Demonstration of Autonomous Coring and Caching for a Mars Sample Return Campaign Concept

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Abstract—**An end-to-end sample acquisition and caching system has been built and tested with capabilities applicable to sample acquisition and caching for a potential 2018 mission to Mars to collect samples for eventual return to Earth. The system provides full capability to robotically perform the end-to-end sample acquisition and caching process including placing a sample tube in a coring bit, attaching the bit to the sampling tool, coring a rock and acquiring the core sample in the tube, transferring the bit to the caching mechanism, removing the sample tube from the bit, sealing the filled sample tube with a plug, and storing the tube in the sample cache canister. This paper describes the hardware and robotic steps for the sample acquisition and caching process.**

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1. INTRODUCTION

NASA and the European Space Agency are working together on a Mars 2018 Joint Rover Mission to potentially send a rover to Mars to perform in-situ exploration and to collect samples for return to Earth in a subsequent mission. It is anticipated that NASA's contribution to the mission would include the sample acquisition and caching (SAC) subsystem which would acquire rock core and soil samples and store them in a sample cache canister. The canister would be placed on the ground after being filled with rock and soil samples. A subsequent mission would retrieve the cache canister and load it into a Mars Ascent Vehicle (MAV) which would launch and release the cache canister into passive orbit around Mars. A third mission would rendezvous with the cache canister and return it to Earth [1].

Figure 1: Integrated sample acquisition and caching prototype subsystem

The architectural concept of the SAC subsystem was described in a prior publication [2]. A prior implementation of the subsystem with a subset of capabilities is described in [3].

Key preliminary requirements for the SAC subsystem are listed below. A larger list of preliminary requirements can be found in [3]. These requirements were generated in anticipation of similar mission requirements but actual mission requirements have not yet been specified.

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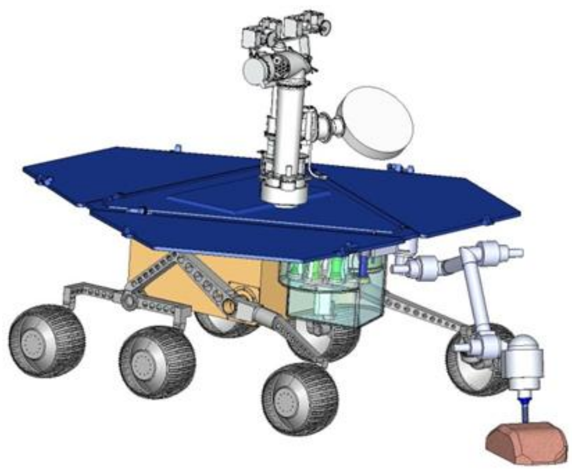

Figure 2: IMSAH coring tool deployment

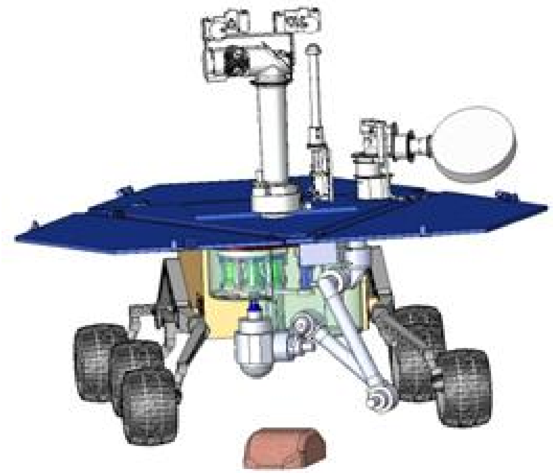

Figure 3: Bit change-out and sample transfer configuration

- Acquire cores approximately 1.1 cm diameter and 7 cm long.
- Store 28 acquired samples in the cache canister.
- Store 3 sample blanks in the cache canister.
- Be able to store 7 additional acquired samples available for exchange with samples stored in the cache canister.
- Be able to place the cache canister on the ground after all the samples have been collected.
- Allow for the cache canister to be removed from the rover by an external robotic system in the event that the rover becomes inoperable.
- Acquire cores including unmodified surface rind or from rock with an abraded surface.
- Be able to eject a bit that is stuck in a rock.
- Survive catastrophic slip conditions, i.e., if the rover slips down the slope uncontrollably during sample acquisition.
- Store samples in individual, sealed sample tubes.
- Fill the cache canister such that it could be returned to Earth (i.e. close-packed).
- Measure the sample with 75% volume or mass accuracy.
- Minimize sample contamination to satisfy Planetary Protection and Contamination Control requirements.

The system described in this paper is a proposed technology readiness level (TRL) 4 version of the subsystem that will satisfy the requirements for the SAC subsystem for the proposed 2018 mission. The system hardware is shown in Figure 1. The paper is organized as follows. Section 2 describes the system architecture, Section 3 describes the sampling tool, Section 4 describes the robotic arm, Section 5 describes the caching mechanism, Section 6 describes the software environment, Section 7 describes experimental results with the system, and Section 8 provides conclusions.

2. SAC System Architecture

The Sample Acquisition and Caching subsystem is implemented using the Integrated Mars Sample Acquisition and Handling (IMSAH) architecture [2]. The IMSAH architecture was developed to meet the anticipated mission requirements. The IMSAH architecture is made up of three elements, the Sample Acquisition Tool (SAT), the Instrument Deployment Arm (IDA), and the Sample Handling, Encapsulation, and Containerization (SHEC) mechanism. The sample acquisition and caching process is depicted in Figures 2 and 3.

Key elements of the IMSAH architecture are listed below.

- The sample is acquired directly into its sample tube in the coring bit; this eliminates the risks associated with handling raw samples of unknown geometry.
- Bit change-out is used to transfer the sample from the coring tool to the sample caching mechanism.
- Rotary percussion is used for coring into rocks; rotary percussion requires low weight on bit, does not induce bit walk, and allows for robust hole start relative to rotary drag alternatives.
- Tool deployment, alignment and feed is accomplished using a five degree-of-freedom (DOF) deployment arm.

Figure 4: Sample Acquisition Tool (SAT)

The operations process for the system is listed below:

1. SHEC transfer arm removes an empty tube from the cache canister and inserts it into a bit stored in the bit carousel.
2. Deployment arm docks the SAT to the bit in the bit carousel and the bit is attached to the SAT.
3. Deployment arm deploys SAT to the surface.
4. SAT acquires a core sample directly into its sample tube in the bit, breaks off and retains the core; the deployment arm provides tool alignment and feed during coring.
5. Deployment arm transfers the SAT to the rover-mounted SHEC mechanism and releases the coring bit in the SHEC bit carousel.
6. SHEC transfer arm removes the sample-filled tube from the coring bit, measures the sample, seals the tube, and stores the tube in the cache canister.

3. SAMPLE ACQUISITION TOOL

The TRL 4 SAT is shown in Figure 4 and further described in [4]. The SAT has the following functional capabilities: coring, core break-off, bit capture/release, and passive linear feed.

Figure 5: SAT core break-off pinching mechanism

Coring is implemented using a coupled rotary percussive actuator. One actuator drives the rotational motion and a percussion mechanism. Prior testing was used to determine the desired fixed relationship between rotation speed, impact frequency, and impact energy.

Core break-off is accomplished by cleaving the core with a pinching mechanism, as shown in Figure 5. Opposing sharp fingers are forced into the core by pulling a constraining ramp up against the fingers. This approach has multiple benefits. The fingers ensure cleaving on a defined cleaving plane thus minimizing the uncertainty of where and how the core is broken. Also, the fingers then act to retain the core in the bit.

Bit capture and release is accomplished using a magnetic chuck. The coring bit has a steel plate which attaches and detaches from the magnetic chuck. The magnetic chuck has two permanent magnets, one fixed and the other is rotated to attach or detach the coring bit. A benefit of the magnetic chuck is that it allows for release of the bit under side load conditions which is required as part of the requirement for the system to survive a catastrophic slip event.

The SAT is attached to the instrument deployment arm through two linear springs. The linear springs serve two primary functions. First, they provide some isolation of the percussive energy generated by the SAT from affecting the turret-mounted instruments. Second, they provide a passive drill feed function. During the coring process, the instrument deployment arm aligns a bit in the hole and preloads the bit by pushing against the springs. The arm then sets its brakes while the SAT cores which minimizes the power consumed by the arm during the coring process. While the SAT cores, the springs provide preload and linear motion during a coring stroke of about 1cm. After the coring step, the arm brakes are released and the bit is realigned and preloaded and the sequence repeats until the coring process is complete.

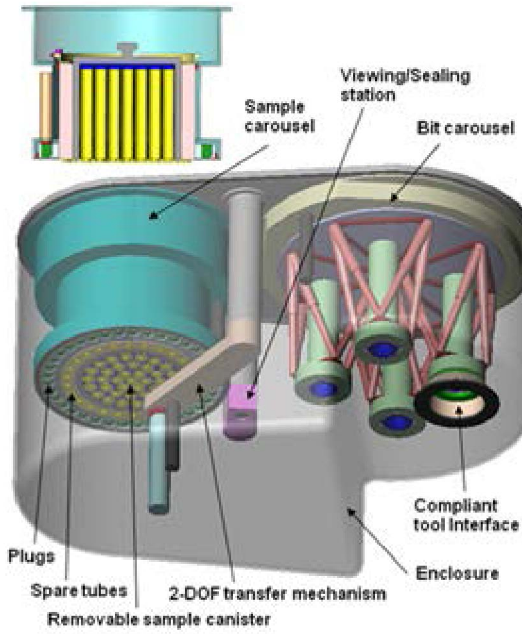

Figure 6: SHEC mechanism design

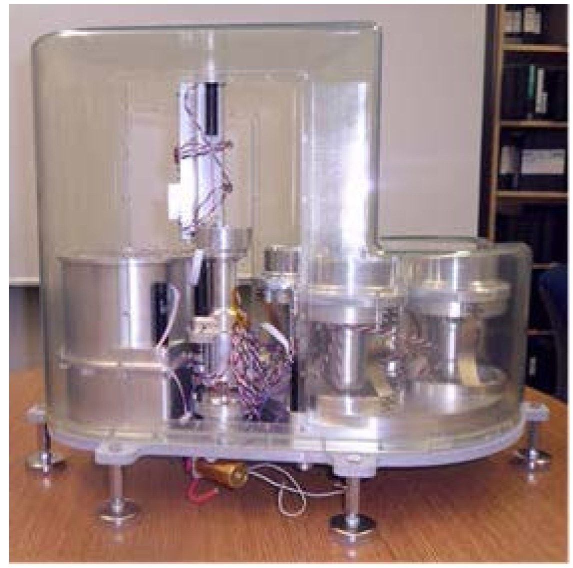

Figure 7: TRL 4 SHEC with enclosure

4. Instrument Deployment Arm

The instrument deployment arm was built to enable the end-to-end demonstration of sample acquisition and caching. It is of similar design and kinematics to the five degree-of-freedom (DOF) manipulators from the Mars Exploration Rover and Mars Science Laboratory missions. A new functionality of the arm is the addition of a 6-axis force-torque sensor (FTS). This sensor is needed for preload and alignment of a bit in a coring hole and for alignment of a bit in a SHEC bit chamber. A commercial force-torque sensor was used in this demonstration.

5. Sample Handling, Encapsulation, and Containerization Mechanism

The Sample Handling, Encapsulation, and Containerization (SHEC) mechanism would be located on the rover. It would provide the following functionality: bit exchange; loading and unloading of sample tubes in the coring bits; sample measurement; sample tube sealing; storage of sample tubes in the cache canister; and release of the canister for removal to the ground. Figure 6 illustrates the functionality of the SHEC and Figure 7 shows the TRL 4 SHEC with its enclosure. The enclosure limits the paths for contamination by providing only two access ports. The design includes one access port for bit exchange at the bit carousel and one access port above the cache canister for removal of the cache canister before placing it on the ground. In the TRL 4 version of the SHEC the bit access port and the cache access port both have doors that open via actuators. The SHEC design was previously described in [5] and concepts under investigation for sample sealing in the SHEC are described in [6].

6. Software Environment

The primary software modules for the system are shown in Figure 8. Software within the modules is written in C and C++. Communication between modules is accomplished using the ATHLETE Software Architecture Platform (ASAP) in a manner similar to JPL flight software. ASAP provides messaging services between modules including event handling and callback functions. Modules complete processing of each message and then wait for the next message to arrive. A system timer sends a periodic message to the FTS module which collects the force-torque sensor data and then sends a message with the data to the SAMP module. In this way the SAMP module provides closed loop control based on the timer frequency. Higher level sequences are coordinated by the SAMP module. When needed the SAMP module sends messages to the ARM, SAT, and SHEC modules. The ARM module provides instrument deployment arm sensing and motion. The SAT module provides SAT sensing and motion. The SHEC module provides SHEC sensing and motion. ARM, SAT, and SHEC modules can implement commands (sent as messages) in internal hierarchical state machines if needed. The ARM, SAT, and SHEC modules send commands to the MOT module which then communicates with the motor controllers to actuate the motors in the system. The SAMP module receives periodic state updates from the low-level modules and coordinates operation between the ARM, SAT, and SHEC modules.

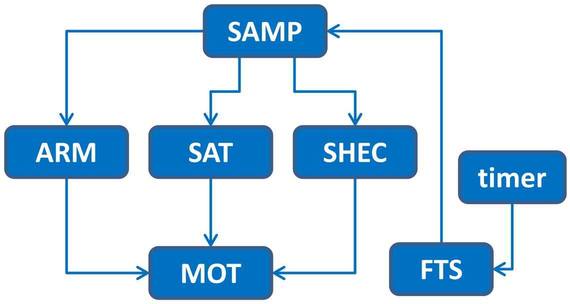

Figure 8: Software modules

7. End-To-End Sample Acquisition and Caching

The sequence for the demonstration of end-to-end sample acquisition and caching is listed below.

1. SHEC: Remove empty sample tube from cache canister.
2. SHEC: Move sample tube to below bit.
3. SHEC: Insert sample tube into bit.
4. SHEC: Rotate bit chamber to bit port.
5. IDA: Move SAT to SHEC bit port.
6. IDA/SAT/SHEC: Dock and attach bit to SAT.
7. IDA: Remove bit from SHEC.
8. IDA: Deploy SAT to sampling location.
9. IDA/SAT: Hole start.
10. IDA/SAT: Core.
11. SAT: Core-breakoff.
12. IDA: Remove SAT bit from hole.
13. IDA: Move SAT to SHEC bit port.
14. IDA: Insert bit into SHEC bit chamber.
15. IDA/SAT/SHEC: Release bit into SHEC.
16. IDA: Move SAT away from SHEC.
17. SHEC: Remove sample tube from bit.
18. SHEC: Insert plug into sample tube and measure sample.
19. SHEC: Transfer and insert sample tube into the cache canister.

The integrated hardware system for the demonstration is shown in Figure 1 and the demonstration of sample acquisition and caching is shown in Figures 9-24.

Figure 9: Remove sample tube from cache canister

Figure 10: Insert sample tube in bit

Figure 11: Rotate bit carousel to position bit chamber at bit port and dock SAT with bit

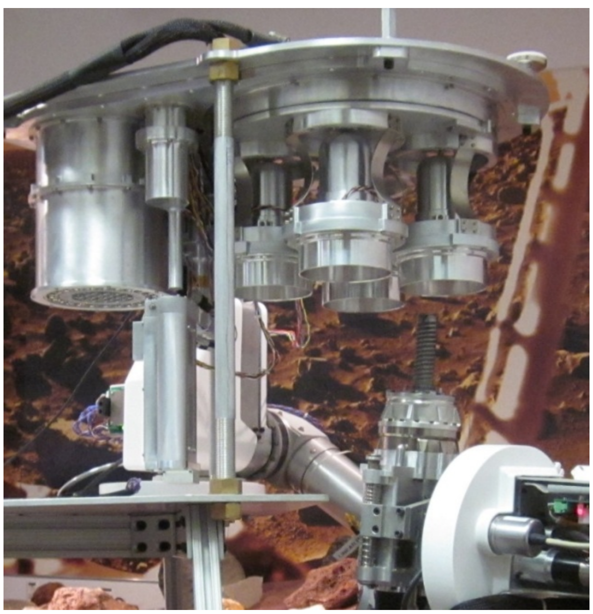

Figure 12: Remove bit from bit chamber in bit carousel

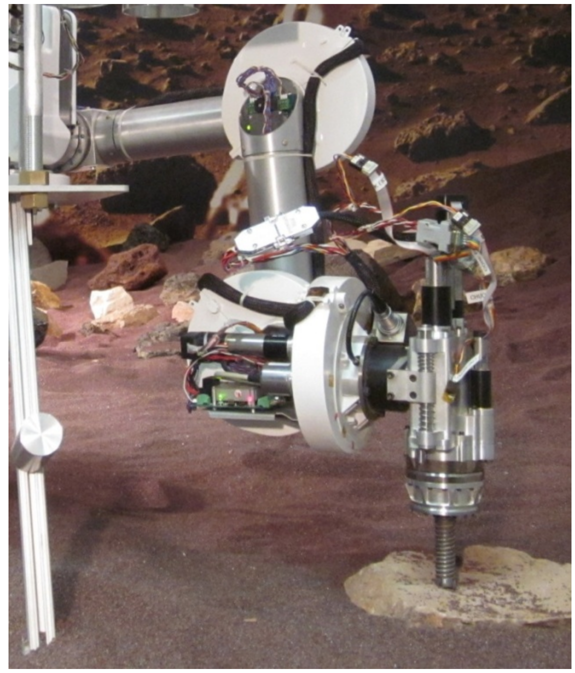

Figure 13: Deploy SAT to rock

Figure 14: Core, break-off core, retain core, and remove core bit from hole

Figure 15: Dock bit in bit chamber

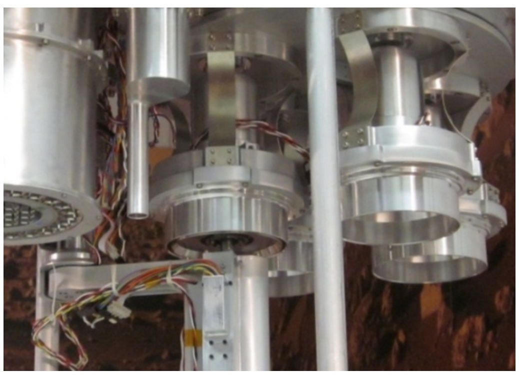

Figure 16: Align bit with transfer arm and remove sample tube

Figure 17: Measure sample

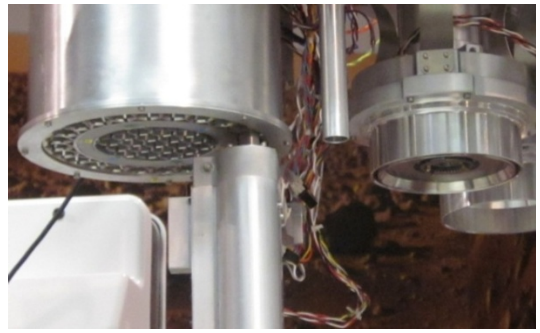

Figure 18: Insert plug in sample tube

Figure 19: Store filled sample tube in cache canister

Figure 20: Open cache lid to prepare to remove cache

Figure 21: Dock with cache canister

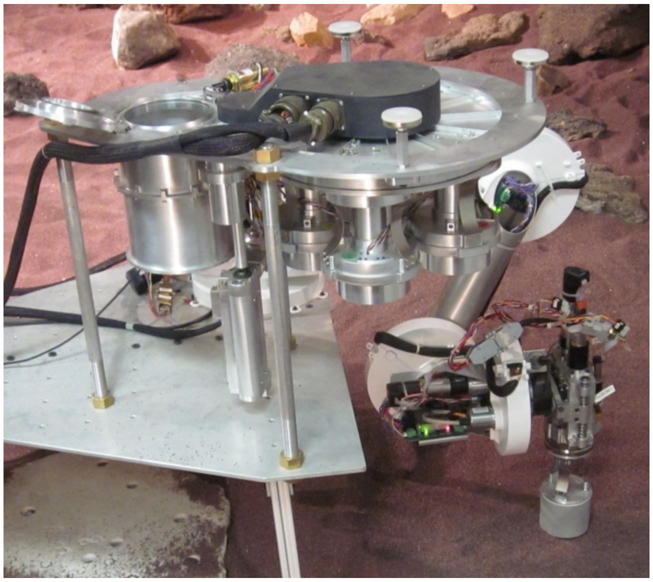

Figure 23: Place cache canister on the ground

Figure 22: Remove cache canister

Figure 24: Release cache canister on the ground

8. CONCLUSIONS

A TRL 4 sample acquisition and caching system that supports end-to-end sample acquisition and caching for a potential 2018 Mars mission has been developed. The system represents the first system that would provide all the functionality needed for robotic end-to-end sample acquisition and caching for the 2018 mission.

ACKNOWLEDGEMENTS

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BIOGRAPHIES

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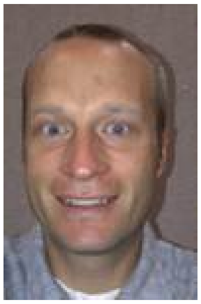

Kerry Klein *is an engineer in the Planetary Sampling and Handling Group of the Jet Propulsion Laboratory. He received his B.S. and M.S. in mechanical engineering from the University of California Santa Barbara in 2002 and 2004 respectively. He has been at JPL since 2004 and has worked on TPF-C, SIM, and MSL. Kerry was the mechanical lead engineer for the MSL Powder Acquisition Drill Feed Mechanism and provided extensive support for the Drill's unit level verification and validation. His current area of focus has been on the development of autonomous planetary sampling systems.*

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