Mars 2020 Rover Adaptive Caching Assembly: Caching Martian Samples for Potential Earth Return

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Abstract

The Adaptive Caching Assembly (ACA) is part of the Sampling and Caching System on the Mars 2020 Perseverance Rover and consists of multiple stations that process, hermetically seal, and store sample tubes containing collected Martian material, either rock cores or regolith samples, in preparation for caching on the surface of Mars. The ACA stations consist of seven active degrees-of-freedom, as well as a large number of passive mechanisms that must operate in extreme Mars temperature and pressure conditions. A robotic arm within the Rover manipulates the sample tubes between ACA stations as part of an end-to-end sampling sequence and utilizes a compliant end effector to accommodate misalignments during station interactions. Stringent hardware cleanliness requirements were dictated to ensure collected samples would not be compromised, which significantly impacted the design, assembly, and test operations of the ACA. Three ACAs were assembled to support ground testing and flight operations, which were exposed to environmental testing to validate functionality in Mars-like conditions. A number of challenges existed from design through test, including volume constraints, mechanism controllability and operation, the effects of tight tolerances, and cleanliness requirements.

Introduction

The Adaptive Caching Assembly is part of the Sampling and Caching System (SCS) on the Perseverance Rover (Figure 1), which successfully launched on July 30, 2020, and will land on Mars in February 2021. The Rover’s primary mission has a duration of one-and-a-half Martian years, or approximately three Earth years. The Mars 2020 Perseverance Rover design is heavily based on the Mars Science Laboratory (MSL) Curiosity Rover, which has been operating on the surface of Mars since August 2012; however, Perseverance is outfitted with a new sampling system and scientific instrument suite to address the new mission goals. The Perseverance Rover has four main science objectives: looking for habitability, seeking biosignatures, caching samples, and preparing for humans [1]. Seven science instruments are located on the Rover to address many of these objectives via remote and in-situ observations and operations.

Sampling and Caching System

The Sampling and Caching System’s purpose is to create the cache of scientifically selected and documented Martian materials by collecting rock cores and regolith samples, packaging these materials into hermetically sealed sample tubes, and depositing them on the Martian surface for potential return to Earth. These packaged samples must meet stringent science-driven contamination control requirements which drive the physical architecture and hardware implementation: less than 10 ppb organic carbon, less than 1 terrestrial viable organism per sample, and limits on inorganic contamination on elements that impact returned sample science. SCS must also perform rock abrasion and dust removal operations to prepare surfaces for scientific instrument assessment, and then position the instruments for the assessment.

SCS consists of two robotic systems which work in conjunction with each other to perform the mission functions: one MSL-like robotic system on the outside of the Rover consisting of a Robotic Arm and Turret, and one new autonomous robotic system on the inside of the Rover called the Adaptive Caching Assembly.

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The robotic system on the outside consists of a 5 degree-of-freedom (DOF) Robotic Arm (RA), similar to the robotic arm implemented on the Curiosity rover, and a Turret assembly mounted to the end of the RA. The Turret assembly contains a new rotary-percussive drill (also referred to as the Corer), components of which are described in [2], [3], and [4]; a ground contact sensor; a gas dust removal tool (gDRT), using puffs of nitrogen to remove dust from abraded surfaces; and two instruments, PIXL (Planetary Instrument for X-ray Lithochemistry) and SHERLOC (Scanning Habitable Environments with Raman and Luminescence for Organics and Chemicals), for in-situ science.

The robotic system (i.e., ACA) on the inside of the Rover consists of a 3-DOF Sample Handling Assembly (SHA) that manipulates sample tubes, gloves, and covers. Sample tubes with collected Martian material are processed within the ACA by moving the tube between stations using the SHA to support the following functions: assess the volume of sample material collected, image the sample tube (multiple instances), dispense a hermetic seal into the sample tube, activate the hermetic seal to preserve the collected sample, store the sealed sample tube until ready to drop, and finally drop-off the sealed sample tube to the surface of Mars at prescribed locations.

Figure 2 illustrates the SCS architecture and how the two robotic systems interact. Sample tubes stored inside the ACA are inserted through the lower Bit Carousel (BC) door into sampling bits stored in the BC. The BC rotor rotates the bit/tube to the upper door where the RA docks the Corer to the BC and the Corer acquires the bit/tube using its actuated degrees-of-freedom. The RA undocks the Corer and then places and preloads the Corer on the intended target. The Corer acquires a sample into the sample tube inside the bit. After sample acquisition, the RA docks the Corer with the BC and the Corer transfers the filled sample tube (still in the bit) to the BC. The RA undocks the Corer, and the BC rotates to orient the filled sample tube for removal from the bit. After BC rotor motion, the filled sample tube is removed from the bit by the SHA within the ACA and is ready to be processed using the ACA stations (Figure 3). Once the acquired sample has been imaged in the sample tube, its volume has been measured, the sample tube has been hermetically sealed, and stored for future deposit on the Martian surface, the process repeats for the suite of sample tubes available within the ACA. The remainder of this paper will focus on the ACA portion of the Sampling and Caching System.
Adaptive Caching Assembly Description and Operations

The ACA consists of stations/components as identified in Figure 3 (CAD images), and Figures 4 and 5 (as-built images):

Figure 3. ACA CAD images with stations identified, rotated to a bottom up view for visibility.
Left image: SHA stowed for launch, and bit carousel doors closed.
Right image: SHA extended for sample tube operations, and bit carousel doors open.
The Caching Component Mounting Deck (CCMD) is a monolithic titanium structure to which all ACA stations interface, and interfaces to the Rover via three bipod assemblies. All ACA stations are made from titanium to minimize thermally induced position errors for robotic operations using the SHA. While the ACA is designed to fit within the Rover for launch through landing, surface operations on Mars require the SHA to extend approximately 200 mm below the Rover’s bellypan. Therefore, an ejectable bellypan was implemented directly below the ACA volume, which is released after landing to provide the SHA with an unobstructed volume to extend into during operations. Surface features are assessed via Rover imaging prior to SHA motion to prevent contact with potential obstacles below the Rover.
The ACA consists of 7 active degrees of freedom via gear motor assemblies (planetary gearboxes mated to brushless motors with magnetic detent brakes) described in [5]. The gear motors support actuation of the Bit Carousel, SHA, End Effector (EE), and Sealing Station. A significant number of passive ball lock mechanisms are implemented throughout the ACA to support locking and unlocking of hardware from various stations/components via SHA interaction. Hardware using ball lock mechanisms/features include the bits, sample tubes, gloves, covers, EE tube gripper, and the seal dispenser. A set of ball lock mechanism design guidelines were developed across the ACA to ensure consistency for each use case and included details such as recommended geometry and clearances for mechanism features. These guidelines also accounted for dust inclusion in the mechanisms, which is a real concern for proper functionality.

**ACA Operations**

A high-level end-to-end flow of the sample collection, processing, storage, and tube drop-off for a single collected sample, focused on ACA operations, is shown in Figure 6. Every step, with the exception of the three Sample Collection steps involving the Corer, requires a robotic interaction between the SHA and an ACA station utilizing appropriate force and position limits to safeguard the hardware. The entire operation from Sample Collection through Sample Storage executes autonomously in a few hours. If a fault were to occur during the sequence, the ACA is capable of recovering autonomously in some cases; otherwise, operations will stop and the Rover will "phone home" for assistance before proceeding. All Sample Processing steps identified as imaging or assessment based are for documentation purposes only (to support sample return selection), and are not decisional for proceeding through the full sequence, meaning operations will not stop based on the results of those activities unless a non-recoverable fault were to occur.

![Figure 6. End-to-end sequence for caching each sample tube on Mars](image-url)

Instead of dropping off each sample tube once it’s processed, the current expected strategy is to place the processed sample tube into storage until enough samples are collected in a particular region of interest, at which point a group of samples will be dropped off at a designated location for caching. The location of drop-off will be meticulously documented to support potential future retrieval and return to Earth, since the sample tubes could become covered with dust and not easily visible. More than one drop-off location for groups of sample tubes may be designated during the mission based on the number of regions of interest visited for sampling activities.
Planetary Protection and Contamination Control

Because integrity of the collected samples is essential for future scientific evaluation on Earth, stringent Planetary Protection (PP) and Contamination Control (CC) requirements were levied on the ACA hardware to ensure samples would not be compromised by earthborn contaminants. Contamination concerns significantly drove design and material choices as well as assembly methods and resulted in less than straightforward test and qualification flows. Special hardware handling techniques were developed for both assembly and testing of contamination sensitive hardware.

ACA hardware is classified in terms of cleanliness needs based on proximity to collected sample material (i.e., Martian rock and dust). Hardware that directly contacts sample material is defined as Sample Intimate Hardware (SIH). Hardware that contacts SIH items, but not directly sample material is deemed Sample Handling Hardware (SHH), while all remaining ACA hardware is considered Other. SIH items, including the sample tubes, hermetic seals, bits, and volume station, have the most stringent handling constraints and required sterile assembly techniques in an ISO 5 cleanroom. SHH items include the hermetic seal dispensers, gloves and covers, and the vision station, which were assembled in similar conditions to the SIH hardware.

Other hardware included the Sealing Station, SHA, EE, Drop-off Station, and Parking Lots, which did not require sterile assembly and handling constraints. While the Sealing Station directly contacts a sample tube prior to seal activation, it is considered Other since a hermetic seal will be installed in the sample tube at this point and the potential for introducing contamination into the sample tube is not credible. The BC actually falls into both SHH and Other categories, with internally and externally located hardware requiring different levels of cleanliness. Since the BC houses the bits used to collect material, internal cleanliness was important to not introduce contaminants to sample tubes during interactions; however, aseptic techniques were not levied due to the materials required for mechanism functionality over environments, such as wet lubrication. External cleanliness was equivalent to the Other items since the BC enclosure provides protection to the internal hardware.

All piece parts were precision cleaned prior to assembly using approved solvents for the implemented materials and coatings. SIH hardware was cleaned to very stringent cleanliness levels, which allowed approximately one particle of no more than 50 microns in size per 0.1 m², defined as Particle Cleanliness Level (PCL) 50. Other hardware was cleaned to typical cleanliness levels, which allows for one particle of no more than 300 microns in size per 0.1 m², defined as PCL 300. As the particle size decreases, the number of allowed particles per 0.1 m² increases, as defined in industry standard IEST-STD-CC1246, Product Cleanliness Levels – Applications, Requirements, and Determination. In addition to a stringent PCL count, SIH hardware required Non-Volatile Residue (NVR) cleanliness verification to ensure contaminants such as oils and greases were sufficiently removed to a level of A/10, which means no more than 0.1 mg per 0.1 m² remained after cleaning. For a number of SIH items, precision cleaning more than once was required to achieve the required levels. Hardware was not released for assembly until cleanliness verification was completed.

To ensure SIH cleanliness could be maintained as the hardware was manipulated per the operational sequence, steps were taken to avoid contact between SIH and Other items. A glove, which is attached to each sample tube, was implemented to prevent the EE tube gripper from directly interfacing with a sample tube. The glove is “clean” on the sample tube interface side, and “dirty” on the EE interface side. Each sample tube with glove attached is stored within a sheath. Clearances between the sample tube and sheath ensure the sample tube only contacts surfaces considered clean, while also accounting for position accuracy of the SHA during sample tube manipulations at a sheath. The glove serves as a Fluid Mechanical Particle Barrier (FMPB), which based on Computational Fluid Dynamics analysis constrains contamination from reaching clean hardware. The FMPB does this by restricting flow into the sheath via specific (tight) hardware clearances between the glove and sheath in critical locations, which results in a maximum expected penetration height for particles that may enter a sheath, deemed the “bug line”. During insertion into and removal from a sheath, a sample tube may contact sheath surfaces if they are located above the “bug line”, which are deemed clean. The hermetic seal dispensers and volume station employ covers with
a similar FMPB feature to maintain hardware cleanliness requirements for hermetic seals and the volume probe prior to and between usage on Mars. In the dispensers and volume station, the sample tube may only contact surfaces considered clean similar to within a sheath. Refer to Figures 19, 20, and 21 for depictions of a glove and covers in their respective installed cases.

In addition to precision cleaning and FMPB hardware features to achieve and maintain SIH hardware cleanliness, a high temperature bake-out at 350°C in air for a minimum of 1 hour was prescribed. This bake-out initiates combustion cleaning for the elimination of viable organisms and the reduction of organic carbon on hardware surfaces and occurs as the last process prior to hardware delivery to the Kennedy Space Center for installation into the Rover. As a result, the SIH and associated SHH items must participate in the bake-out together as an assembly, which includes the STSA and the DVT assemblies. Material selection was critical for all STSA and DVT hardware to ensure compatibility with the high temperature bake-out. Spring materials such as Elgiloy were implemented versus typical stainless steel options. High temperature compatible materials were implemented such as Ti-6Al-4V and A286, as well as dry film lubrications such as molybdenum disulfide (MoS2) and tungsten disulfide (WS2). Non-metallics were not permitted due to the temperature requirement.

All other ACA hardware was exposed to both a station-level and a full ACA-level bake-out at 110°C for durations up to 141 hours. These bake-outs were a Dry-Heat Microbial Reduction for PP purposes, as well as to meet surface cleanliness and outgassing requirements for CC. Thermoelectrically Controlled Quartz Crystal Microbalance was implemented to verify outgassing rates were met during bake-outs in thermal vacuum environments.

Overall, the PP and CC constraints introduced a number of challenges that resulted in novel hardware solutions, as well as hardware processing changes along the way due to lessons learned discussed later in this paper.

ACA Station Descriptions

Bit Carousel

The Bit Carousel (BC) is mounted to the CCMD on the ACA and extends through a cut-out in the Rover top deck and front panel to accommodate both tube and bit exchange operations. A non-permeable fabric close-out covers the gap between the BC and Rover structures to prevent contamination from entering the ACA volume within the Rover from above.

The docking assembly is the critical interface between the ACA and Turret for bit exchange operations with the Corer and is mounted to the front of the BC (Figure 7). During bit exchange, four docking posts on the Corer structure engage the docking cones on the docking assembly as the RA brings the Turret closer to the BC. Due to the kinematics of the 5-DOF RA, continued advancement of the Corer results in a rotation of the Corer on the end of the RA, meaning the docking posts are now rotating with respect to the docking assembly. The docking assembly therefore rides on a passive bearing mechanism that compensates for this Corer rotation. The bearing mechanism consists of a dry film lubricated four-point contact (X-type) bearing from Kaydon, implemented due to packaging limitations. Docking is considered complete once contact switch mechanisms located at the bottom of each docking cone are fully activated and the desired preload force is achieved. A minimum of 3 out of 4 switch activations are required to proceed. Because of the induced rotation during docking, a single speed variable reluctance resolver from Ducommun, Inc. is implemented on the docking assembly to measure the resulting amount of rotation, which is used to adjust for Corer-to-bit orientation during bit exchange. When the Turret undocks from the BC, a return spring mechanism brings the docking assembly back to its original position to support the next docking operation. The return spring mechanism consists of a cam roller design, with a detent in the cam to center the mechanism, and the roller located at the end of a flexure to enforce re-centering.
Internal to the BC is a rotor mechanism assembly which actuates the carousel's rotor structure to a desired position for either tube or bit exchange operations (Figure 8). The rotor structure is the primary interface within the BC for the bit holders with bits installed, as well as a sample tube sheath with a sample tube and glove installed. The rotor mechanism assembly consists of an electronically commutated gear motor, harmonic drive, and dual speed resolver from Ducommun Inc., with a back-to-back set of angular contact bearings spaced apart to carry both launch and operational loads. Wet lubrication is used within the rotor mechanism components, which requires heating for proper functionality at cold temperatures on Mars. A spring energized Teflon seal is used to prevent debris from entering the mechanism within the rotor assembly. Additionally, spring energized Teflon seals are used to prevent wet lubrication from migrating into the carousel, which would be a contamination concern for the bits. The rotor mechanism does not contain a hard stop and is free to rotate clockwise (CW) or counterclockwise (CCW) indefinitely as commanded. The gear motor contains no brake, and only relies on a magnetic detent for holding position.

Inside the BC resides a suite of nine bits to support coring (6x), regolith collection (1x), and abrading (2x) operations. These bits are “locked” within bit holders when not in use to survive not only launch vibration and Rover traverse loading, but both bit exchange with the Corer and tube exchange with the SHA. The bit holders contain both axial and radial cam rollers to align a bit within a holder and minimize tipping which could be detrimental for tube-to-bit insertion. In addition, an axial spring mechanism provides compliance to accommodate misalignments during bit insertion and removal activities from a bit holder via the drill.

The BC assembly contains an upper and lower opening in its structure. The lower entry point allows for sample tubes to be inserted into bits for sample acquisition, as well as removal from a bit once a sample has been collected (Figure 8). The upper entry point supports bit exchange operations with the Corer assembly. Both of these openings utilize a one-time deployment door to maintain cleanliness of the hardware within the BC until release on the surface of Mars. Both doors consist of a passive spring-actuated hinge mechanism held closed by a latch that is deployed via a release mechanism. The release mechanism is a series of passive spring-actuated mechanisms initiated by a separation nut non-explosive actuator (NEA) device from Ensign-Bickford Aerospace & Defense Company.
When the doors are closed, a HEPA filter allows for venting during launch depressurization, and to minimize contamination from entering the BC prior to door actuation on the surface of Mars. Once the doors are deployed on Mars, crushable honeycomb absorbs the shock and determines the final resting position of the doors during surface operations on Mars. This position has been factored into the overall assembly to ensure inadvertent contact does not occur with surrounding hardware, and sufficient clearance exists for interfacing hardware, such as the Turret/Corer during docking.

Sample Handling Assembly
The SHA is a 3-DOF robotic arm approximately 0.5-meter long with a compliant, single DOF End Effector (EE) mounted at the end of the arm (Figure 9). The SHA is responsible for all sample tube, glove, and cover manipulations between ACA stations. In order to reach the required operational work space in the ACA, the SHA uses a prismatic joint, identified as the Z-stage, which is actuated by an electronically-commutated gear motor assembly; and two revolute joints, identified as the shoulder and elbow joints, which are actuated by electronically-commutated gear motors with harmonic drives and dual speed absolute position resolvers. The Z-stage is responsible for the linear motion of the SHA, and is designed to allow the EE, or any component (i.e., sample tube, glove, cover) on the EE, to interact with the ACA stations utilizing a minimum preload capability of 350 N. This applies only during station interactions when the SHA is retracted and not fully extended. A minimum clearance of 4 mm between the top of a hermetically sealed sample tube attached to the EE and the lowest feature of each ACA station is accommodated when the SHA is fully extended such that the sample tube can be manipulated safely in free space within the ACA volume.

The Z-stage consists of an outer housing that directly interfaces to the CCMD, and an internal translation tube called the slide adapter that mounts to the shoulder (Figure 10). A welded metal bellows between the outer housing and the shoulder closes out the Z-stage and protects the internal components from Martian dust. The slide adapter translates against the outer housing using two sets of eight track roller bearings: one set is attached to the end of the outer housing and preloaded against the external surfaces of the slide adapter and the other set is attached to the slide adapter and preloaded against the internal surfaces of the outer housing. These track roller bearings are set sufficiently apart to carry the cross-axis moment and side loads, and with the slide adapter and the bore of the outer housing having square cross-sections, the
preloaded track roller bearings support torsion loads and minimize rotations between the slide adapter and outer housing.

A lead screw mechanism drives the slide adapter with the lead screw and actuator assembly mounted to the outer housing and the nut mounted to the slide adapter. Both the lead screw and nut are mounted with gimbals to isolate the lead screw from any bending and radial loads. To limit the travel of the Z-stage, hard stop tabs are mounted directly to the free end of the lead screw and directly contact tabs on the nut gimbal when fully extended and tabs in the shoulder when fully retracted.

The shoulder and elbow joints provide precise lateral positioning and placement of the EE at all stations with sufficient torque capability during station interactions, as well as holding torque during Rover traverse stow. Both joints are identical in design and utilize the structural member of the arm as housings for the joints. The gearmotor directly attaches to the gearmotor housing with the output connected to the wave generator of the harmonic drive through an Oldham coupling. Downstream of the harmonic drive is the output shaft that is supported by a back-to-back duplex bearing pair separated by a spacer for increased stiffness and reduction in wobble. To further reduce misalignments, the output shaft is pinned and match drilled to the flex spline of the harmonic drive. Embedded in the output shaft is the dual speed resolver from Ducommun Inc. to provide precise position feedback and knowledge of the joint.

When stowed for launch, the SHA is restrained by two NEA separation nut mechanisms, similar to the devices used for the BC door releases. One NEA is used to launch-restrain the Z-stage assembly, while the other is used to launch-restrain the SHA forearm, located at the end of the arm before the EE interface.
End Effector
The EE is mounted at the end of the SHA and interfaces with gloves, with sample tubes via gloves, and covers to be manipulated and moved throughout the ACA. The EE is comprised of two primary components: A Tube Gripper Assembly (TGA) which secures covers or sample tubes via gloves during manipulation via a ball lock interface; and the Remote Center of Compliance Mechanism (RCCM) which provides compliance for all SHA to station interactions (Figure 11). A third component, the Lockout System, secures the RCCM during launch and traverse (Figure 12).

The TGA has an electronically commutated gearmotor that is mounted to the angular deflection plate of the RCCM with the output of the gearmotor directly connected to a ball screw mechanism (Figure 13). A pair of angular contact bearings support the ball screw mechanism as well as the gearmotor. The nut of the ball screw is attached to a plunger, which when the ball screw rotates either extends or retracts the plunger. In the retracted state, the ball lock groove of the plunger lines up with the ball sockets of the upper housing, which puts the ball locks in the released state. When the plunger extends, the balls extend out of the upper housing to allow the EE to grip against a cover or a glove (with sample tube). The TGA also contains a 6 degree-of-freedom force-torque sensor with the inner diameter mounted to the TGA upper housing and the outer diameter mounted to the TGA lower housing. The force/torque sensor protects the SHA, EE, and stations during operations against inadvertent loading during SHA free space motion and limiting loads during station interaction.

The RCCM compliant mechanism is designed to lower the necessary loads required to align the EE during station interactions (Figure 14). The concept comes from robotic end effectors that use a remote center of compliance approach to insert a peg into a hole as described in [6] to minimize the chance of jamming in close tolerated parts. The RCCM compliance is achieved through two sets of machined flexures: Lateral Flexures, which provide the lateral/translational compliance to the mechanism, and Angular Flexures, which provide the angular compliance to the mechanism. Both sets of flexures can be twisted about the z-axis for rotational compliance.

To reduce the chances of a fatigue failure, the flexures of the RCCM are locked out during launch as well as Rover traverse. This is achieved through the Lockout System mechanism internal to the EE that interfaces with a cam mounted to the shoulder of the SHA (Figure 12). The main structural component of the Lockout System is the RCCM housing, which has two spring loaded lock rods, one bolted and one floating, that slide into bushings in the RCCM housing. The cover plate interfaces with the opposite end of
the lock rod. Affixed to a clevis directly adjacent to the lock rod and cover plate interface is a roller supported by a shoulder bolt and locking nut. This roller rides on a clearance-fit bushing and is supported on both faces by thrust washers. When the roller engages the cam during stow operations, the cover plate compresses towards the RCCM housing and restraints the RCCM by a series of pins and holes present at both the lateral and angular stages. These interfaces restrain motion of the RCCM via a load path back to the primary structure, the RCCM housing.

**Sealing Station**

The Sealing Station supports two functions within the ACA: to activate a hermetic seal within a sample tube, and to drop-off a sample tube from the Rover for retrieval by a potential future sample return mission. To accomplish these functions, the Sealing Station consists of two mechanism assemblies, a ram mechanism to conduct seal activation, and a gripper mechanism to support the sample tube during seal activation as well as perform sample tube drop-off, as described in [7]. The ram mechanism is capable of generating more than 20 kN with a stroke of approximately 16 mm (Figure 15). To achieve this, a gear motor drives a gear train that connects to a planetary roller screw from SKF, Inc. that provides the linear
motion necessary to mechanically activate a hermetic seal within a sample tube, within a small package. The gripper mechanism is actuated via a gear motor connected through a gear train to the gripper, which opens and closes to “grip” or release a sample tube within the station. A kicker is attached to the gripper mechanism, which rotates with the actuated gripper, to enforce a sample tube to release from the station during the drop-off sequence. Figure 16 shows a cross-section of the Sealing Station with the ram in contact with a hermetic seal at the start of the seal activation sequence within a sample tube, and the kicker in a retracted position. The ram will travel approximately 3.5 mm from this position until the ram hard stops on the gripper at which point the hermetic seal has been fully activated within the sample tube. Full activation occurs when the hermetic seal knife-edge feature has fully expanded into the sample tube wall, thereby creating a seal.

![Figure 15. Sealing Station Ram and Gripper](image1.jpg)

![Figure 16. Cross-Section of Sealing Station with Sample Tube in Position for Hermetic Seal Activation.](image2.jpg)

**Sample Tube Storage Assembly**
The STSA houses thirty-nine flight sample tube assemblies within storage sheaths (Figure 17). Within each sheath is a sample tube and a glove. Figure 19 shows a cross-section of an empty sample tube with glove attached in a sheath. A glove serves two purposes: 1) Prevents contamination from entering a sheath to maintain sample tube cleanliness, and 2) Provides an interface between the SHA and sample tube for manipulation within the ACA. Due to cleanliness concerns, a sample tube is not to directly contact the EE of the SHA.

The sample tube consists of a passive ball lock mechanism with two states, engaged or disengaged. The engaged state has the balls pushed outward into a groove to “lock” the sample tube into a sheath or bit. The disengaged state allows the balls to retract to support sample tube removal from a sheath or bit via the SHA. With the glove attached to a sample tube, a multi-stage ball-lock activation process is required for sample tube manipulation. To manipulate a sample tube, the EE tube gripper first extends its plunger into a glove which ball locks the two together. With the tube gripper and glove locked together, the tube gripper plunger continues to extend, which pushes on the glove plunger. Depending on the amount of tube gripper plunger travel, the glove can be engaged or disengaged from a sample tube. Continued extension of the tube gripper plunger eventually results in the glove plunger pushing on the sample tube plunger, thereby disengaging the sample tube ball lock allowing for sample tube removal from a sheath or bit. Retraction of the tube gripper plunger provides the opposite effect and allows for sample tube ball lock engagement into a sheath or bit.
Dispense, Volume, Tube Assembly
The DVT assembly consists of hermetic seal dispensers (D), a volume station (VS), sample tubes (ST) with gloves in a sheath, and a sample tube parking lot (STPL), all integrated to a single mounting plate (Figure 18).

There are seven hermetic seal dispensers, with each dispenser containing seven seals in a stack protected by a cover when not in use (Figure 20). A cover is only removed when a sample tube, with an acquired sample inside, is ready to retrieve a hermetic seal from a dispenser. Covers remain installed otherwise to minimize hermetic seal exposure to the environment and maintain cleanliness. The seal dispenser uses a two-stage passive ball lock mechanism to allow for the advancement of a single hermetic seal for dispensing into a sample tube, while also preventing the remaining seals in a stack from falling out. The SHA brings a sample tube into a dispenser which activates the ball-lock mechanism, and results in release of a hermetic seal into a sample tube. Once a seal is dispensed into a sample tube, refer to [8] for seal activation details at the sealing station.

Volume assessment is conducted via the SHA bringing a sample tube into contact with the volume probe to a prescribed load limit. From this operation, the amount of sample material collected can be determined, while minimizing potential damage to a sample. A cover protects the volume probe when not in use (Figure 21). Covers utilize a passive ball lock mechanism to lock and unlock from the dispensers, volume station, and the cover parking lots.

Three sample tube storage locations exist on the DVT similar to those on the STSA. A Sample Tube Parking Lot (STPL) is a modified sample tube storage sheath that allows for a sample tube to be stored without a glove. This capability allows for standalone glove operations in the ACA.
Assembly and Test Program

Three ACA units were assembled to support ground testing and flight operations: an Engineering Model (EM), Flight Model 1 (FM1), and Flight Model 2 (FM2). The EM unit was assembled first, consisting of flight-like stations, and was used for early ground testing of the flight hardware design, including algorithm development of station interactions for flight software purposes. Successful first-time end-to-end operations were conducted on the EM ACA in an Earth ambient environment. The EM unit was moved into a thermal vacuum chamber where it is currently part of an SCS testbed for full end-to-end testing at Mars pressure and temperature using analog samples. This testbed is known as QMDT, or Qualification Model Dirty Testing, where dirty testing is conducted to allow for evaluation of hardware life and performance through dust interaction. Drilling into rocks generates a lot of dust, which can be monitored to understand where it goes, and how well the mechanisms continue to operate over time in that environment. This testbed is as flight-like as possible, utilizing a QM (Qualification Model) Corer attached to an QM Turret on an EM RA, with the EM ACA.

The FM1 ACA was assembled after the EM ACA and was the first ACA to be exposed to 3-axis random vibration and thermal vacuum functional testing. Since station interaction sequences were not developed in time for FM1 functional testing, only range of motion and aliveness checks were performed for active mechanisms, and no passive mechanisms were tested, which would require robotic manipulation via the SHA. The functional check-outs were conducted before and after vibration testing, as well as at cold temperatures (-110°C and -70°C) and Mars pressure (between 5 and 10 torr) in a thermal vacuum chamber to verify functionality. Heat-to-use operations were verified below -70°C for wet lubricated mechanisms. Upon the completion of ACA-level testing, the FM1 ACA was installed in the flight Rover to support Assembly, Test, and Launch Operations (ATLO) testing with the flight vehicle. This testing included random vibration and functional testing of the Rover in thermal vacuum at Mars pressure and temperature and is part of validation for flight readiness. During the Rover thermal vacuum test campaign, limited station interaction was performed on the FM1 ACA to validate force and position sensing of ACA hardware via flight avionics, which was the only opportunity with the flight vehicle at Mars conditions prior to launch. Since the entire Sampling and Caching System was available on the Rover during thermal vacuum testing, bit exchange operations were conducted, which allowed for the flight RA to dock with the FM1 BC and the Corer to remove and return bits to the carousel. The opportunity to test this functionality on the flight vehicle
was a significant risk reduction effort; therefore, the flight bits were installed in the FM1 BC just prior to delivery to ATLO.

While the FM1 ACA was in ATLO testing, the FM2 ACA was being assembled. The FM1 and FM2 ACA units were intended to be identical, but this did not occur due to findings from the FM1 ACA thermal vacuum test. A modification to the linear stage mechanism on the FM2 SHA was implemented to improve robustness over temperature and life. Because of this improvement, the FM2 SHA was designated the flight unit, and ultimately the decision was made to upgrade the FM2 ACA to flight as well. This decision was not made lightly and would mean that the FM2 ACA would not participate with the flight Rover at environments until actual launch and surface operations at Mars. This was deemed acceptable for the following reasons: 1) ACA units are interchangeable in the Rover at the three bipod interfaces, with no mass impact or structural feature differences between the FM1 and FM2 units, 2) the FM2 ACA was exposed to a complete environmental test program at the ACA-level, which included 3-axis random vibration and thermal vacuum functional testing which incorporated full end-to-end sequences (with the exception of bit exchange and sample acquisition operations), and 3) after the FM2 ACA is installed in the flight Rover in ATLO, a ground test was conducted that included an end-to-end functional test within the ACA using a non-flight sample tube, hermetic seal and seal dispenser hardware, which exercised/verified force and position sensing using flight avionics.

Because the FM1 BC had been verified in the Rover thermal vacuum test with the flight bits installed, and is interchangeable between ACA units, the FM1 BC was designated the flight unit. Removal of the BC from the ACA is required as part of Rover integration/de-integration, so an interface break is necessary regardless. As a result, the eventual flight ACA will be a mix of FM1 and FM2 ACA hardware. Maintaining a consistent test flow and history was critical for understanding mechanism life as well as for documentation/configuration management purposes.

Due to PP and CC constraints on SIH and SHH items, additional STSA and DVT assemblies were required to support ground testing and not compromise cleanliness of the flight hardware. In addition to an EM and QM STSA and DVT assembly, an ATLO flight model was developed to support Rover level activities in ATLO, including environmental testing, while a sterile flight model was established for flight with extensive PP and CC oversight to ensure stringent cleanliness constraints are being adhered to. To verify functionality of the sterile flight model hardware prior to flight, a test program was conducted that exercised sample tube interactions with sheaths and bits, as well as seal dispensing at both ambient and Mars temperature and pressure conditions. The sterile flight model assemblies were also exposed to a 3-axis random vibration test for launch dynamics verification. Because of the stringent cleanliness requirements that had to be maintained for the hardware, clean tents and special handling requirements were implemented. At the completion of the test campaign, the hardware went through a final cleaning operation followed by bake-out. The sterile flight model hardware is integrated into the Rover as late as possible prior to launch, directly from the bake-out, and requires a clean air purge within the ACA volume up to the moment of launch to maintain cleanliness. Functional testing once integrated in the Rover is prohibited to avoid compromising cleanliness. As a result of this limitation, the QM STSA and DVT assembly will be exposed to the flight bake-out as well followed by testing at Mars pressure and temperature in QMDT to verify functionality and performance by similarity.

Challenges

The ACA has had to overcome a number of significant design and test challenges, including volume constraints, tight tolerances, hardware cleanliness and operational issues. As a result, quite a bit of planning and re-planning was necessary to ensure requirements could be met, and the right tests were conducted. Being flexible is key when working in this mode. Having two ACA flight models, FM1 and FM2, and the ability to swap hardware between the two, allowed for some flexibility. As previously noted, the final flight ACA configuration is a combination of FM1 and FM2 ACA stations.
SHA reachability and Z-stage travel constraints were a significant driver of the ACA configuration. From initial flight concept to final configuration, the ACA went through well over 50 different configuration layouts. The ACA had to fit within the defined volume in the Rover, while preventing ACA stations from interfering with each other, particularly during robotic operations. SHA geometry was dictated by the ACA volume in the Rover, with link lengths maximized to allow for motion within the Rover with clearances to structure of approximately 10 mm. Placement of the SHA on the CCMD was the result of ensuring the SHA could successfully reach all ACA stations and operate with sufficient position accuracy and force margin. This placement required the SHA to flip (invert) in the Rover, meaning the SHA would fully extend and rotate back on itself in the opposite direction at the elbow joint, extending the reachable workspace in the available volume. While the SHA Z-stage extends below the Rover bellypan during operations, it must fit within the Rover volume for launch through landing which limits overall available travel. The resulting SHA Z-stage travel drives ACA station and component heights to ensure sufficient clearances exist during robotic operations. A hermetically sealed tube on a glove on the EE results in the largest stack-up on the SHA requiring the largest Z-travel, while maintaining approximately 10 mm of clearance between the top of the seal and bottom of the ACA stations. In a few locations, clearance is reduced to as low as 4 mm, which is the result of design maturity of ACA hardware within existing constraints. Analysis and test verified acceptability of these close clearances.

Because of SHA-driven hardware height limitations, sample tube, glove, and cover ball lock mechanisms were constrained such that their required spring forces could not be achieved with a single spring solution in the available volume. As a result, nested compression springs were implemented that are counter wound to avoid unwanted interaction (i.e., intertwining). In addition, the sample tube ball lock mechanism could not support a sufficient length-over-diameter (L/D) ratio for close clearance sliding components, which increases the chances of wedging/jamming. The glove and cover mechanism designs achieved adequate L/D ratios, minimizing their risk of issues. During hardware testing, sample tube ball lock mechanisms exhibited jamming in the ball lock mechanisms, which was mitigated by the addition of sputtered moly-disulfide dry film lubrication to hardware that was previously bare within the assembly to reduce friction that was attributed to a number of failures. Follow-on testing showed no issues across environments, providing confidence in the corrective action implemented.

SHA operations were conducted from the start using flight software to ensure the hardware and software worked in sync, as well as ensured fault protection and positioning required to operate the SHA within the ACA volume limits were in place to protect the hardware. While this is beneficial for proving out hardware/software behavior, this introduced a number of challenges since the ACA was operated using Actuator Electrical Ground Support Equipment (AEGSE) versus the flight avionics Rover Motor Control Assembly (RMCA) during ACA-level testing. Behavior differences between controllers existed that impacted position error during operation. For example, if a motor gets bogged down and needs more current to reach a position, the RMCA will allow a temporary increase (i.e., boost) in current that allows a motor to reach position within about ±1 hall count. While AEGSE attempted to match the RMCA boost current behavior, significant position errors occurred during hard stop calibration activities affecting functionality. Therefore, two operational modes were developed for the AEGSE to achieve similar position accuracy as the RMCA for all functional activities: boost current was disabled to accommodate hard stop calibration, while boost current was enabled for nominal functions.

Force control response was impacted when using flight software for SHA operations. Response times for force control were unexpectedly high as a result of filters on the force torque sensor signal causing force overshoots. Additional force overshoots occurred as the motor controller accelerated the motor through the speed range where the motor detent brake interacts with the motor to avoid erratic behavior. The combined overshoots reduce force limits, which results in a reduction of the SHA-to-station interaction operational margin by approximately 10%, as well as more occurrences of force overshoot nuisance faults. Software updates were made prior to launch to correct these overshoots, regaining operational margin required for surface operations.
While ensuring the ACA functions properly has been a challenge on Earth, this is only exacerbated by having to operate in a Mars environment where extreme temperature differences as well as exposure to, and operations within, a dusty environment are commonplace. With an operating range of -110°C to +50°C, this can result in significant CTE effects and/or gradients, especially due to heat-to-use conditions at cold, that need to be accounted for to ensure proper fits and functionality. Testing at Mars temperatures was conducted to verify hardware functionality and performance, which identified a number of issues. One example is significant drag increases at cold temperatures due to Teflon spring-energized seals used in dynamic applications, which are implemented in a number of locations within the BC. Ultimately, the springs were removed from the seal, leaving the Teflon jacket, which still exhibited too much drag on its own. Therefore, the jacket was cut to allow for expansion and contraction significantly reducing drag, while not detrimentally affecting the performance of the seal. These changes were successfully validated by test. Using spring-energized seals in a dynamic application over a large temperature range, and particularly cold, must be evaluated closely for potential signs of fit or drag issues due to CTE.

Because of cold temperature exposure, all of the wet lubricated mechanisms require heating for operation, with a minimum allowable heat-to-use temperature of -70°C used for ground testing. Braycote 600 and 601EF are used in various ACA mechanisms, which were found to contribute to high drag conditions impacting performance at cold temperatures (starting below approximately -40°C). The SHA and EE both contain high life linear motion mechanisms where cold temperature testing revealed operational issues resulting in warmer heat-to-use temperatures being prescribed. These changes are implemented to preserve mechanism life and/or to support mechanism functionality with appropriate force/torque margins for operations on Mars.

During ACA testing in thermal vacuum at Mars pressure and temperature, a number of sample tubes failed to insert properly into bits and sheaths at -110°C. These failures did not occur during Earth ambient testing using the exact same hardware prior to thermal vacuum. An investigation identified two key findings. The first was related to the tight clearances between the tube and sheath/bit, which were required for proper ball lock mechanism functionality. However, system errors due to factors such as tolerances, deflections, controller errors, etc. exceeded the clearances of the mating hardware. In addition, the geometry of the hardware included non-axisymmetric features which offered catch opportunities due to the tight clearances and resulting machining. As a result, the compliant mechanism on the EE struggled to compensate. Performing lateral offsets prior to sample tube insertions favorably aligned tube features with the bits and sheaths resulting in successful operations. While the operational fix was successful, being mindful of what a compliant mechanism is being asked to do within a very constrained design might lead one to different implementation strategies.

The second key finding was related to a critical hardware configuration that was incorrectly modified for testing. The EE contains a cable bundle that exits the force-torque sensor and was strain relieved with specific tie-downs such that the cabling would not affect EE operations, including at cold temperatures where stiffness could increase by about a factor of two. For the thermal vacuum test, thermocouple (TC) wires were routed along the EE cable bundle and tied down in a few locations. The TC wires were added just before the thermal vacuum test and therefore not part of any ambient testing prior to environments. As a result, the EE RCCM ended up being stiffer than the intended design point at cold temperature, which contributed to tube insertion failures. The test was actually stopped to allow for correction of this issue once identified. The cable bundle tie downs with the TCs were removed and the test continued successfully. When instrumenting hardware for a test, be very careful that the introduction of test components (i.e., TCs and their respective cabling) will not impede expected functionality of the hardware under test.

Friction values were found to be much higher than expected during testing with hardware that had been exposed to both stringent precision cleaning and the high temperature bake-out at 350°C in air for 1 hour (for combustion cleaning). This was determined during FM2 ACA testing using non-flight sample tubes and gloves that had been processed flight-like (cleaning and bake-out) and failures in the ball lock mechanisms were observed. This was the first opportunity to test hardware processed in a flight-like manner. The final flight hardware cleaning and bake-out processes were developed concurrently with hardware development.
While development testing had been conducted early on to validate the cleaning and bake-out efficacy, the overall process was not 100% flight-like, and may account for the discrepancy in findings. A detailed investigation of the hardware from FM2 ACA testing yielded a number of findings. The stringent precision cleaning operation cleaned the surfaces so well that higher friction was exhibited between sliding surfaces even during assembly operations. Inspection of components from the suspect sample tubes identified that the bare 440C balls in the ball lock mechanisms had significantly oxidized, resulting in surface changes contributing to higher friction. In addition, moly-disulfide dry film lubrication on ball lock mechanism surfaces had degraded. Pin-on-disk tribometer testing was conducted using flight-like material combinations, which confirmed friction increases of 1.5 to 2 times (reaching up to approximately 0.4) as a result of the bake-out. Per analysis, this increase in friction could be detrimental to proper mechanism functionality, as observed in test. This finding was very late in the project; therefore, a quick solution had to be identified and implemented.

Ultimately, two corrective actions were implemented. The 350°C bake-out in air for a minimum of 1 hour was reduced to a 150°C bake-out in vacuum for 24 hours, which eliminated the adverse material affects previously observed. Concurrently, methods to reduce friction in the ball lock mechanisms were assessed. As a result, the balls within the ball-lock mechanisms for the sample tubes, covers, and dispensers were modified with the addition of a sputtered moly-disulfide dry film lubrication to help reduce friction. Pin-on-disk tribometer testing of these modifications showed a significant decrease in friction with results less than 0.1 (details of tribology findings in work for publication). Implementing this change actually addressed a few concerns identified through design and test, such as the aforementioned L/D concern in the sample tube ball lock mechanisms, and a concern with worn dry film lubricated surfaces observed in the seal dispensers after test. Validation of these changes using both flight-like and the flight hardware was performed over environments without issues. With the change in the bake-out criteria, additional cleaning steps were implemented as required for PP and CC compliance just prior to the bake-out.

Tight tolerances were used throughout the ACA, on the order of microns in a number of passive mechanism locations required to ensure position accuracy could be achieved with SHA interactions. Working in microns meant a lot of manufacturing challenges and discrepancies. Verification of tolerances was critical to ensure hardware was acceptable to use and required very precise CMM (coordinate measuring machine) inspection (on the order of less than 1 micron in some cases, and typically less than 3 microns). When working with tolerances so tight, verifying assembly-level dimensions may be warranted vs. relying on piece part inspection data. This became apparent for hermetic seals which contain piece parts designed in 5 micron increments as required to meet sealing requirements. It was unknown that hermetic seal components were expanding during seal assembly. This issue was not identified until hermetic seals failed to dispense successfully into sample tubes during test. Root cause was identified as fit issues where the seal was too large to fit within a sample tube. Seal-to-tube pairing takes into account a number of factors, but ultimately the seal has to fit in the sample tube. Inspection of hermetic seal assemblies yielded larger diameters for the components that must fit within a tube which had been CMM inspected previously. Therefore, all hermetic seals were reinspected at the assembled state using optical measurement equipment in the cleanroom to not compromise hardware cleanliness. With this information, the flight hermetic seals were assessed against the flight sample tubes to ensure sufficient clearances exist for dispensing, with ideal pairing arrangements identified for surface operations.

Dust accumulation on hardware can become a significant problem during operations. Accommodating anticipated dust in the ACA during operations resulted in designs either attempting to provide a path for dust to exit if possible, or the implementation of seals to prevent dust intrusion in the first place to protect sensitive mechanisms (i.e., bearings, screw mechanisms, etc.). Standalone dirty development testing was conducted on ACA hardware that will be exposed to significantly dusty environments during the mission. This testing included the BC exterior mechanisms (i.e., docking assembly and upper door release), which will not be exposed to the dusty environment for the duration of the mission, but also susceptible to debris strikes during the Rover landing event. These mechanisms exhibited robustness to excessively dusty conditions. Dirty testing in the QMDT venue revealed significant dust accumulation on critical sample tube and glove surfaces. While some dust accumulation on sample tube surfaces was expected and
accommodated for in station designs and/or operations, excessive dust accumulation on sample tube and
glove surfaces after removal from a bit post-sample acquisition can detrimentally impact operations.
Therefore, operational dust mitigation efforts are being developed for validation in QMDT to ensure robust
solutions are available for the flight hardware should an issue exist on Mars.

**Summary**

The ACA is a complex assembly of mechanisms required to perform a number of functions to meet Mars
2020 science objectives. A number of challenges existed for the development, assembly, and test of the
ACA. Detailed test campaigns were completed to validate the flight hardware and software prior to
integration onto the Rover, which identified a number of issues that were addressed as quickly as possible
to not impact the mission. After the launch of Mars 2020, the remaining ACA units will continue to provide
critical ground-based learning opportunities to improve the robustness of operations on Mars.

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commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not
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Designing and developing the ACA, as well as the subsequent assembly and testing, relied on a significant
number of people who dedicated many long hours to make the ACA a reality. It would be impossible to list
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**References**