Sample Acquisition and Caching using Detachable Scoops for Mars Sample Return

P. Younse[1], A. Stroupe[1], T. Huntsberger[1], M. Garrett[1], J. L. Eigenbrode[2], L. G. Benning[3], M. Fogel[4], A. Steele[4], AMASE 2008 Team

[1]Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109
Paulo.J.Younse@jpl.nasa.gov

[2]Goddard Space Flight Center
Code 699, Greenbelt, MD 20771
Jennifer.L.Eigenbrode@nasa.gov

[3]Earth and Biosphere Institute
School of Earth and Environment
University of Leeds, LS2 9JT, UK
liane@earth.leeds.ac.uk

[4]Carnegie Institution of Washington
Washington DC 20015
fogel@gl.ciw.edu

Abstract—Future Mars sample return missions would require technology to robotically acquire and cache multiple samples for delivery back to Earth. Anticipating the need to acquire samples and prevent cross-contamination, individual detachable scoops and caching boxes were designed for use with a rover. Four sample scoop/cache assemblies were mounted onto the back of Mars technology rover Sample Return Rover 2000 (SRR2K) at the Jet Propulsion Laboratory. A robotic arm on the rover was used to open and close the cache boxes. A clamping mechanism designed for the end effector of the robotic arm attached and detached individual scoops and performed the scooping for sample collection. The spring-loaded cache boxes had a labyrinth seal incorporated into the lid to provide a bio-barrier from external contaminants. The sample collection and caching system was tested, along with a cleaning protocol, to ensure cleanliness of the samples for life-detection studies August 2008 in Svalbard, Norway during the Arctic Mars Analog Svalbard Expedition (AMASE).[12]

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1. INTRODUCTION

Future Mars sample return missions would require technology to robotically acquire and cache multiple samples for delivery back to Earth. Returned samples would increase our understanding of Martian atmospheric, biologic, and geologic processes, as well as assess hazards to human exploration [6].

Various techniques have been researched, developed, and demonstrated for sample acquisition [1]. Sampling on Mars was performed using scoops with Viking 1 and 2, and more recently with the Phoenix Lander [8]. Mars Science Laboratory will use a percussive drill, capable of drilling into the surface or rocks and acquiring the powder for analysis. ESA's ExoMars plans to have a drill to acquire soil samples down to 2 m deep [7].

Caching of Martian samples has been researched for various sample methods, such as coring and scooping. [5] describes a Sample Caching Subsystem (SCS) to transfer a sample from a coring tool to a sample container. Mars Science Laboratory plans to store scooped samples in a small container on the front of the rover. The sample cache will be capable of storing 5-10 rock samples, each around 0.5-1.5 cm [4]. This sample cache has the option of being retrieved later by a potential a Mars Sample Return mission.

The sampling technique described in this paper is an actuated scoop at the end of a robotic arm mounted on the

Sample Return Rover 2000 (SRR2K) at the Jet Propulsion Laboratory. To prevent cross-contamination between samples, four separate detachable scoops were utilized to collect four separate samples. A spring-loaded cache box was used to store the scoops both before and after use, along with the sample. A bio-barrier seal was incorporated along the rim of the cache box and lid to limit contamination between the scoops and external environment.

2. SAMPLE CACHING SYSTEM DESIGN

The sample caching system design consisted of the development of a detachable titanium scoop, a motorized scoop clamping mechanism to attach and detach scoops, and a cache container. The system was designed to mount onto and be operated by the SRR2K rover platform.

SRR2K Rover Platform

SRR2K is a small rover measuring 72 cm long x 60 cm wide x 47 cm high (Figure 1). Navigation is performed using forward and aft hazard avoidance stereo camera pairs. The rover contains a rocker suspension with four independently drivable and steerable wheels. A four-degree of freedom robotic arm is mounted on the front end of the rover base plate. The arm has a mass of 5 kg, can carry a 3 kg payload, and can be controlled to 3mm accuracy. A turret at the wrist joint of the arm allows use of multiple science instruments. A six-axis force-torque sensor mounted at the base of the turret is used for force feedback. The detachable scoop actuator and a microimager are mounted on the turret. The back of the rover has a hard-mounted platform used to attach four cache containers for the scoops and samples.

Figure 1 – SRR2K rover

Detachable Scoop Design

Scoops were designed and built with Titanium 6AL4V (Figure 2). Titanium was selected for strength and hardness to protect the inner surfaces from scratching, as well as its inert and non-reactive properties. The scoops were machined from a single block of titanium and cut with a radii on internal edges to assist with easy cleaning and sterilization by removing sharp internal corners and seams that would develop from multiple pieces. The internal cavity of the scoops allow sampling of up to 68 cc of material.

Notched features were designed into the side edges of the scoops, which keep the two halves aligned when closed to prevent them from sliding apart when not held by the scoop clamping mechanism. Teeth were cut at the ends of the scoops to assist with digging and scraping samples. Two tabs on the back of the scoops are used to grasp onto by a pair of fingers on the scoop clamping mechanism for use.

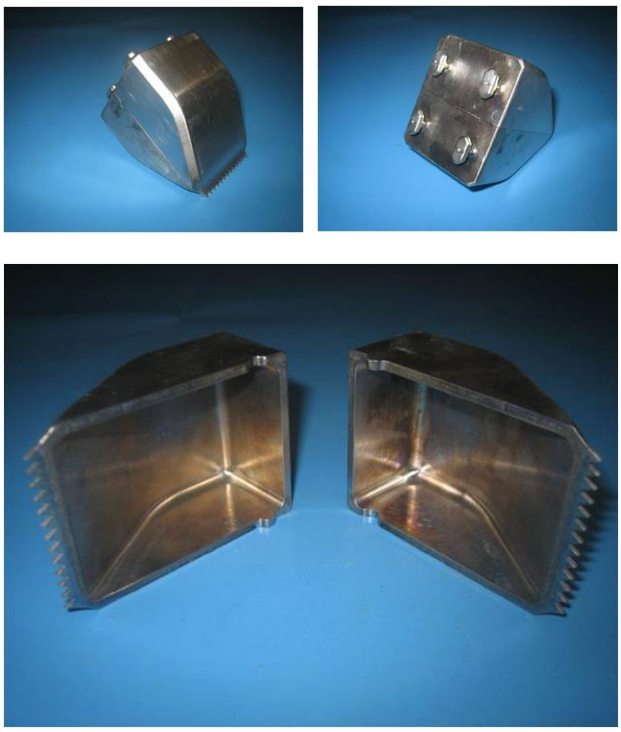


Figure 2 – Detachable scoop

Scoop Clamping Mechanism

A scoop clamping mechanism was designed to grip onto sample scoops, hold them during scooping operations, and release them for sample caching (Figure 3). The mechanism was designed to position on top of the scoops, with the tabs on the back of the scoops seated into openings on the bottom of the mechanism (Figure 4). Chamfers on the edges of the openings allow for 6 mm misalignment during insertion.

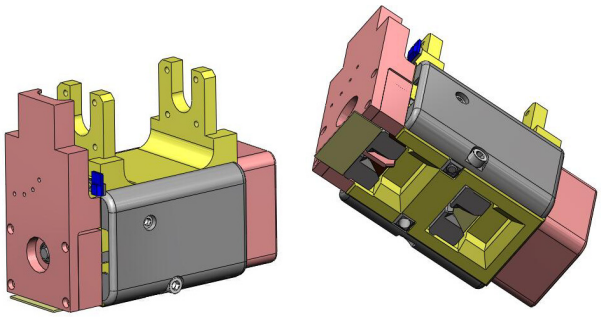


Figure 3 – Scoop clamping mechanism

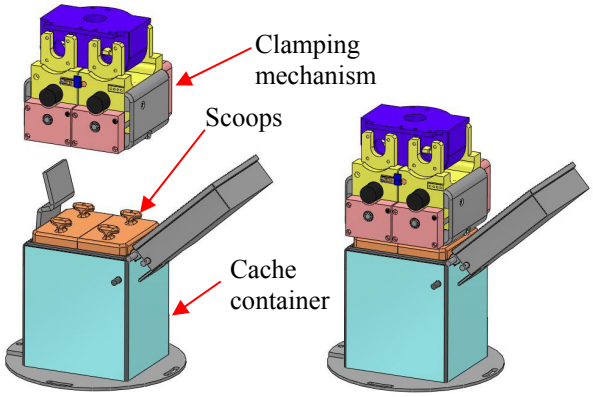


Figure 4 – Clamping mechanism attaching to scoops

The scoop clamping mechanism is driven by a brushed 1.5 W, 1.54 mNm continuous Maxon DC motor with a 246:1 planetary gear head, a 4:1 pinion/spur gear drive, and a 3.6 mm diameter, 1.64 turns/cm Acme screw. Two scoop fingers attached to two Acme nuts are driven by the Acme screw. The mechanism is capable of providing up to 111 N axial clamping force for each scoop finger (limited by a 111 N load rating of the Acme nuts). The stroke of the clamping mechanism is 0.85 cm. The housing was built from a rapid prototyped aluminum filled composite polyamide SLS material for its strong and lightweight material properties. An Acme drive was chosen for its high force application and non-backdrivable properties to securely lock the scoops in place during operation. A section view of the mechanism is shown in Figure 5.

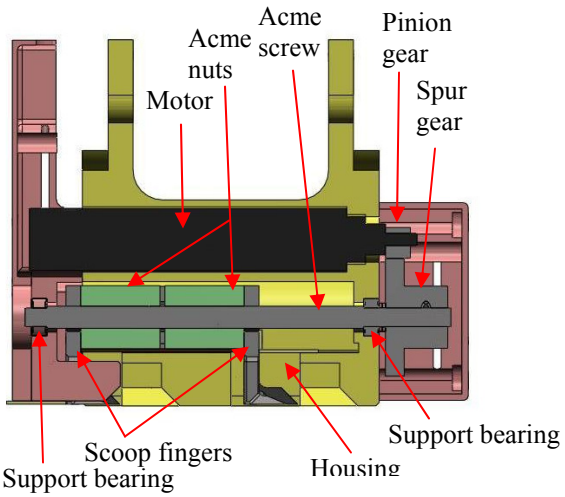


Figure 5 – Section view of scoop clamping mechanism

To clamp onto the scoop, the Acme screw is driven by the motor, sliding the scoop fingers under the scoop tabs (Figure 6). Ramped edges of the fingers help pull the scoops up and into the bottom of the housing. Hall sensors are used to detect when the clamp mechanism is in the fully open or fully closed position (Figure 7). A small neodymium cube magnet mounted to the front scoop finger activates these switches.

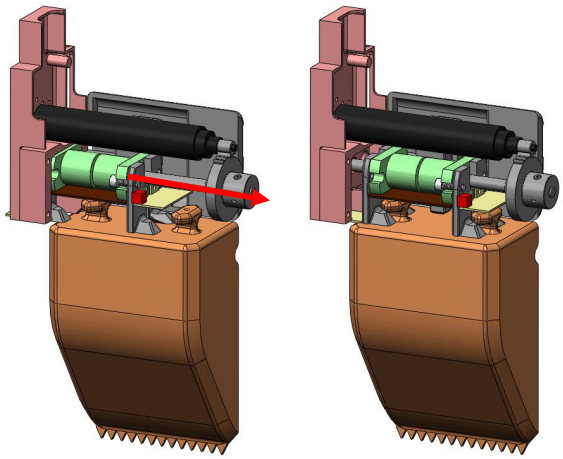


Figure 6 – Scoop clamping operation

A spring-loaded plunger serves as a contact switch to determine when the clamp mechanism is fully over and in contact with the scoop (Figure 7). This contact state is detected by a hall sensor mounted in the housing, which is triggered by another neodymium magnet in line with the plunger and plunger spring. To release the scoop, the Acme screw is driven in the reverse direction, sliding the scoop fingers out from under the scoop tabs. The spring-loaded plunger then serves to help eject the scoop out of the mechanism during release.

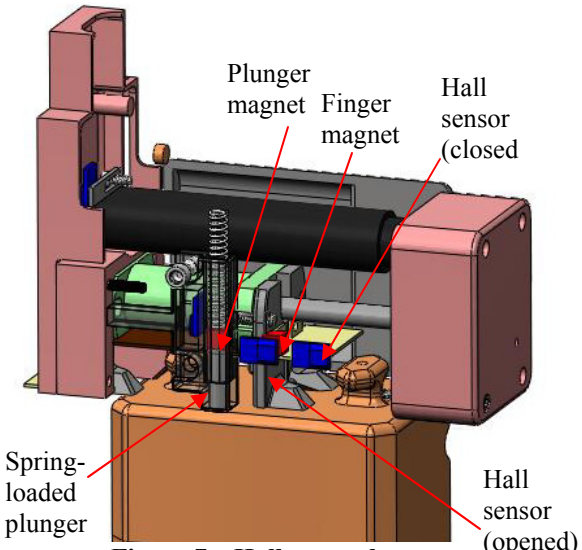


Figure 7 – Hall sensor layout

Cache Container Design

A cache container was designed to store the scoops and samples (Figure 8). A flexible lock on the front of the container keeps the lid closed on the container. The lid is spring-loaded to open when the scoop clamping mechanism flexes the lock open. Like the detachable scoops, the cache container is built with Titanium 6AL4V, machined from a single block of titanium, and cut with a radii on internal edges to assist with easy cleaning and sterilizing. The extension springs were sized to open the lid independent of container orientation with respect to gravity.

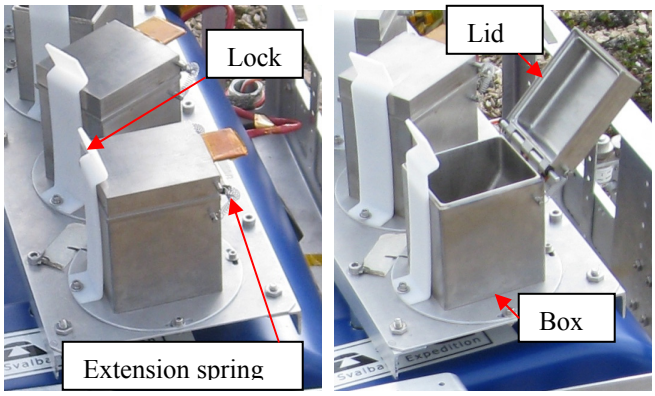


Figure 8 – Cache container

A labyrinth seal was cut around the edge of the lid as a bio-barrier to help minimize biological and particulate contamination during sample storage (Figure 9). The seal was developed from bio-barrier research done by the Biotechnology and Planetary Protection Group at the Jet Propulsion Laboratory, which showed bio-barrier effectiveness in reducing spore migration across seal gaps [9].

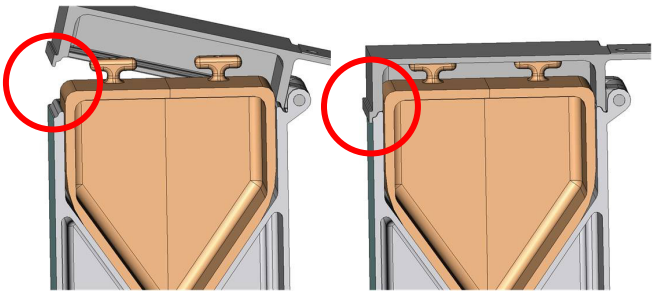


Figure 9 – Labyrinth seal on cache container

Four containers were mounted onto a plate on the back of the SRR2K rover. The rover arm is limited to four degrees of the freedom. The arm can translate the end effector in the x, y, and z directions, but can only rotate along the turret axis (joint 4). To accommodate for the two rotation limitations of the arm, (1) the plate the containers are fixed to is parallel to the rover body plate, and (2) each container is individually orientated tangent to the end effector rotation along joint 1.

System Operation

The SRR2K rover operates off a PC104 stack with a 266 MHz processor. The arm, scoop, and scoop clamp actuators operate off a 28 V NiMH battery power supply. The following sequence is performed for a sampling operation:

(1) The robotic arm positions the end effector with the empty scoop clamp mechanism over the closed cache container (Figure 10a). The clamp mechanism is translated down onto the lid of the cache container until the spring-loaded plunger limit switch in the mechanism is triggered (Figure 10b), ensuring the arm is in the correct position for opening the lid.

(2) The arm translates the clamp mechanism forward along the top of the lid to deflect the flexible lock, unlocking the lid (Figure 10c) and allowing it to spring open (Figure 10d).

(3) The clamp mechanism is positioned over the scoops in the cache container (Figure 11a) and approached onto the scoop tabs until one of the spring-loaded plunger limit switches is triggered (Figure 11b).

(4) To be certain that both clamp mechanisms are fully in contact with their relative scoops (in a case where the clamp mechanisms are not properly orientated to the scoops), the wrist joint of the arm rotates incrementally until the spring-loaded plungers of both clamp mechanisms are triggered simultaneously.

(5) The Acme screw drives of the clamp mechanisms are activated, clamping and securing the scoops by the tabs. The screw drives are stopped as each of the "closed" indicator hall sensors are triggered (Figure 11c).

(6) The arm translates vertically, removing the scoops from the container (Figure 11d).

(7) The arm opens the scoops, collects a sample (Figure 12), tilts the scoops up with the wrist joint to get the sample to fall within the lower scoop, and then fully closes the scoops with the sample enclosed inside (Figure 13a). A hall sensor mounted to one of the clamp mechanisms, triggered by a magnet mounted to the other clamp mechanism, is used to detect if the scoops have been fully closed and not jammed open due to part of the sample hanging over the edge of the scoops.

(8) The arm places the scoop back into the container (Figure 13b). During placement, a force-torque sensor on the end effector detects any large contact forces, which occur if the scoop is not aligned correctly with the container, and automatically adjusts until a smooth placement motion is achieved. The arm continues to place the scoop into the cache container until the force-torque sensor detects that the scoop has reached the bottom of the container.

(9) The Acme screw drives of the clamp mechanisms are activated, releasing the scoops by the tabs (Figure 13c). The screws are stopped as each of "opened" indicator hall sensors are triggered.

(10) The arm retracts the clamp mechanism off the scoops (Figure 13d).

(11) The arm places the clamp mechanism behind the opened cache container lid (Figure 14a), translates forward to close the lid (Figure 14b), and translates down to press and lock the lid until one of the spring-loaded plunger limit switches is triggered, indicating that the cache container is fully closed (Figure 14c).

(12) The arm retracts and prepares to open the next cache container for subsequent sampling (Figure 14d).

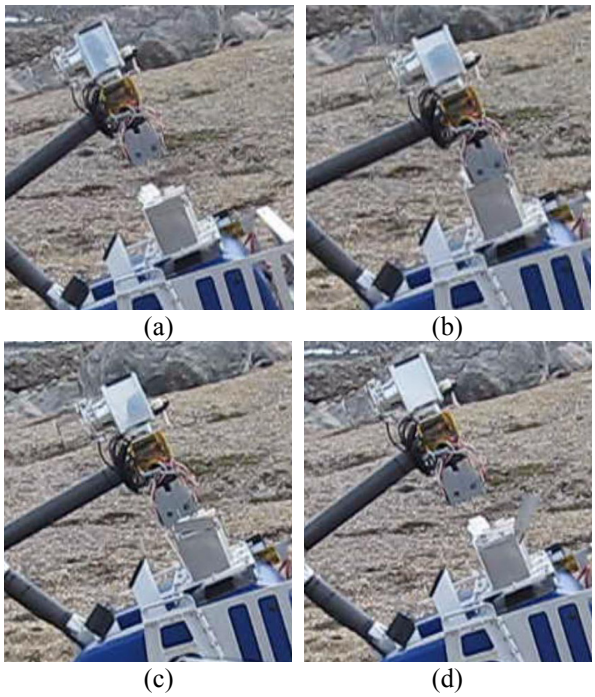


Figure 10 (Sequence 1 and 2) – Cache container opening sequence: (a) End effector positioned above cache box, (b) clamp mechanism translated down onto lid until contact, (c) clamp mechanism translated forward to unlock lid, (d) clamp mechanism retracted while lid opens.

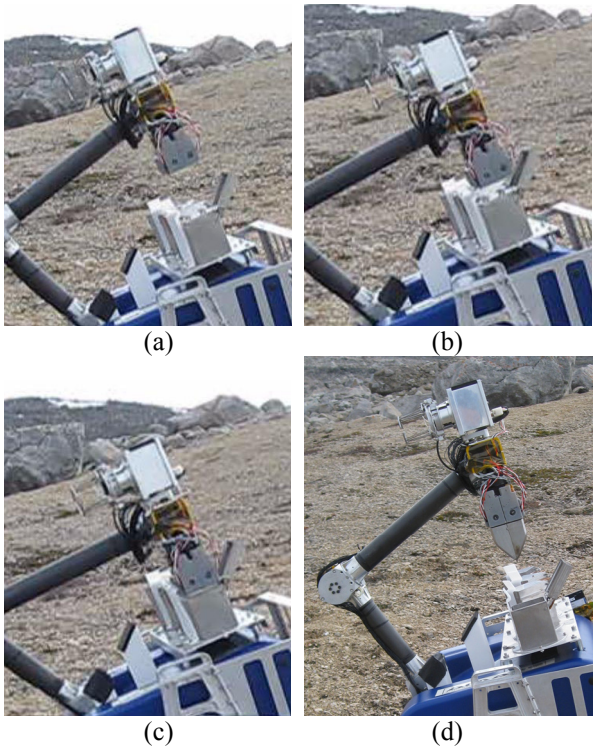


Figure 11 (Sequence 3-6) – Scoop attachment sequence: (a) End effector positioned above scoop, (b) clamp mechanism translated down onto scoops until contact, (c) clamp mechanism attached to scoops, (d) scoops pulled out of cache box.

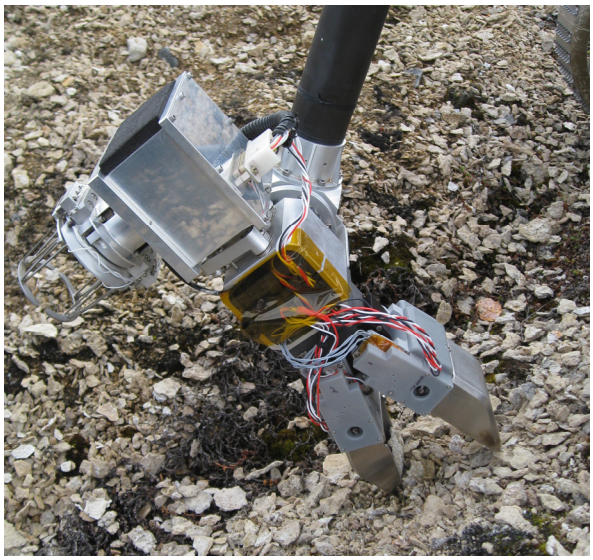
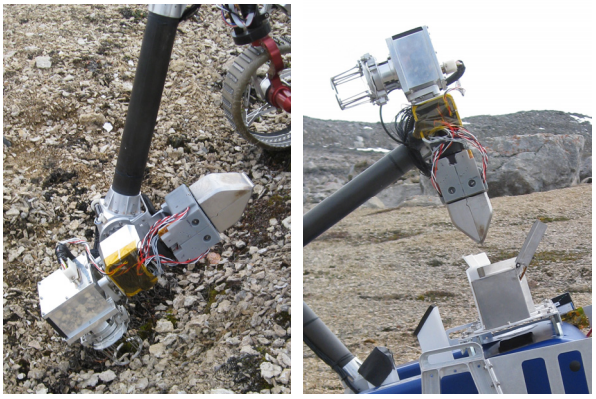
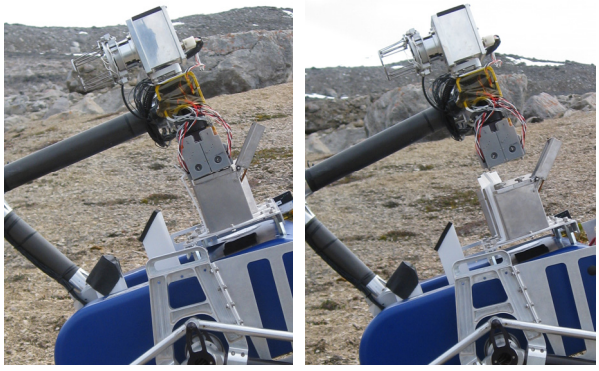


Figure 12 (Sequence 7) – Sample acquisition with scoop

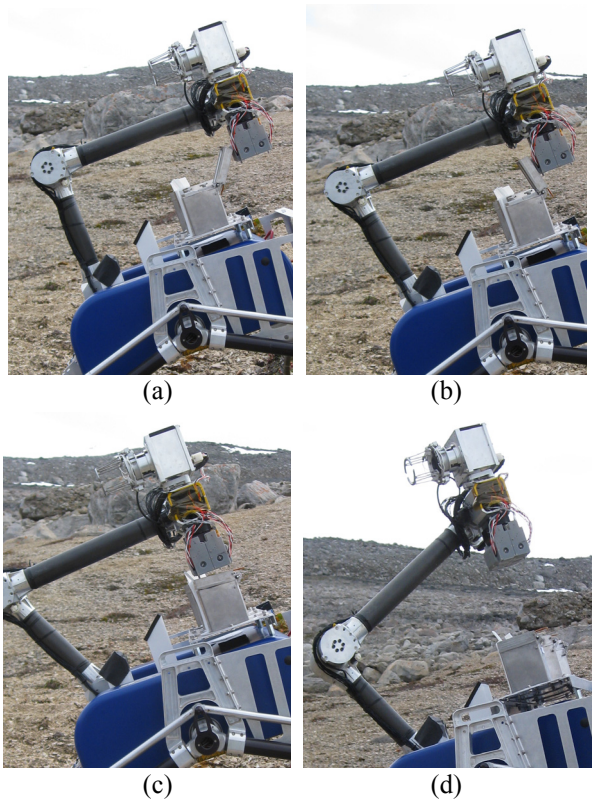


(a) (b)



(c) (d)

Figure 13 (Sequence 7-10) – Sample caching sequence: (a) Scoops closed with sample, (b) scoops placed into cache box, (c) clamp mechanism detached from scoops, (d) clamp mechanism retracted from scoops and cache box.



(a) (b) (c) (d)

Figure 14 (Sequence 11-12) – Cache container closing sequence: (a) Clamp mechanism placed behind lid, (b) clamp mechanism translated forward to close lid, (c) clamp mechanism translated down to lock and press down on lid until contact switch triggered, (d) clamp mechanism retracted for next sample operation.

3. SAMPLE SCOOP STERILIZATION

The titanium rover scoops and inner-surfaces of the scoop housing were cleaned using a modified version of the decontamination and sterilization protocol described by [10], which is aimed at removing particulates, biological, and other organic contaminates. The scoop was sequentially wiped with sodium hypochlorite, wiped then rinsed with purified water (from a Milli-Q filtration system), followed by wiping with ethanol to remove the majority of dust particles and reagent residues, as well as disinfect, break up cellular material, and remove the polar organics. This was followed by a second series of wiping of all surfaces with hydrogen peroxide to oxidize remaining organics and finally with ethanol. The cleaning was completed with a final rinse in ethanol. Clean scoops where wrapped with aluminum foil previously baked at 500°C. All reagents used for cleaning were filtered using sterile 0.2µm single-use filters and applied using clean-room grade, woven polyethylene wipes with sealed edges. The scoops were held in place with aluminum foil to avoid contact with nitrile gloves. All scoops were cleaned and packed prior to rover deployment and unpacked prior to sample acquisition. This

cleaning protocol has proven to reduce biological and organic contaminants to close to null levels [10].

The cleaning protocol was followed stringently for all 2008 rover samples. No biological contamination evaluation was performed on the samples during the testing. However, previous contamination measurements to test the effectiveness of the cleaning protocol, as well as the scoop and cache container bio barrier, were performed during the previous AMASE 2007 testing, as reported in [11].

4. SAMPLE ACQUISITION TESTING

Sample acquisition testing using the detachable scoop caching system was performed in Svalbard, Norway (78-81° N) during August 2008 as part of AMASE funded under the NASA Astrobiology Science and Technology Program (ASTEP). Svalbard provides a Mars analog for testing, which is of interest to geologists and astrobiologists for developing technology for Mars [2]. Two full tests using the caching system were performed at Jotun Springs and Palander Bay (Figure 15 and Figure 16). Jotun Springs is located at 79°23'N, 13°26'E. The Palander site was situated at the moraine in front of Holtenbreen, which comprises the NE edge of the Glitnefonna icecap (79°34'N, 20°27'E). During the Jotun Springs test, two soil samples were successfully collected and stored in the cache containers as part of the Teamed Robots for Exploration and Science on Steep Areas (TRESSA) cooperative robot system [3]. At Palander Bay, three soil samples were successfully collected and stored in the cache containers.

The one thing during testing that had to be observed was whether the edges of the scoops were free of debris to allow them to fully close with the sample. In some instances, rocks and soil were extending over the edges of the scoops after the scooping operation. In these cases, an external observer was required to instruct the rover operator to send commands to tilt the scoop in various orientations until the debris fell off the edges or into the scoop cavity before the scoops could be closed. Autonomous detection and removal of debris on the scoop edges must be addressed in subsequent vehicle design.

Figure 15 - Jotun Springs test site

Figure 16 – Palander Bay test site

5. FUTURE WORK

The current system requires joint angle coordinates for each operational location to perform the cache container opening, scoop connect, scoop disconnect, and cache container closing. The coordinate points were only valid for sample operations at the rover orientation the training was done at due to variance in arm droop at different rover orientations. This issue can be dealt with by modeling in droop compensation in the arm model, or by using additional sensors or a camera to help correctly guide the end effector's position and orientation during these sequences. Another issue that must be dealt with is detecting and dealing with debris that may attach to the outside or the edges of the scoops that may prevent closure or placement in the cache containers.

The present cache containers are fixed to the back of the rover. In a Mars Sample Return mission scenario, these samples would need to be removed and placed into an ascent vehicle. One concept would be to have a carousel containing a set of sterile sample scoops (Figure 17 and Figure 18). The carousal design in the figure shows six scoops, though it is possible to design the mechanism to hold any number of scoops, depending on mass and volume constraints. A similar operation would be performed where the arm connects to a scoop, gathers a sample, and then detaches and stores the scoop with the sample back into the carousel, which then rotates to a new sample scoop. The collection of scoops could then be removed from the rover either by the current rover arm or an external arm, and placed in the ascent vehicle for the return to earth.

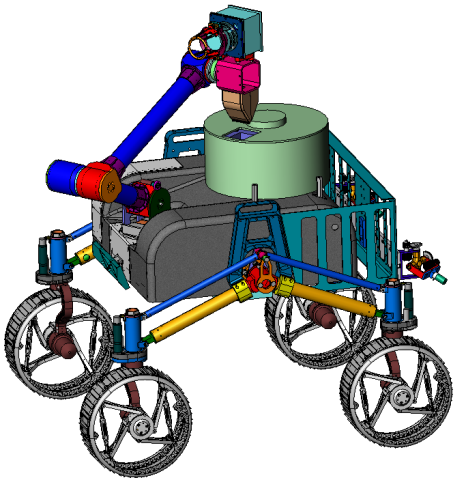


Figure 17 – Sample caching carousel on the rover

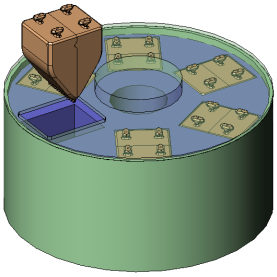


Figure 18 – Sample scoop layout in carousel

6. SUMMARY

This paper described a design of a sample caching system using a set of four detachable scoops, along with four spring-loaded cache containers with bio-barrier seals to help prevent contamination. A sampling operation is performed by opening a cache box, connecting to a clean scoop, collecting a sample, placing the scoop and sample back in the cache box, and closing the lid of the cache box. The system was tested on board the SRR2K rover platform to collect and cache five soil samples in Svalbard, Norway during August 2008 as part of the AMASE expedition funded under the NASA ASTEP program. A cleaning protocol was followed on the scoops and containers to ensure cleanliness of the samples for life-detection studies. Future work may include improving scoop and caching operations through more precise arm modeling and sensor/visual servoing techniques, as well as development of a removable caching carousel.

7. ACKNOWLEDGEMENTS

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BIOGRAPHY

Paulo Younse *is a Staff Engineer for the Robotic Hardware Systems Group at the NASA Jet Propulsion Lab in Pasadena, CA. His experience resides in mechanical design, machine vision, hopping robots, limbed robots, and subsurface drilling. Current projects include Cliffbot, a cooperative robotic system used to explore steep terrain, sample acquisition and caching research for a possible Mars Sample Return, and the powder acquisition drill system for Mars Science Laboratory. 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 has a BS in Mechanical Engineering from California Polytechnic State University (San Luis Obispo, CA) and an ME in Agricultural Engineering from the University of Florida (Gainesville, FL).*

Dr. Ashley Stroupe *is a Senior Engineer at the Jet Propulsion Laboratory in Pasadena, California. She works as a "rover driver" with the Mars Exploration Rover Project, building command sequences to drive the rovers and deploy science instruments. Dr. Stroupe does research focusing on multi-robot teams in complex environments, most recently the TRESSA system. Dr. Stroupe has published multiple conference papers, book chapters, and journal articles in robotics and is an active participant in multiple education and outreach programs. She received a B.S. in physics from Harvey Mudd College in 1990, an M.S. in electrical engineering from George Mason University in 1998, an M.S. in robotics from Carnegie Mellon University in 2001, and a Ph.D. in robotics from Carnegie Mellon University in 2003.*

Dr. Terry Huntsberger *is a Principal Member of the Robotic and Mobility Systems Section at the Jet Propulsion Laboratory where he leads several efforts in the area of autonomous system development. Current projects include the development of autonomous control systems for the Cliffbot ensemble, and various unmanned sea surface and underwater vehicles for the US Navy. He is one of the primary developers of CARACaS (Control Architecture for Robotic Agent Command and Sensing) that is an autonomous multi-agent system for sensor/behavior fusion. He was the primary developer of advanced technologies for autonomous approach, rendezvous, and docking with natural and man-made targets as applied to Sample Return under the FIDO rover task from 1999 to 2003. Prior to joining JPL in 1999, Dr. Huntsberger was an Associate Professor and Founder/Director of the Intelligent Systems Laboratory in the Department of Computer Science at the University of South Carolina (currently an Adjunct Full Professor). He received his Ph.D. in Physics from the University of South Carolina in 1978.*

Mike Garrett *is a Member of Technical Staff in the Robotic Hardware Systems Group at the NASA Jet Propulsion Laboratory in Pasadena CA. He has worked on scientific instruments and spacecraft in a variety of areas including Earth and Space Sciences, Infrared Sciences, Microwave Sciences, and Robotics. He has designed, integrated, and fielded, electronics on a variety of robots and manipulators. Applications include: Mars Science Laboratory, Mars Exploration Rovers, Cliff exploration with both limbed and wheeled rovers; Microgravity rovers; Lunar and Mars limbed and wheeled rovers; Autonomous sea surface and subsurface boats. He earned a BS in Electrical Engineering at California Polytechnic State University Pomona CA.*

Dr. Jennifer Eigenbrode *is an organic biogeochemist and field geologist. She specializes in the use of gas chromatography-mass spectrometry (GCMS) in the analysis of lipids and other hydrocarbons in geological, hydrological, biological samples. Her research focuses on Precambrian records of life, detection of modern microbial life in rocks and ice, and the habitability of Mars (as part of the Science Analysis at Mars instrument team for NASA's 2009 Mars Science Laboratory).*

Dr. Liane Benning *is an experimental biogeochemist at the University of Leeds, UK. Her prime research focuses on the mechanisms and pathways of reactions at the mineral-fluid-microbe interface with a particular emphasis on processes in extreme environments and Mars analogue settings. She develops novel approaches and uses a combination of conventional and synchrotron-bases microscopic and spectroscopic tools to better understand how such interactions affect local or global element and metabolic cycles with specific applications to geothermal hot springs and polar snow and glacial environments.*

Dr. Marilyn Fogel *is a biogeochemist specializing in the use of stable isotopes to trace biochemical and geochemical processes. She obtained her doctorate degree in botany from the University of Texas Marine Science Institute in 1977. For two years, she worked in the laboratory of Thomas C. Hoering as a postdoctoral fellow at the Geophysical Laboratory of the Carnegie Institution of Washington, before she was hired as a permanent staff member there. Fogel has worked on marine, estuarine, and terrestrial ecosystems in both modern and ancient settings. She has pioneered studies of hydrogen, oxygen, carbon, and nitrogen isotopes in organic and inorganic materials. Her work on the paleoclimate of Australia demonstrated that humans had a major impact on the continental ecology that led to the extinction of most of Australia's megafauna. Her field work has taken her to diverse places such as the Sargasso Sea (the major central ocean gyre in the North Atlantic) and the Outback of the Australian continent. Since 1997, she has been involved with the space science community as a member of the National Research Council's Space Studies Board, a founding member of the Committee studying the Origin and Evolution of Life, and a co-investigator on Jet Propulsion Laboratory and Carnegie Institution of Washington's NASA astrobiology teams. Her work with AMASE started in 2003, when she performed isotopic analysis of carbonates in collaboration with Hans Amundsen and Andrew Steele. Since that time, she has participated on three AMASE trips and has provided expertise in biogeochemistry, ecology, and stable isotope systematics.*

Dr. Andrew Steele *is a senior staff scientist at the Carnegie Institution of Washington. Initially a microbiologist, Steele has been involved in research on ALH 84001 showing that an abiotic organic synthesis mechanism explains the organic material in this meteorite and therefore shows that Mars does contain indigenous organics. He has been apart of AMASE and science leader since 2003 and for the last 3 years has been PI on a NASA ASTEP grant to test space flight instrumentation (i.e. SAM and CHEMIN from Mars Science Laboratory) and the Cliffbot rover concept that has become SRR2K. Steele has undertaken a great deal of planning work on Mars mission operations including chairing both the MEPAG committee to design the Astrobiology Field Laboratory (a potential successor to MSL to look for life) and recently to review the sample caching system for a potential Mars sample return. Sample return will be the subject of the next 3 years of AMASE ASTEP activities as Steele was the PI on a successful renewal grant earlier this year.*