCV outer wall, separates the PCV Base from the Deck, and sterilizes all regions along and in between the brazing surfaces. (c) PCV Lid inner wall, the OS, and the PCV Base removed from the Deck.

Earth Entry Vehicle (EEV)—A concept for an EEV design shown in Fig. 10 is assumed to fulfill ROCS Requirements 4 and 10 pertaining to secondary sealing and securing of the Contained OS to the EEV. The system consists of an Aeroshell installed with the SCV Base, an SCV Lid, and an Aeroshell Lid. Connecting the SCV Lid to the PCV Base, as well as the Aeroshell Lid to the Aeroshell occurs along the EEV reference axis and is assumed to require placement accuracy on the order of millimeters and angular accuracy on the order of degrees.

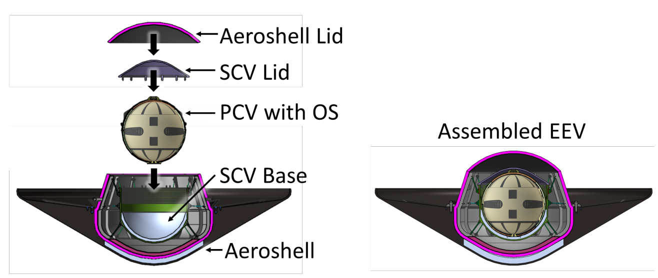


Figure 10: EEV concept.

ROCS Constraints

The assumed system resource allocations for ROCS include:

- **Mass:** Maximum 240 kg (includes BTC system and EEV)

- **Power:** Maximum 500 W switched conditioned power, maximum 4000 W through high-power unregulated bus for BTC operations

- **Volume:** Spacecraft provided keep out volume shown in Fig. 11 based off of a notional SEP orbiter design and a Falcon-9 or Atlas V-411 launch vehicle payload volume

- **Entry and Exit Corridors:** Desired OS entry and exit vectors shown in Fig. 12 to allow for SEP blow-off of the OS during rendezvous for preliminary planetary protection cleaning of Mars material that may be orbiting with the OS and minimize the release of loose, unsterilized particles during the EEV separation event

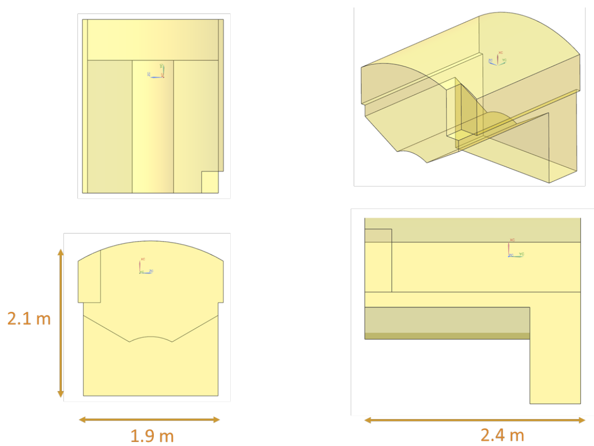


Figure 11: Spacecraft-defined keep out volume.

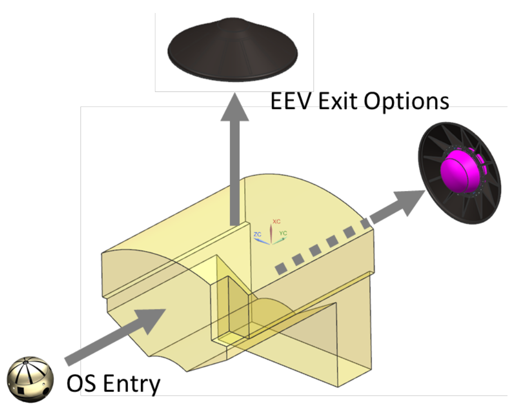


Figure 12: Concept diagram showing desired OS entry and EEV exit vectors.

ROCS Functional Partitioning and Allocation

The ROCS functional elements from Fig. 13 were partitioned into three individual conceptual modules: Capture and Orient Module (COM), Containment Module (CM), and Earth Return Module (ERM). The partitioning of the functions were based on planetary protection cleanliness, operational environment, OS state, and technical challenge. ROCS-level requirements were allocated to each module.

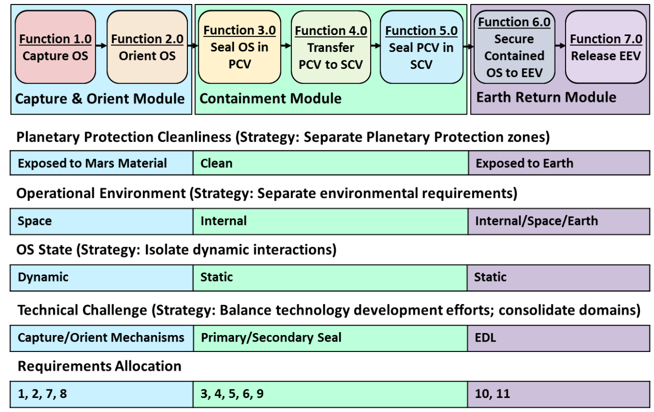


Figure 13: ROCS concept functional partitioning and requirements allocation.

Notional resource allocations to the Capture and Orient Module, Containment Module, and Earth Return Module for mass, power, and volume were made based on mass and volume assumptions of the EEV, PCV, and SCV, the desired OS entry and EEV exit vector options, and the assumption that high-power modules do not significantly overlap during operation. The notional volume allocations are shown in Fig. 14, and mass and power allocations are listed below:

- **Capture and Orient Module:** Maximum 80 kg, maximum 500 W switched conditioned power

- **Containment Module:** Maximum 80 kg, maximum 500 W switched conditioned power, maximum 4000 W through high-power unregulated bus for BTC operations

- **Earth Return Module:** Maximum 80 kg, maximum 500 W switched conditioned power

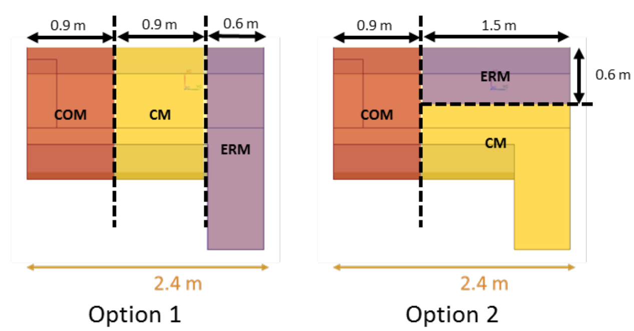


Figure 14: ROCS module volume allocations.

Considerations for ROCS Design

A consideration was made for the ROCS architecture design to provide opportunities to reduce overall planetary protection back contamination risks:

- Recognition that the break-the-chain goal is one of the most critical aspects of the mission, and that the OS state (e.g., dust, velocity, spin rate, form) is one of the most uncertain factors during operations.

Strategies taken for the ROCS architecture design addressing the above planetary protection consideration include:

- Minimization of the physical interactions between the OS and BTC hardware, and allow contact only when the OS is captured, oriented, and fully constrained.
- Allow for ejection of unsterilized hardware surfaces that have physically contacted the OS and are not contained within the Primary Containment Vessel to reduce the probability of unsterilized Mars material being exposed to the Earth in an unlikely fault scenario where the spacecraft carrying ROCS fails to divert after releasing the EEV towards Earth.
- "Close before contact" to close off the capture volume before the OS physically contacts ROCS hardware during OS capture to contain any dust particles on the exterior of the OS that may dislodge upon contact.

A consideration was made for the ROCS architecture design to provide opportunities to reduce project risks:

- Recognition that flexibility with development of the ROCS elements is desirable to respond to potential resource limitations (e.g., staffing, funding, schedule), potential external partnerships, evolving requirements, or infusions of new technologies.

A strategy taken for the ROCS architecture design addressing the above project consideration include:

- Clear functional and spatial partitioning and modularity of functional elements to simplify interfaces and facilitate independent development and testing, as well as provide flexibility to more easily update or replace elements in the case of requirements change or new technology developments.

Note that these strategies are not required for the ROCS concept, but were adopted during the design process due to their potential benefits towards managing risks and opportunities.

Previous ROCS Concepts

Several concepts for on-orbit OS retrieval had been previously developed [7], [2], [8] and are shown in Fig. 15.

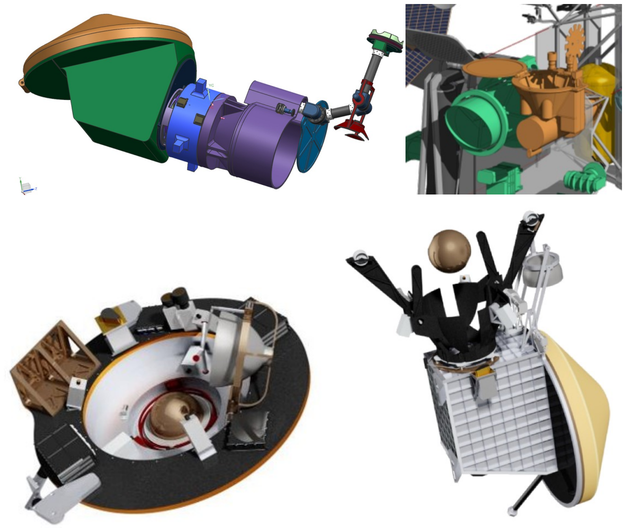


Figure 15: Previous ROCS concepts (Clockwise from top left: Inline Transfer, NeMO 2015, Car Wash, and Minimal).

3. Capture and Orient Module

Capture and Orient Module Functions

The Capture and Orient Module's (COM) primary functions would be to cage and orient the OS. These top-level functions were decomposed within the COM, as shown in Fig. 16. The Capture OS function was decomposed to Detect OS, Constrain OS, and Confirm OS Capture functions. The Orient OS function was decomposed to Orient OS and Confirm OS Orientation. An additional function, Assemble OS into Primary Container, was derived from the Containment Module's Seal OS in PCV function and allocated to the Capture and Orient Module's functions due to its similar Operational Environment and planetary protection cleanliness conditions to those of the COM.

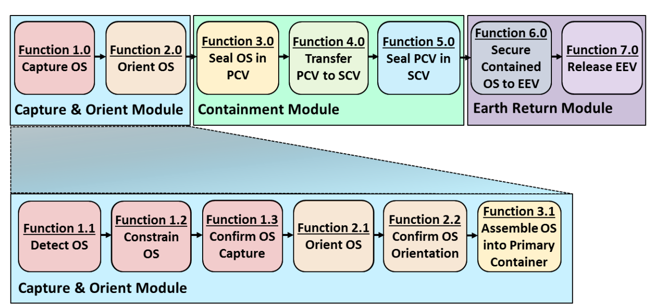


Figure 16: Capture and Orient Module functional decomposition.

Proposed Capture and Orient Module Requirements

Based on the ROCS requirements and COM functions, a proposed set of key and driving requirements were produced, as shown in Tab. 2. The first number of the requirement ID in the table points to the parent requirement from the proposed ROCS requirements listed in Tab. 1.

Requirement 1.1 was derived from ROCS Requirement 1, with the additional implementation strategy of "close before contact" for OS capture. Requirement 2.1 was a direct flow-down from ROCS Requirement 2. Requirement 3.1 was derived from ROCS Requirement 3 to properly configure the OS with the PCV prior to the break-the-chain operations. Requirements 7.1 and 8.1 were derived from ROCS Requirements 7 and 8, calling for the COM to orient the OS relative to the PCV as an intermediate step towards final orientation relative to the EEV.

Table 2: Proposed key and driving requirements for the Capture and Orient Module.

ID	Proposed Requirements for Capture and Orient Module Concept
1.1	The Capture and Orient Module shall **capture the OS** in Mars orbit with characteristics as specified in the Mission to Future Missions ICD **prior to OS contact with any ROCS hardware**.
2.1	The Capture and Orient Module shall **provide on-orbit confirmation of OS capture**.
3.1	The Capture and Orient Module shall **assemble the OS into the Primary Containment Vessel.**
7.1	The Capture and Orient Module shall **control orientation of the OS reference axis within ±5 degrees relative to the Primary Containment Vessel reference axis.**
8.1	The Capture and Orient Module shall **provide on-orbit confirmation of proper OS orientation** relative to the Primary Containment Vessel.

Capture and Orient Module Assumed Interactions

Fig. 17 shows the primary external entities and their key interactions with the COM. External entities include the CM, the OS, and GSE used for system integration and test. The PCV Lid is highlighted within the CM since it must be manipulated by the COM for the Assemble OS into Primary Container function. Both the GSE and CM provide mechanical mounting, power, and commands for integration, testing, and operations. Additionally, the CM may transmit heat to the COM during the BTC brazing operation. Power and command signals were decided to be routed through the CM to reduce system interfaces with the spacecraft, as well as confine separation to just the COM-CM interface in the case where ejection of unsterilized hardware exposed to the OS is required. The COM feeds back to the CM and GSE telemetry, sensor data, dynamics from capture and manipulation of the OS, and the OS itself. The OS potentially exposes the COM to Mars material and contact dynamics. The COM exposes the OS to mechanical constraint, load, and dynamics for manipulation and packaging into the PCV. Additionally, the COM may provide optical active sensing of the OS for capture and orientation operations.

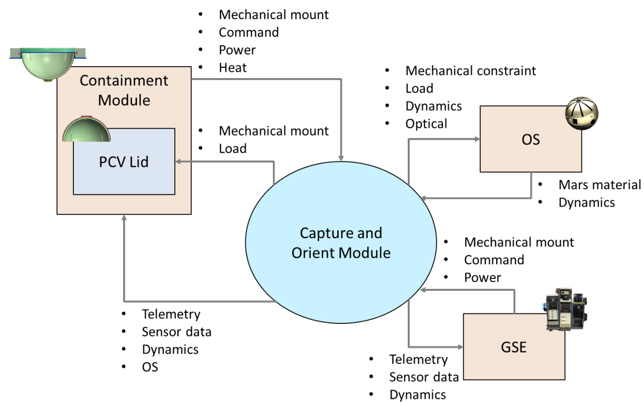


Figure 17: Capture and Orient Module context diagram.

Capture and Orient Module Assumptions and Interfaces

The ROCS assumptions and interfaces for the OS, OS rendezvous, and BTC directly apply to the COM. Primary physical interfaces are highlighted in red in Fig. 18. Electrical interfaces between the COM, CM, and GSE for command, data, and power, as well as the mechanical mounting interfaces would potentially exist at the COM-CM Interface Plane.

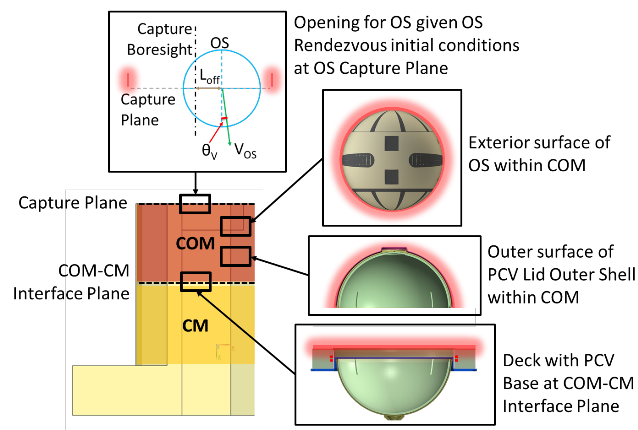


Figure 18: Primary physical interfaces with the Capture and Orient Module.

Capture and Orient Module Constraints

The assumed system resource allocations for the Capture and Orient Module include:

- **Mass:** Maximum 80 kg (not including PCV Lid)
- **Power:** Maximum 500 W switched conditioned power
- **Volume:** ROCS allocated volume shown in Fig. 19
- **Entry and Exit Corridors:** Desired OS entry, as well as OS and PCV Lid Inner Wall exit vectors shown in Fig. 19

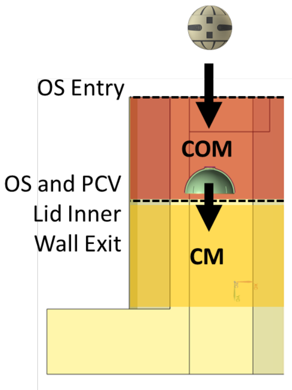


Figure 19: OS and PCV Lid Inner Wall entry and exit vectors.

Capture and Orient Module Functional Partitioning and Allocation

The Capture and Orient Module subsystems from Fig. 16 were partitioned into three individual elements: Capture Subsystem, Orientation Subsystem, and Transfer Subsystem, as shown in Fig. 20. The partitioning of the functions were based on their overarching ROCS-level function, time dependency, and kinematic function. COM-level requirements were allocated to each element.

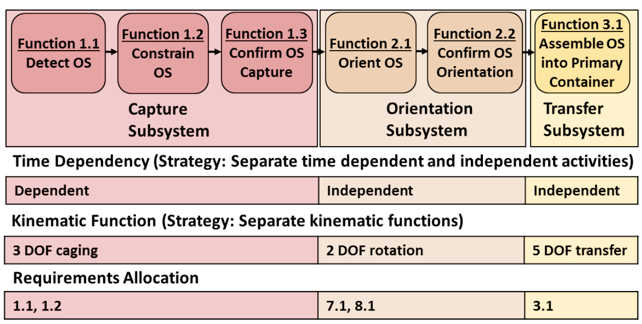


Figure 20: Capture and Orient Module partitioning and requirements allocation.

Notional resource allocations to the Capture, Orientation, and Transfer Subsystems of equal distributions of mass and power were made based on an assessment of comparable complexities and the assumption that high-power subsystems do not significantly overlap during operation. The notional mass and power allocations are listed below:

- **Capture:** Maximum 27 kg, maximum 500 W switched conditioned power
- **Orientation:** Maximum 26 kg, maximum 500 W switched conditioned power
- **Transfer:** Maximum 27 kg, maximum 500 W switched conditioned power

Due to potential interactions amongst the elements through transfer of the OS, volume allocations were not made at this level. Note that Capture and Orient Module mechanical structure and avionics are assumed to be included in the mass allocations.

Considerations for Capture and Orient Module Design

The same considerations made for the ROCS Architecture Design for planetary protection and project risk were taken for the Capture and Orient Module. Therefore, the same strategies (i.e. minimization of physical interaction of the OS and CM hardware, ejection of unsterilized hardware, “close before contact,” clear partitioning and modularity) were adopted for the Module.

An additional consideration was made for the Capture and Orient Module design to provide opportunities for verification and validation (V&V) efforts:

- Recognition that zero gravity contact dynamics during OS capture are difficult to analyze, simulate, and test

A strategy taken for the Capture and Orient Module design addressing the above V&V consideration includes:

- “Close before contact” during OS capture to fully cage the OS in the COM prior to it contacting any hardware, relieving the need to analyze or test contact dynamics of the OS during capture (this would be required to ensure the OS does not bounce out of the COM if it was not yet fully caged)
- Design of all mechanisms to be tested or demonstrated in a 1G environment to reduce the need to perform 0G testing or demonstration of OS capture (e.g., gravity offload, neutral buoyancy, parabolic flight, or on-orbit experimentation)

4. Design Methodology

A design methodology based on creative problem solving was used to develop and evaluate design solutions both at the module and subsystem levels. The process consisted of defining the problem relative to primary functional requirements, performing a trade study of relevant technological concepts in various domains, evaluating the concepts at multiple levels using a set of criteria within an evaluation matrix, assessing compatibility amongst the elements in a compatibility matrix, synthesizing new concepts, and performing a final evaluation of the concepts to identify a preferred implementation for the architecture design. The process applied concepts, principles, and strategies from the fields of systems engineering, cognitive psychology, and education [9]. An important component of the design methodology is a set of evaluation criteria used to judge the various design alternatives. The evaluation criteria used for the Capture and Orient Module and its subsystems are described in the next section.

Evaluation Criteria

A set of evaluation criteria was created to trade the various technologies against potential functional and non-functional requirements for a notional MSR. Sixty-one criteria were identified based on institutional engineering design principles, system engineering best practices, and considerations for benefits, risks, and mission success at the project, program, and campaign levels. The purpose of developing these criteria was to assist in evaluating and down-selecting to a preferred set of systems and subsystems. The list does not, and was not meant to, cover the full list of requirements for a mission concept, but was intended as a method for evaluating system technologies as part of the trade study.

Extrinsic Design Criteria—The **Environments** category includes environments that an orbiter would be subjected to during launch, cruise, and orbit. These criteria include non-operational and operational temperature range, radiation, vacuum, microgravity, pyrotechnic shock, and vibration.

The **Planetary Protection (PP) and Contamination Control (CC)** category includes items that may affect planetary protection and contamination control processes. These criteria include PP bake out temperature, cleanliness, and clean-ability.

Intrinsic Design Criteria—The **System Resources** category includes mass, power, energy, volume, and the net mass returned to Earth in a possible EEV.

The **System Parameters** category includes actuator count, mechanism count, and sensor count, as well as the use of high force/torque operations.

Life Cycle Criteria—The **Development** category includes the early phase of the project lifecycle. These criteria include Concept Maturity Level (CML) [10], analyzability, scalability, subsystem and system compatibility, multi-usability, complexity, and internal modularity.

The **Fabrication** category includes the middle of the project lifecycle. These criteria include prototypability, producibility, adjustability, and inspectability.

The **Integration and Test** category includes the later phase of the project lifecycle. These criteria include assemblability, accessibility, telemetrability, V&Vability, testability in a 1G environment, and failure transparency.

The **Operations** category includes the operational phase of the project lifecycle. These criteria include minimization of sensor burden, determinism, controllability, autonomy, and accuracy.

Effectiveness Criteria—The **System Success** category includes items that may contribute to failure. These include reliability, robustness, space aging (ability to survive long exposure to a space environment), resetability, redeployability, graceful degradation, and single fault tolerance.

The **Risk** category includes a system's sensitivity to risk with the intention of mitigating it. This includes sensitivity to design, fabrication, assembly, and test flaws, as well as sensitivity to operational damage.

Programmatic Criteria—The **Project Impact** category focuses on related development costs. These include costs for R&D, production, and V&V.

The **Program Impact** category considers items external to the project. These include the impact that the system could have on the OS design, as well as applicability to future missions.

The **Returned Science Impact** category addresses risk to the returned sample science. These include the sample thermal, magnetic, and radiation histories, as well as the sample structural integrity.

Selection of Technology for Further Study

All concepts assessed in the technology trade studies were scored amongst the evaluation criteria and summed to give a final score. A Recommended Concepts Table summarizes the results of the trade studies, showing a prioritized list of concepts selected based on their high evaluation scores, as well as other considerations such as the system concepts' compatibilities with other system elements. A selective set of determinant criteria deemed both important to the system and that clearly distinguish the system concepts from one another are highlighted in the table. The format of this table provides a means to recommend system concepts both quantitatively (i.e. total evaluation scores relative to the evaluation criteria) and qualitatively (e.g., system concepts that show good compatibility with other systems and possess other rationale important to the project but difficult to quantitatively score).

5. PROPOSED CONCEPT DESIGN

Trade study, concept generation, and concept evaluation activities were performed for the primary functions of the Capture, Orientation, and Transfer Subsystems, as these were seen as the key drivers for the COM architecture design:

- **Function 1.2:** Constrain OS
- **Function 2.1:** Orient OS
- **Function 3.1:** Assemble OS into Primary Container

Similarly, a trade study, concept generation, and concept evaluation was performed for the COM. Preferred concept designs for the COM, Capture Subsystem, Orientation Subsystem, and Transfer Subsystem were proposed.

Capture Subsystem

The Capture Subsystem would be responsible for acquiring a free-floating, orbiting OS and delivering it to subsequent ROCS subsystems for processing. It would be the first subsystem to directly interact with the OS following rendezvous operations, but, depending on the overall architecture, may also be operated post-capture to assist with other operations (see Transfer section). To this end, an ideal Capture Subsystem would need to at minimum reliably collect the OS from orbit in a manner which is highly robust to errors in relative position and velocity, as well as be compatible with subsequent subsystems to facilitate orientation and transfer operations.

Philosophy—The ROCS operational concept for Mars Sample Return would begin with the launch and orbital rendezvous of the OS in Low Martian Orbit. The ROCS payload would have to then acquire the OS, permitting further manipulation operations while preventing accidental escape of the OS. In this context, capture can be defined as the initial act of confining the OS within the ROCS system to facilitate OS processing without risk of escape.

As the Capture Subsystem would be the first to directly interact with and manipulate the free-floating OS, special attention must be given to the moment of first contact, as the resulting interactions between OS and ROCS hardware could result in OS escape before the capture operation has been completed. To prevent such a "bounce-out" scenario, a dynamics model predicting OS-mechanism interactions and deflections may be required to inform mission operations. Alternatively, the mechanism could be designed to surround the OS, physically preventing it from escaping, prior to first contact. While the former dynamics model is possible, the latter approach using a surrounding mechanism to close before contact is preferred due to its independence from mechanism geometry and contact dynamics.

A reliable subsystem would also need to tolerate uncertainty during the rendezvous and capture operations, namely OS intercept trajectory, velocity, and spin rate. This would affect where and when the OS contacts the capture mechanism, as well as how the OS reacts to this contact. Active or passive methods should be employed to address all of these sources of uncertainty, though passive methods may minimize complexity and increase reliability.

Once captured, the OS would then have to be oriented to ensure proper alignment of the sample tubes for Earth entry and landing. This would require a transfer of the OS from the Capture Subsystem to the Orientation Subsystem, which may be performed either by the Capture Subsystem itself or by the Transfer Subsystem. A capture method which fully controls, or constrains, the position of the OS could simultaneously feed the OS directly into the orientation mechanism, while a caging-only capture mechanism may require the assistance of a separate transfer mechanism.

Approach—Early brainstorming activities and background research yielded various methods for capturing objects, whether through direct mechanical contact, electric or magnetic fields, or chemical interactions. These methods can be classified into three major categories:

- **Coarse Capture**: Methods that rely on interactions between the mechanism and object in a way which is largely geometry independent; that is, the object(s) may be asymmetric or widely varying from one another without inhibiting the functionality of the capture system. Examples of coarse-capture devices include buckets, nets, and fly paper. This approach tends to tolerate variations in object shape, position, and velocity, in addition to requiring little actuation, but capture mechanisms may need to be large in size relative to the target object. Coarse-capture methods tend to function well for caging, though not necessarily for precise manipulation of the captured object. Many methods also rely on gravity, water currents, or other external forces to prevent the escape of the target object, so additional active or passive mechanisms may be required to operate in the ROCS environment to cage the object.

- **Precision Capture:** Methods that utilize mechanisms which rely on a dedicated, localized feature on the target object to engage with. Once constrained, the mechanism can easily manipulate the target as-needed. Examples of precision-capture systems include ISS docking adapters and Canadarm grippers. This approach generally requires precise alignment between the capture mechanism and target, and is often sensitive to lateral and rotational drift.

- **Compliant Capture:** Methods that use mechanisms or flexible components to simultaneously capture and constrain the target object while tolerating a moderate range of positional or geometric uncertainty. Examples of compliant capture mechanisms include universal grippers [11], tentacles, and fish-inspired conforming end-effectors. This approach enables manipulation of the target post-capture without a dedicated, localized capture feature by engaging with the overall surface of the target itself. However, these mechanisms tend to be complex and/or rely on soft goods, which may increase liability in the space environment.

- **Hybrid Capture**: Methods created through the combination of the above categories, where the resultant capabilities and limitations are a function of the original methods and mechanisms. An example is a robotic hand: open, pre-grasp configuration resembles a bucket, while actuation permits compliant capture and constraint.

Given the various approaches to capturing an object and the strengths and weaknesses of their respective implementations, a more formal comparison of these methods within the context of ROCS will further guide the design of the conceptual Capture Subsystem.

Trade Study—A trade study was performed to characterize current methods of capturing objects and identify key features which would be appropriate for the ROCS application. The background research produced dozens of unique methods for capturing objects, from bio-inspired mechanisms to robotic manipulators (Fig. 21). Flight-heritage systems, such as docking mechanisms for the International Space Station and Soyuz spacecraft, were also considered. Each approach, as well as several earlier concepts of ROCS capture mechanisms, were evaluated against the aforementioned ROCS evaluation criteria and scored to identify their respective strengths and weaknesses. Total evaluation scores for each mechanism were computed based on their individual criteria scores and the criteria weights, which allowed for an initial concept down-select and identification of opportunities for design improvement.

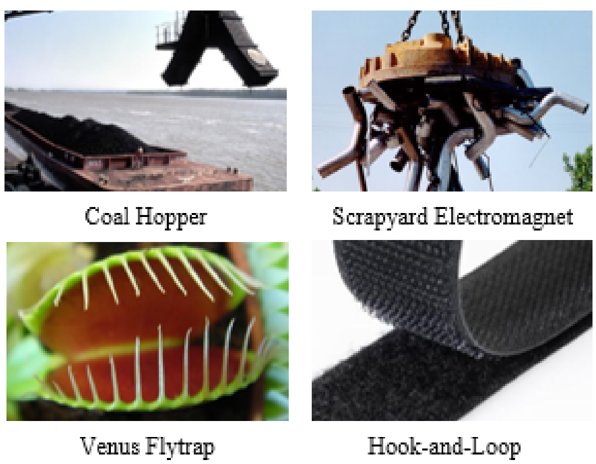


Figure 21: Examples of Capture Mechanisms considered in the trade study.

Trade Study Results—The trade study indicated that coarse capture methods, such as door-style mechanisms and permanent magnets, were most appropriate from a simplicity, development, and reliability standpoint, and would facilitate OS capture with little actuation while allowing for a large range of rendezvous uncertainty tolerance. If precise positional control was required post-capture, compliant and hybrid mechanisms such as conforming claws and funnel-shaped buckets with rotating arms performed well (Fig. 22).

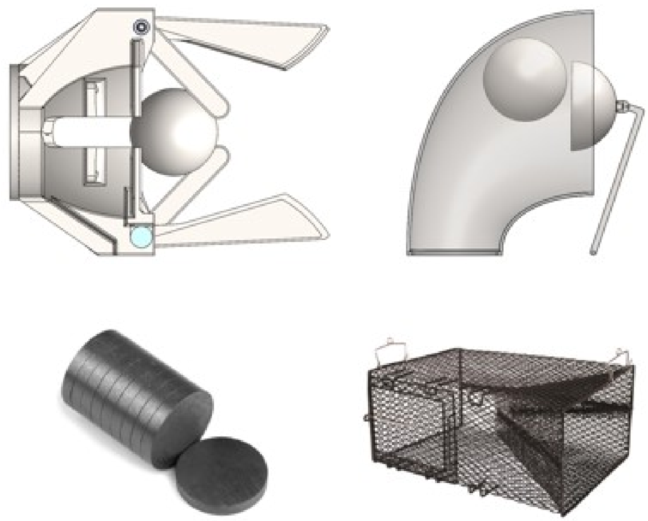


Figure 22: Examples of well-performing capture methods (clockwise from top left: Multi-Blade Cone, Dorade-Vent Cone, Fish Trap, Permanent Magnets).

While flight-heritage capture mechanisms are technologies proven to be effective in a space environment, they did not perform well in this trade study due to their dependence on interfacing with a dedicated feature on the target. Typically, this would not be an issue for spacecraft with attitude control, but considering that the OS could tumble about an unknown axis, dependence on such a target for capture would be unreliable in this application.

To down-select from the available capture mechanisms, total evaluation scores, compatibility with the Orientation Subsystem and BTC hardware (i.e. PCV Lid and PCV Base), and geometric dependencies on the OS, were considered. The results of this evaluation are shown in Tab. 3.

Table 3: Recommended Concepts Table for Capture Mechanisms (Red = Poor, Yellow = Medium, Green = Good).

Capture	Mass	1G Testable	Resetable	Impact on OS	Compatability w/Orientation	Compatability w/BTC	Rank
Door/Lid	Green	Green	Green	Green	Red	Red	1
Dorade Vent Cone	Yellow	Yellow	Green	Green	Green	Green	2
Bladed Capture Cone	Yellow	Yellow	Green	Green	Green	Yellow	3
Fish Trap	Green	Green	Yellow	Green	Red	Red	4
Permanent Magnet	Green	Green	Green	Red	Yellow	Red	5

Technology Chosen for Further Study—Given the overall high performance of several coarse, compliant, and hybrid mechanisms, the primary deciding factors were whether or not the Capture Subsystem itself must constrain the OS for insertion into the Orientation Subsystem, and if the Capture Subsystem must be used for subsequent transfer operations. It was concluded that neither of these features were necessary, as they would be redundant to the capabilities of the Transfer Subsystem in performing OS insertion into the Orientation Subsystem and, later, the Primary Containment Vessel. This removed the need for features inherent in the compliant and hybrid capture mechanisms, and the following lid-style coarse capture method was proposed as the best solution.

A lid-style capture mechanism featuring a large aperture and an actuated lid to control OS entry and egress was chosen for further study. The lid-style capture mechanism would operate during rendezvous and capture operations, during which the aperture would be exposed and the orbiter would maneuver it towards the OS. Once the OS has entered the aperture, the lid would close, thereby caging the OS within ROCS. The interior volume of the caging region is sized to ensure that the OS cannot deflect off of hardware and exit the payload before the lid has sufficiently closed. The lid would then remain closed for the remainder of the mission, ensuring that the OS cannot escape during the orientation and transfer operations. Should it be required from a containment assurance standpoint, a solid lid (as opposed to a mesh or truss-style lid) may serve the additional function of limiting the propagation of dust and debris released by the OS from collisions and manipulations.

Several variations exist within this approach, differing in the path of lid closure and actuation method (Figs. 23 and 24). Additionally, sensors may be integrated with each of these approaches to trigger mechanism operation and verify successful OS caging.

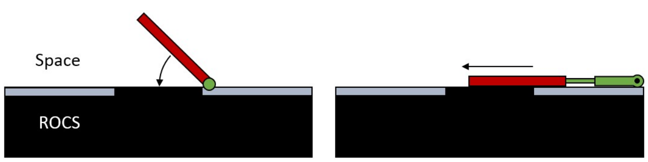


Figure 23: Rotary and sliding doors.

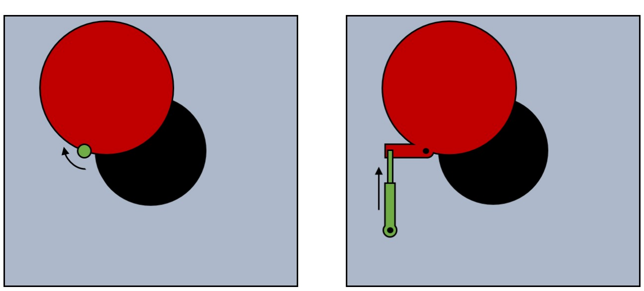


Figure 24: Rotary aperture-parallel lids.

When considering simplicity and minimizing time to enclose the OS, the aperture-parallel, rotary-actuated variant was proposed as the most appropriate design, as opposed to more traditional door-style designs, though linear actuation with an aperture-parallel lid is also viable.

A concept of operations for a capture mechanism is shown in Fig. 25. Capture operations begin with the rotary lid exposing the aperture during OS rendezvous. The OS passes through the aperture and is monitored by one or more close-range sensors to inform the capture operation. Once the OS has sufficiently entered the capture volume, the lid rotates parallel to the aperture and closes it, thereby capturing the OS. Once capture is complete, the lid remains closed for the duration of the mission.

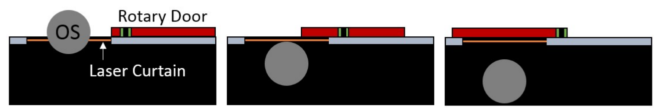


Figure 25: Operation of example capture mechanism.

Orientation Subsystem

The Orientation Subsystem would be responsible for orienting a rotationally unconstrained OS and constraining a minimum of two rotational degrees of freedom relative to the OS central axis. Orientation is one of the most important functions that ROCS would perform from a planetary protection and science preservation standpoint, as doing so helps protect the hermetic seals, which function to both retain gases and volatiles within the sealed region of the sample tube, as well as limit external contaminants from entering the sealed region of the sample tube. An ideal Orientation Subsystem would orient two of the three rotational degrees of freedom that the OS possesses, be deterministic, retain the OS after orientation has been achieved, and be compatible with the other subsystems so that further processes can be accomplished.

Philosophy—The orientation of an object is dictated by the three rotational degrees of freedom (yaw, pitch, and roll). An object is considered oriented when these three degrees of freedom attain a preferred set of specified or desired reference attitudes. The position of an object is dictated by the three translational degrees of freedom. To fully define and constrain an object in space, control of all three rotational and all three translational degrees of freedom is needed.

The need to orient the OS can be traced to the requirement that the sample tubes' hermetic seals must survive Earth-landing conditions. To perform this task, the OS would have to be constrained within the EEV in at least a minimum of five degrees of freedom—three translational and two rotational. The OS may rotate about its vertically symmetric axis, which is parallel to the sample tubes' bore axis (Fig. 7).

To solve this issue in a robust way, it was assumed that the orientation of the OS is unknown until after it has been captured. This assumption is especially important when considering the dynamics that could be experienced by the

OS, which could be launched from the MAV with a spin rate, and spacecraft interactions that could further impart a spin on the OS. The concepts studied assume a spherical OS. It should also be noted that additional features on the OS allow for various orientation methods. However, the addition of features to the OS may be costly at the programmatic level due to mass and volume impact on other elements of the Mars Sample Return campaign. For this reason, orientation methods that require the addition of mass and volume, either through internal features, external features, or internal sensors, are less desirable.

Approach—The brainstorming activities and research into the state of the art, state of technology, and previous ROCS concepts uncovered various methods for manipulating an object in space. In order to orient an object, it must first be constrained. Once constrained, the object may then be manipulated to control its orientation. To analyze methods of orientation, the concept of robotic prehension was investigated, which was divided into the following categories [12]:

- **Impactive Prehension:** The retention force provided by these tools is based on the physical effects of Newtonian mechanics, mainly associated with mass points and forces, and requiring more or less extensive mechanisms.

- **Ingressive Prehension:** Gripping methods, which permeate a material surface to some given depth. They are used almost exclusively with soft materials such as fabric, foam, and fibrous components. Ingression could be intrusive or non-intrusive.

- **Astrictive Prehension:** A binding force produced by a field. This field may take the form of air movement (e.g, vacuum suction), magnetism, or electrostatic charge displacement. Almost all forms of astrictive devices rely on some degree of a continuous energy supply to maintain object retention. Vacuum adhesion is suitable for any relatively rigid, non-porous surface. Magneto adhesion is able to operate in vacuum environments, is suitable with magnetically susceptible materials, and has higher power consumption. Electro-adhesion is able to operate in vacuum environments and is suitable for flat, low-mass objects.

- **Contigutive Prehension:** This pertains to grippers whose surface must make direct contact with the object's surface in order to produce prehension (e.g., chemical, thermal, hook-and-loop adhesion, chemo-adhesion, thermo-adhesion).

Reliance on soft, permeable, or adhesive materials that would be in a space environment for several years was considered a reliability risk. In light of this, of the above categories, only two were considered relevant for orienting the OS: Impactive and Astrictive Prehension. A combination of the two, Hybrid Prehension, was also considered. These remaining categories of prehension were used to develop orientation concepts through prehensile manipulation and summarized as:

- **Grasping Mechanism:** A mechanism that orients the OS by controlling all six degrees of freedom by constraining it and then manipulating it.

- **Positioning Mechanism:** A mechanism that orients the OS by controlling its translational degrees of freedom and forcing it into the proper attitude with the use of a surface feature.

- **Orienting Mechanism:** A mechanism that orients the OS by controlling its rotational degrees of freedom.

Given the many different methods available for orienting an object, the evaluation matrix tool (described more fully in [9]) proved useful in comparing and tracking the strengths and weaknesses of the various methods in the context of the ROCS Orientation Subsystem.

Trade Study— A trade study was performed to characterize current methods of orienting an object and functionally decompose these methods so that components relevant to ROCS might be observed. The trade study investigated concepts in the state of the art, state of technology, and previous ROCS concepts. The state of the art and state of technology concepts primarily came from industrial and manufacturing settings, novelty settings, medical applications, and research and development tasks. Most mechanisms assume known properties of the grasped object, such as surface finish, size, shape, and mass. The trade study concepts, as well as previous ROCS orientation concepts, were then functionally decomposed, and the elements were then evaluated against the ROCS criteria to reveal strengths and weaknesses. The decomposition indicated which elements were favorable so that improvements of current concepts could be made and new concepts could be synthesized.

Examples of concepts studied included Flux Pinning, a Wiper Mechanism, and a Motorized Cups Mechanism (Figs. 26-28). Flux pinning uses type-II superconductors cooled below -185°C, during which magnetic flux lines can be "pinned" within the superconductor at a fixed position and orientation. An OS populated with surface permanent magnets can be captured by the cooled superconductors through flux pinning. The Wiper Mechanism consists of two wipers: one fixed and one moving. The OS is oriented by rotating the moving wiper, which guides a pin on the OS along the fixed wiper until it settles in a groove at the final orientation. The Rotating Cups Mechanisms orients the OS using contact friction between the OS and two sets of rotating cups arranged 90-degrees apart. The cups are driven with two actuators: one to drive a ring gear that simultaneously rotates all four cups, and the other to drive a cam that selects which pair of cups will be utilized.

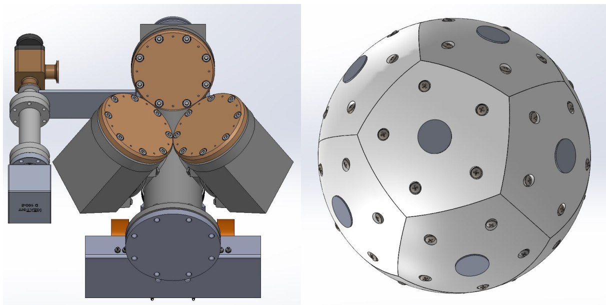


Figure 26: Flux pinning testbed and OS [13].

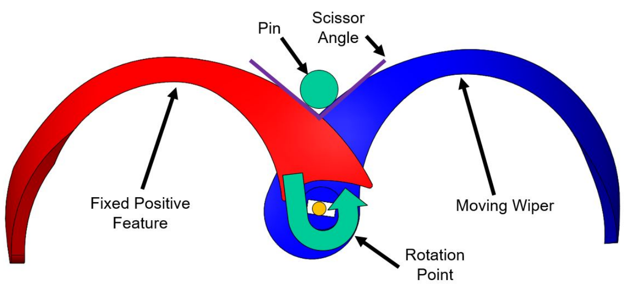


Figure 27: Wiper Mechanism.

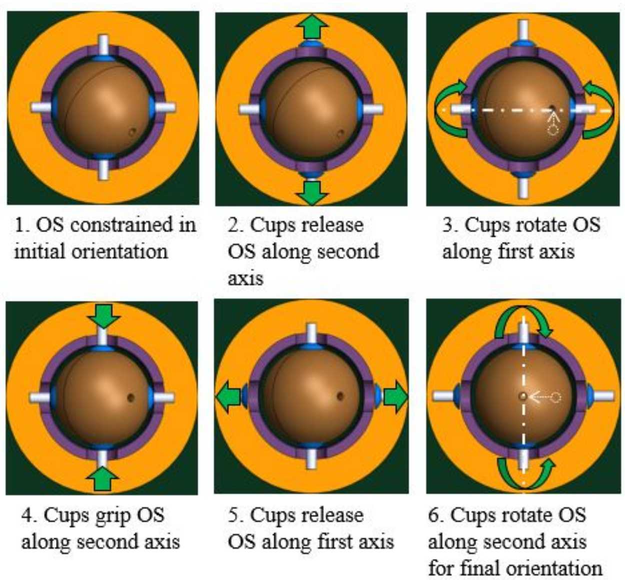


Figure 28: Motorized Cups Mechanism concept of operation.

Trade Study Results—The evaluation of the concepts indicated that impactive friction mechanisms and magnetic systems were the preferred method of orienting the OS from a complexity, reliability, and OS design impact standpoint. Mechanisms such as the Wiper, Motorized Cups, and Flux Pinning received high total evaluation scores (Fig. 29 and Tab. 4).

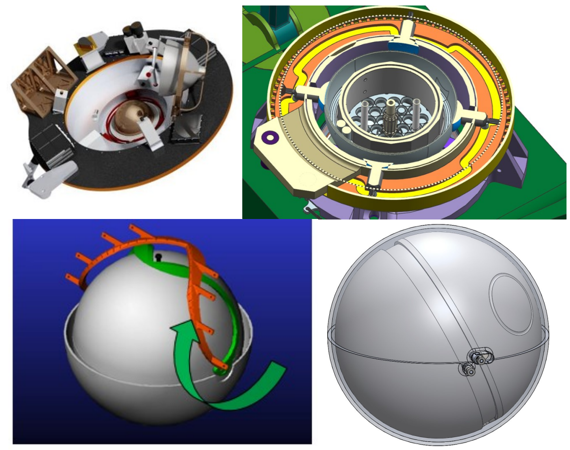


Figure 29: Examples of well-performing orientation methods (clockwise from top left: Flux Pinning, Motorized Cups, Differential Track, and Wiper Mechanism).

Table 4: Recommended Concepts Table for Orientation Mechanisms (Red = Poor, Yellow = Medium, Green = Good).

Orientation	Mass	Determinism	1G Testable	Impact on OS	Complexity	Compatability w/BTC	Rank
Motorized Cups	Yellow	Yellow	Green	Green	Yellow	Green	1
Wiper Mechanism	Green	Green	Yellow	Yellow	Green	Yellow	2
Differential Track	Green	Green	Green	Red	Yellow	Red	3
Sense and Constrain	Red	Red	Green	Yellow	Yellow	Red	4
Flux Pinning	Red	Green	Red	Red	Red	Green	5

Technology Chosen for Further Study—In many of the designs, the OS could be oriented without the functional need for sensors (e.g., Wiper and Flux Pinning), although proper orientation might need to be verified with a sensor. A camera could serve both orientation control and orientation verification functions.

Magnetic systems may require the use of magnetic shielding in the OS to keep magnetic exposure to the samples within allowable science limits. This addition can have a negative effect on additional MSR elements through addition of mass and volume to the OS, which in turn may grow the mass of the MAV, EEV, and ROCS.

The high performance of Impactive Prehension mechanisms indicated that this category of orientation was one of the more favorable options of the study. The benefits of Impactive Prehension mechanisms were that the orientation and retention of the OS could be achieved with fewer actuators than degrees of freedom controlled, and with little to no sensing (e.g., the Wiper Mechanism). Within the architectural tradeoffs (Tab. 4), the Motorized Cups and Wiper mechanisms surpassed the other mechanisms due to their compatibility with the PCV Lid, and the impact the mechanisms have on the OS geometry. However, the Wiper Mechanism would require the use of a positive feature on the OS, which was considered undesirable due to increased risk to other ROCS hardware that may be impacted by the positive feature during OS capture and transfer, as well as risk of the positive feature becoming damaged prior to orientation. For these reasons, the Motorized Cups Mechanism was selected for further study.

Transfer Subsystem

The Transfer Subsystem would be responsible for transferring the OS from or within the capture volume from one subsystem to the next, as well as placing the PCV Lid over the PCV Base. The Transfer Subsystem's design would be dependent on the arrangement of the Capture and Orientation Subsystems with respect to one other and would be affected by the design and operation of those subsystems. The ideal Transfer Subsystem would be compatible with the architectural and workspace needs of the system and meet the required preloads, compliance, and system operational needs.

Philosophy—Within many ROCS concept architectures, there was a fundamental need to transfer the OS from one subsystem to another. In certain architectures where Capture and Transfer are decoupled (Fig. 30), it would be necessary to perform transfer multiple times or in multiple stages. Previous ROCS architectures had mechanisms that perform capture, and either contribute to or completely perform the transfer function. However, the need for additional transfer or Primary Containment Vessel (PCV) Lid placement was still present (e.g., the Carwash concept [8]). It was considered desirable to evaluate these mechanisms from the perspectives of Capture and Transfer due to the differing requirements of each subsystem since a mechanism that performs capture well may not perform transfer well, for example. Due to these reasons, an evaluation of transfer mechanisms as a separate entity was deemed necessary to assist in down-selecting to the preferred mechanisms.

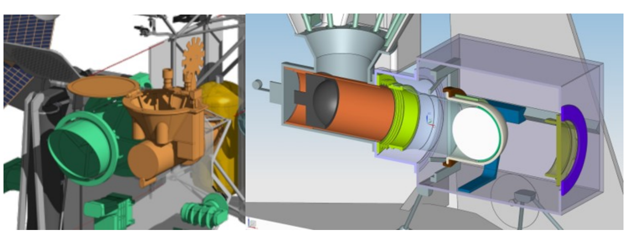


Figure 30: Paddle and Linear Transfer [2].

To perform the evaluation process and decouple the processes of Capture and Transfer that occurred simultaneously in some previous concept architectures, the following distinction was made: a mechanism causing any translational manipulation after the point at which the OS is caged was considered a transfer mechanism. Whether or not this transfer was achieved through the Capture Subsystem or some independent or semi-independent Transfer Subsystem, the evaluation could be performed such that the best transfer mechanisms might be indicated.

In the previously studied ROCS architectures, even if the function of transfer is not contained within or shared with the Capture Subsystem, much of the Transfer Subsystem's design is dependent on the selection and organization of the Capture, Orientation, and BTC Subsystems. The selection of the transfer mechanism is based on selecting and combining the best mechanism(s) that can perform transfer from one subsystem to the other. This leaves the selection to be more architecture-based and less of a driving factor in the design.

This idea can be seen in the differences between the mechanisms designed for the previous concepts. These generally come in one of two forms: Inline Transfer, where the Capture and Orient Subsystems share a central axis, or Out-of-Line Transfer, where the Capture and Orient Subsystems do not share a central axis (Fig. 31). Suitable mechanisms could then be paired with other subsystems or recombined to perform the motion necessary for transfer. A notional transfer mechanism may have accuracy requirements (both positional and angular) as well as preload requirements that could be driven by the PCV Lid and PCV Base interface. The addition of a compliant mechanism may be necessary based on the architecture and PCV interface. For example, a two degree of freedom (DOF) rotationally operated mechanism that must guide a linear attachment feature along a linear path while maintaining parallel coincidence may require a compliant mechanism capable of accommodating the error associated with attempting to guide the end effector along such a path.

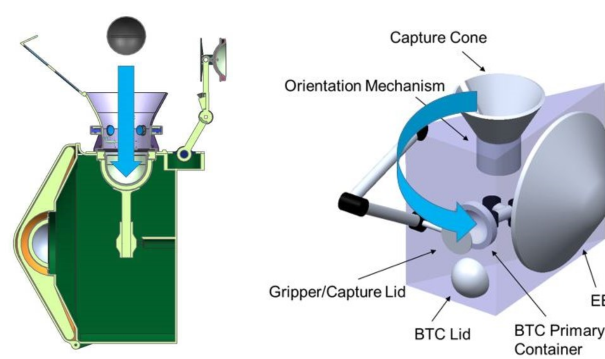


Figure 31: Examples of Inline (left) and Out-of-Line Transfer (right).

Approach— Brainstorming activities and research led to the identification of many methods for transferring an object. The concepts discovered can be divided into the following groups: applied force, electromagnetic, fluid flow, thermal expansion, vibration, photovoltaic, potential energy loss (springs and chemical), and translating the frame (rather than the object). The methods that were determined to have both good repeatability and capability to place and supply a preload to the PCV were the applied force methods (e.g., mechanical manipulation). These were the primary methods focused on in the trade study.

Trade Study—The trade study investigated mechanisms that performed transfer through applied force. Transfer devices that are used in the commercial, defense, public safety, and aerospace industries were identified, functionally decomposed, evaluated, and compared. Previous ROCS concepts were also evaluated using the same methods. The transfer mechanism components scored against the ROCS criteria, and a normalized sum was calculated. This process aided in down-selecting from the broad array of transfer mechanism concepts, as well as pointing towards recombination possibilities.

Trade Study Results—The trade study indicated that lower degree of freedom transfer methods were preferred from a complexity, development, and reliability viewpoint. The top transfer mechanisms identified are shown in Fig. 32 and Tab. 5. A more detailed version of the Recommended Concepts Table for Transfer Mechanisms can be seen in [9].

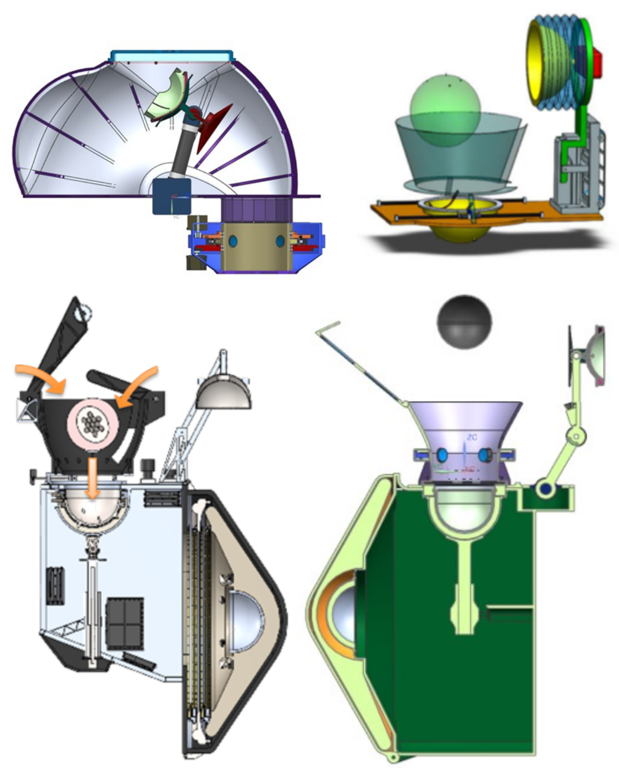
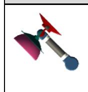
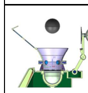
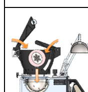


Figure 32: Examples of well-performing transfer methods [8] (clockwise from top left: 2 DOF Turret Arm, Douter, 3 DOF Turret Arm, and Blades).

Table 5: Recommended Concepts Table for Transfer Mechanisms (Red = Poor, Yellow = Medium, Green = Good).

Transfer		Mass	BTC Hardware Protection	Complexity	Actuator Count	Compatibility w/BTC	Rank
	2 DOF Turret Arm	Green	Green	Yellow	Yellow	Red	1
	3 DOF Turret Arm	Yellow	Green	Red	Red	Green	2
	Douter	Green	Red	Yellow	Green	Green	3
	Blades	Yellow	Yellow	Red	Red	Yellow	4
	Crane	Red	Red	Green	Yellow	Green	5

Technology Chosen for Further Study—The 2 DOF Turret Arm possessed the ability to protect the BTC hardware from risk of damage from the OS during transfer (by rotating the PCV Lid around on the wrist joint and using a dedicated tool for OS transfer) and had a good balance of low mass and complexity. Based on these observations, the 2 DOF Turret Arm with a wrist that has a paddle for protecting the BTC hardware was selected for further study (Fig 33). The arm may require the addition of a compliant mechanism if linear motion is required for functions such as latching the PCV Lid onto the OS and assembling the PCV Lid to PCV Base.

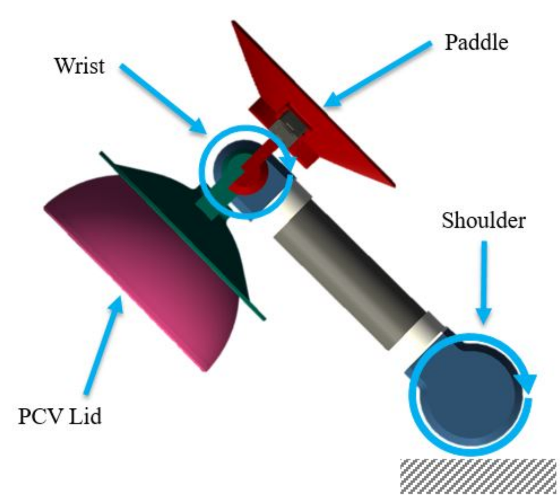


Figure 33: 2 DOF Turret Arm proposed for the Transfer Subsystem.

Capture and Orient Module

The primary functions of the Capture and Orient Module would be to capture the free-floating OS, orient the OS, and transfer the OS into the Primary Containment Vessel. This would require the combination of functional elements for capture, orientation, and transfer.

Philosophy—Developing a system to perform all three functions of capture, orientation, and transfer would require the integration of multiple hardware subsystems focused on performing one of more of the functions. Keys to developing a high-performing system lay in selecting subsystems that themselves exhibit a high level of performance, as well as integrate well with one another. Understanding the potential subsystems' performance capabilities and their compatibilities with one another is crucial to achieve this. Additionally, choosing subsystems that can be integrated in a way that allows for clean partitioning and modularity can help facilitate independent development and testing, reduce the potential for risky interactions between subsystems, and provide flexibility to update or replace elements (in the case of requirements change or new technology developments). Physically spacing out subsystems can also make the system more robust to subsystem volume growth.

The Capture and Orient Module would also have to stay within the allocated mass, volume, and power constraints. Total mass and volume are functions of the individual subsystem masses and volumes, along with any additional hardware required for their integration. Power needs depend on the individual power needs of the subsystems, as well as how many need to operate simultaneously to perform their given functions. Designing a system where individual subsystems can operate independently from one another in a sequence can help reduce the total power required during operations.

Finally, module-level requirements and considerations would also need to be addressed for the integrated system as a whole. These include "close before contact," containment of dust within the module following first contact with the OS, and ability to eject all mechanisms that were physically exposed to the OS prior to containment.

Approach—The design of the Capture and Orient Module was approached through first reviewing previous ROCS concepts, evaluating the concepts to assess how they perform against the evaluation criteria, and assessing their compatibility with external system elements. Second, alternatives for the various ROCS subsystems (i.e. Capture, Orientation, and Transfer) were reviewed, evaluated, and assessed relative to their compatibility with other subsystems. Third, new Capture and Orient Module architectures were developed: incremental improvements on existing architectures and novel systems with unique subsystem configurations. Fourth, all module architectures were compared and evaluated to arrive at a preferred Capture and Orient Module architecture.

Trade Study—Since in-orbit robotic sample return has not been previously performed, and no other systems were identified that demonstrate an integrated capture, orientation, and transfer function like that required of the Capture and Orient Module, the trade study focused solely on previous ROCS concept designs. Examples of previous well-performing ROCS concepts that provide capture, orientation, and transfer are described in [2] and [8], and shown in Fig. 34. These concepts, as well as newly generated concepts, were analyzed, evaluated, and compared.

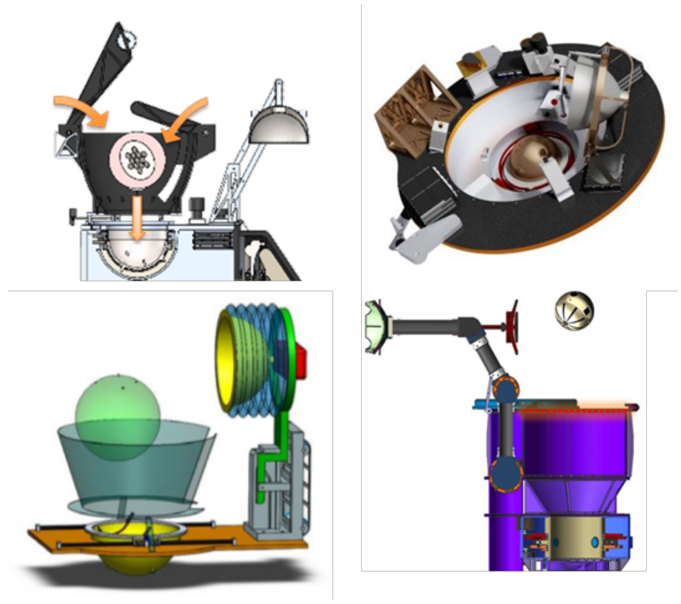
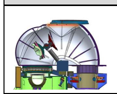
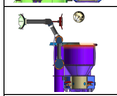
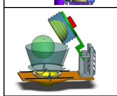
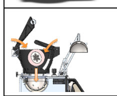


Figure 34: Examples of well-performing Capture, Orientation, and Transfer concepts (clockwise from top left: Carwash [8], Minimal [2], Inline Transfer [2], and MOSTT Concept 3 [8]).

Trade Study Results—Several ROCS concepts fell out of the option space due to their absence of the orientation function. Other concepts evaluated poorly with regards to development, fabrication, integration and test, operations, system success, risk, and project impact. Concepts that scored high amongst the evaluation criteria and/or were of interest amongst the architecture team were the Car Wash, Minimal, Douter, Inline Transfer, and MACARONE (MArs CApture and ReOrientation for the proposed NExt Mars Obiter) concepts. Tab. 6 compares each of these concepts over a selected set of determinant criteria that were considered high in importance and discriminative. A more detailed version of the Recommended Concepts Table for the Capture and Orient Architectures can be seen in [9].

Table 6: Recommended Concepts Table for Capture and Orient Architectures (Red = Poor, Yellow = Medium, Green = Good).

	Capture, Orientation, and Transfer	Dust Encapsulation	1G Testable	Impact on OS	BTC Hardware Protection	Determinism	Rank
	MACARONE	Green	Green	Green	Green	Yellow	1
	Inline Transfer	Red	Green	Green	Green	Yellow	2
	MOSTT Concept 3	Red	Yellow	Yellow	Red	Green	3
	Car Wash	Red	Green	Yellow	Red	Red	4
	Minimal	Yellow	Red	Red	Yellow	Green	5

Technology Chosen for Further Study—The MACARONE concept was chosen for the Capture and Orient Module architecture. The MACARONE concept configuration is shown in Fig. 35, as well as in Fig. 39 in more detail. The concept uses a sliding trap door for capture, a Motorized Cups Mechanism for orientation, and a 2 DOF Turret Arm with a paddle for transfer. The subsystems are configured along an arc based on the transfer arm kinematics, with the Orientation Subsystem and PCV Base along the COM-CM Interface Plane at the end of the arc.

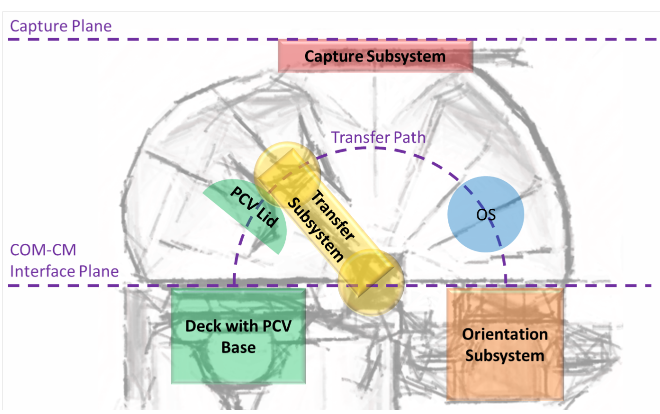


Figure 35: Capture and Orient Module MACARONE concept layout.

The Capture Subsystem is placed above and in the middle of the arc to feed the OS into the transfer path. The Capture Subsystem lays tangent to the Capture Shell in order to have the least impact on the geometry of the Shell for the given capture aperture diameter. The Capture Shell constrains the OS along the transfer path to allow the Transfer Arm to lead it into the Orientation Subsystem for orientation. A bulge along the outer perimeter of the Capture Shell on the PCV Base side provides room for the Transfer Arm to rotate the OS and PCV Lid around and over the PCV Base. The Orientation Subsystem was placed next to PCV Base to take advantage of the CM Deck for structural support, keep a single reference datum for mounting the subsystems, produce a large capture volume, and allow for vertical growth margin for the Orientation Subsystem (if needed), while also keeping mass close to the central axis of ROCS. A concept of operations for the MACARONE concept is shown in Figs. 36 and 37.

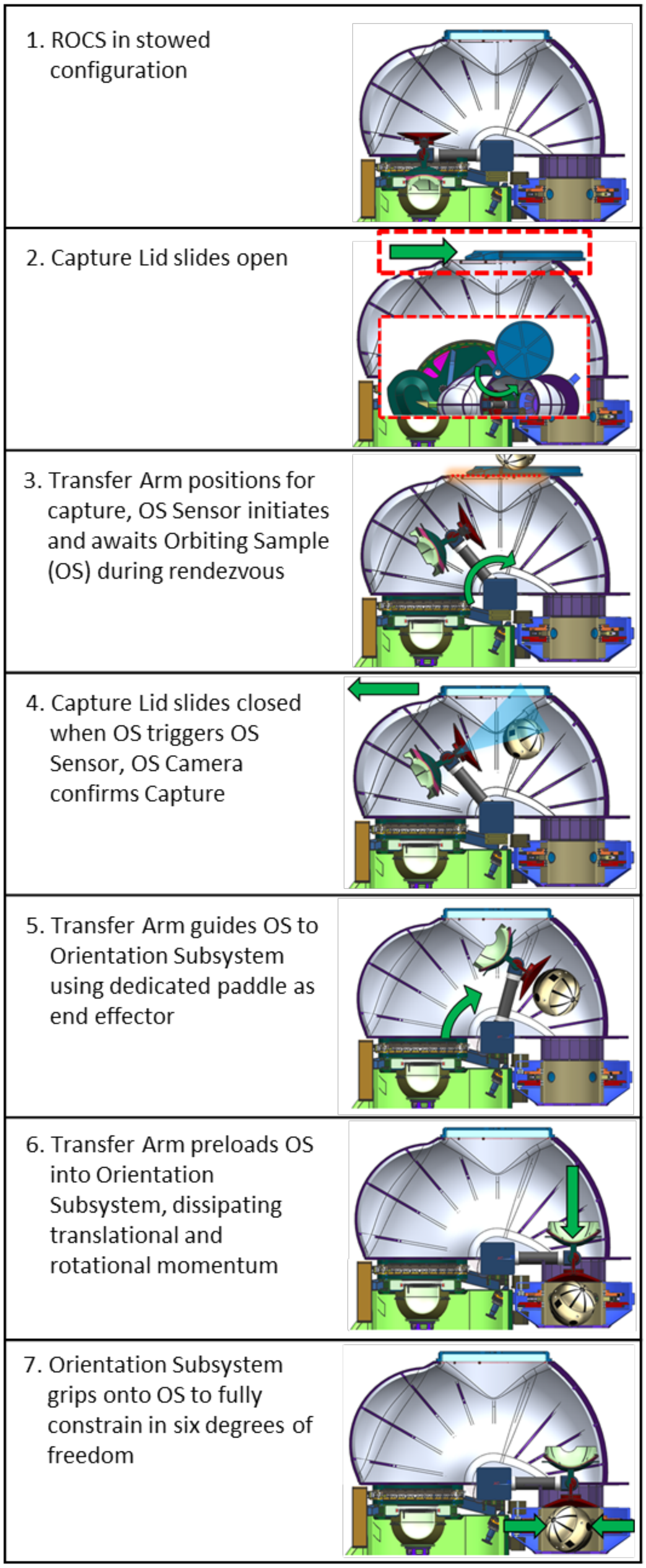


Figure 36: Capture and Orient Module Concept of Operations, Part 1.

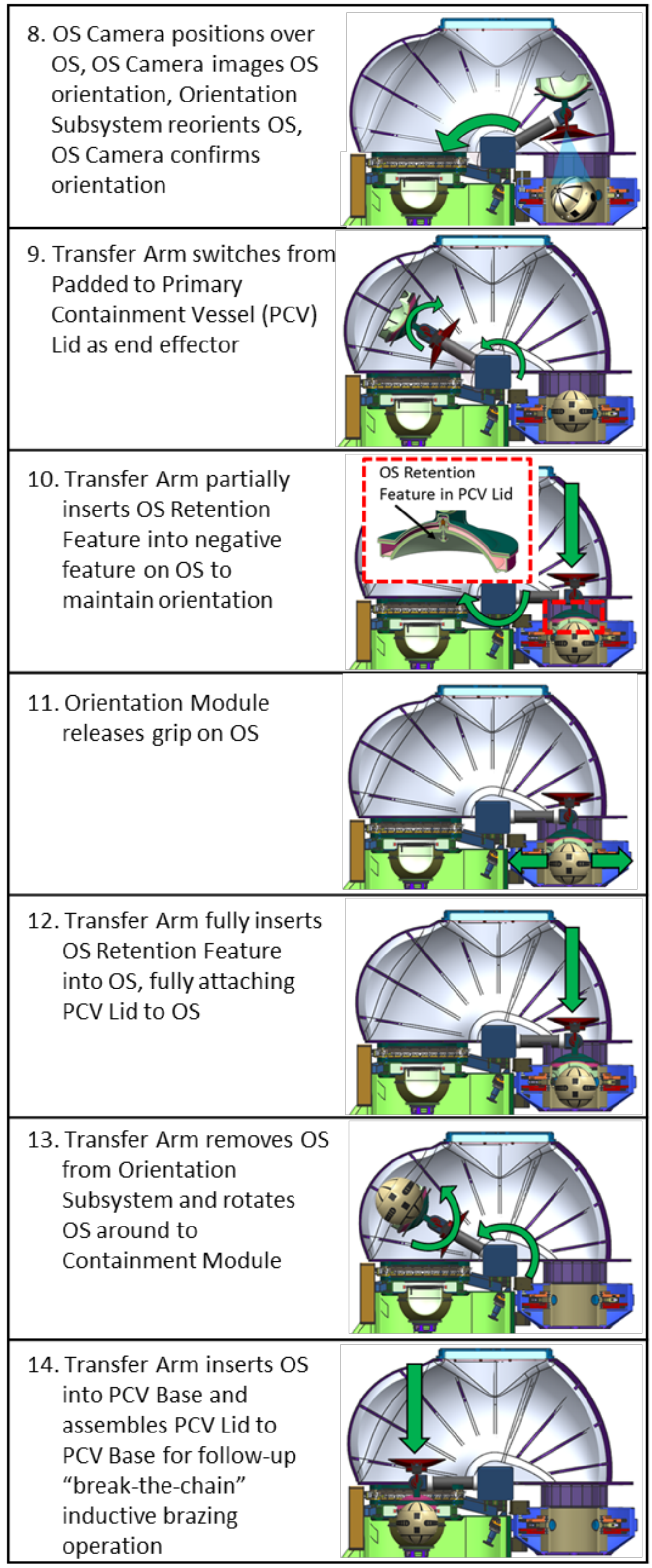


Figure 37: Capture and Orient Module Concept of Operations, Part 2.

Integrated ROCS Concept

The MACARONE COM integrated with a conceptual CM and ERM in a potential ROCS design is shown in Fig. 38 and 39. Fig. 40 shows the ROCS design within the ROCS payload's allocated keep out volume. Fig. 41 shows potential release of the Capture and Orient Module containing all remaining unsterilized hardware surfaces that are assumed to have been exposed to OS prior to containerization in the Primary Containment Vessel. OS entry and EEV exit vectors relative to ROCS mounted onto a notional SEP orbiter is shown in Fig. 42.

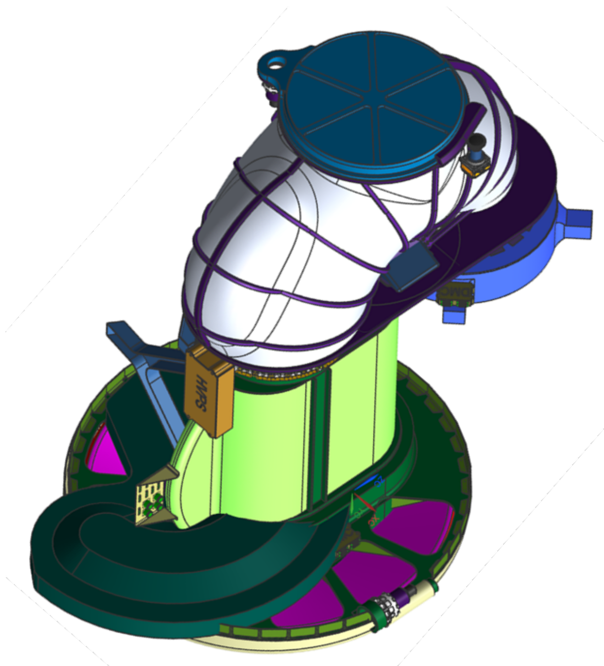


Figure 38: Integrated ROCS concept.

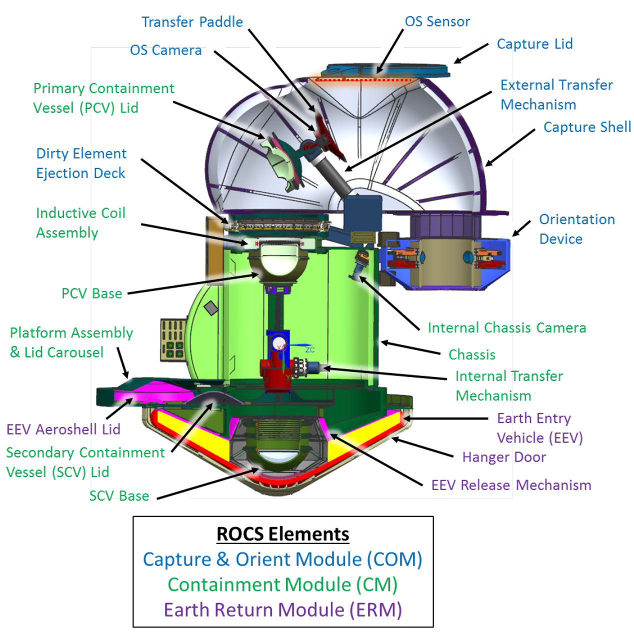


Figure 39: ROCS elements and primary components.

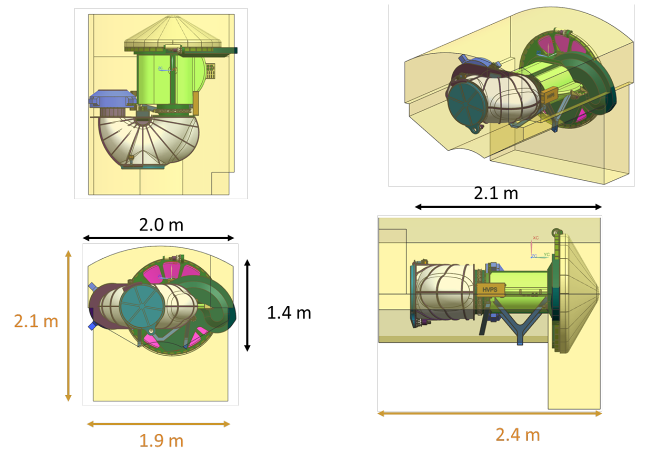


Figure 40: ROCS configuration within spacecraft keep out volume.

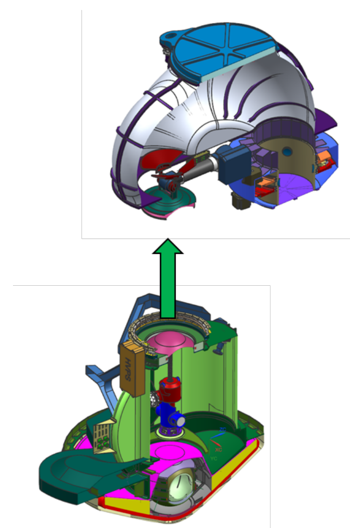


Figure 41: Ejection of Capture and Orient Module.

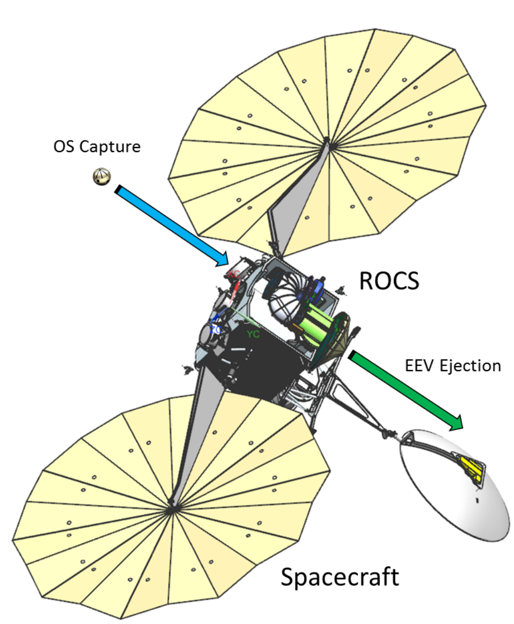


Figure 42: ROCS mounted onto a notional SEP orbiter.

6. FUTURE WORK

Trade studies are currently underway for sensors for OS detection for capture, capture confirmation, and pose estimation for orientation confirmation, as well as options for ejecting the Capture and Orient Module for planetary protection concerns. A Technology Readiness Level (TRL) 4 (breadboard validation in a laboratory environment), full-scale design is planned for development at the Jet Propulsion Laboratory. Upon assembly, subsystem level testing will be performed, as well as integration with CM and ERM prototypes to test end-to-end ROCS concept functionality from OS capture to EEV release.

7. SUMMARY

An orbiting sample capture and orientation system architecture for a Rendezvous and Orbiting Sample Capture System (ROCS) concept was developed to enable spacecraft-based, in-orbit capture, orientation, and transfer of a Mars sample container into a containment vessel as part of a concept study for potential Mars Sample Return. The studied system performs the following functions: OS detection, OS constraint, OS capture confirmation, OS orientation, OS orientation confirmation, and assembly of the OS into a Primary Containment Vessel for follow-up operations to seal off the OS for Earth return. System benefits include system modularity, development flexibility, testability in a 1G environment, analyzability without the need to simulate or test for 0G contact dynamics due to the "close before contact" strategy, encapsulation of potential Mars material on the outer surface of the OS due to the "close before contact" strategy, and ability to be ejected from the spacecraft following completion of operations. The system shows potential for integration with additional Containment Module and Earth Return Module concepts within the ROCS payload. Additional trade studies are underway for lower level elements, and development of a TRL 4-level system with end-to-end testing is planned for the future at the Jet Propulsion Laboratory.

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BIOGRAPHY

Paulo Younse *is a robotics engineer for the Robotic Vehicles and Manipulators Group at the NASA – Jet Propulsion Lab in Pasadena, CA. His experience resides in mechanical design, machine vision, systems engineering, systems architecture, and planetary sample collection. He is currently working on the Mars 2020 rover developing the sample tube hermetic seals to preserve samples for potential Earth return. Previous experience includes work on unmanned underwater vehicles at the Boeing Company and visual navigation and control for agricultural robots at the University of Florida. He received a B.S. in Mechanical Engineering from California Polytechnic State University (San Luis Obispo, CA) and an M.E. in Agricultural Engineering from the University of Florida (Gainesville, FL).*

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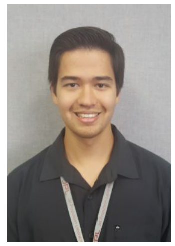
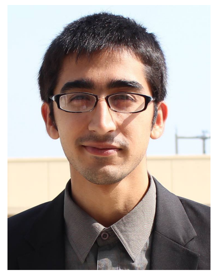
Marco Dolci *is part of the Robotic Vehicles and Manipulators Group at the NASA – Jet Propulsion Laboratory as a Robotics Systems Engineer. He is also a Politecnico di Torino Aerospace Engineering Ph.D. candidate. Marco received an M.S. in Space Engineering, and has experience in space systems, orbital mechanics, attitude determination and control systems, space environment, payloads, and CubeSats. Marco received a B.S. and M.S. in Physics with experience in data analysis, antennas, optics, cosmic rays and astrophysics.*



Preston Ohta *is a spacecraft mechatronics engineer at the NASA – Jet Propulsion Laboratory. He is working on instrument accommodation for the Mars 2020 rover and is developing capture and orientation mechanisms for the Mars Sample Return campaign. Prior to JPL, he graduated from Carnegie Mellon University with a dual degree in Mechanical Engineering and Robotics, where he developed mechanically compliant robotic systems in the CMU Soft Robotics and Bionics Laboratory.*



Karan Lalla *is an undergraduate senior at California Polytechnic State University, Pomona. He will earn his B.S. degree in Mechanical Engineering in December 2017. His experience includes the design and development of both mechanical and control systems for a drill developed at Orbital ATK Systems. He has also aided in NASA Jet Propulsion Laboratory's development of a test protocol and procedure for analyzing the surface roughness on the inner surface of abraded titanium tubes using confocal microscopy. His current work includes the development of a braze seal for hermetically sealing a cache of rock cores obtained from Mars for future return to Earth. In addition, he is currently generating concepts for sensors to be used in the Mars Sample Return campaign. He will be begin working towards a master's degree at California Polytechnic State University, Pomona beginning in January 2018.*

Eric Olds *is a Mechanical Systems Engineer contracting to the NASA Jet Propulsion Laboratory from Sierra Lobo, Inc. He has over 20 years of experience working in engineering, and has worked extensively in electronics packaging, RF amplifier housings, mechanical structures, and mechanisms for space flight. He was the lead Mechanical Engineer on the CheMin science instrument operating on the Mars Science Laboratory (Curiosity) Rover. Previous experience includes spacecraft operations and systems testing for Lockheed Martin. He received his B.S. in Aerospace Engineering from the University of California, Los Angeles.*