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# A Geology Sampling System for Small Bodies

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**Human exploration of microgravity bodies is being investigated as a precursor to a Mars surface mission. Asteroids, comets, dwarf planets, and the moons of Mars all fall into this microgravity category and some are being discussed as potential mission targets. Obtaining geological samples for return to Earth will be a major objective for any mission to a small body. Currently, the knowledge base for geology sampling in microgravity is in its infancy. Humans interacting with non-engineered surfaces in microgravity environment pose unique challenges. In preparation for such missions a team at the NASA Johnson Space Center has been working to gain experience on how to safely obtain numerous sample types in such an environment. This paper describes the type of samples the science community is interested in, highlights notable prototype work, and discusses an integrated geology sampling solution.**

## Nomenclature

*APFR* = Articulating Portable Foot Restraint
*ARCM* = Asteroid Redirect Crewed Mission
*ARES* = Astromaterials Research and Exploration Science
*ARM* = Asteroid Redirect Mission
*ARV* = Asteroid Redirect Vehicle
*BAA* = Broad Agency Announcement
*BRT* = Body Restraint Tether
*CAPTEM* = Curation and Analysis Planning Team for Extraterrestrial Materials
*CLB* = Crew Lock Bag
*COTS* = Commercial Off The Shelf
*DRM* = Design Reference Mission
*EE* = End Effector
*EMU* = Extravehicular Mobility Unit

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*EVA* = Extravehicular Activity
*FR* = Foot Restraint
*ISS* = International Space Station
*JAXA* = Japan Aerospace Exploration Agency
*JPL* = Jet Propulsion Laboratory
*JSC* = Johnson Space Center
*MACES* = Modified Advanced Crew Escape Suit
*MMWS* = Modular Mini Work Station
*NASA* = National Aeronautics and Space Administration
*NBL* = Neutral Buoyancy Lab
*NEEMO* = NASA Extreme Environment Mission Operations
*OSIRIS-REx* = Origins-Spectral Interpretation-Resource Identification-Security - Regolith Explorer
*PFR* = Portable Foot Restraint
*SB* = Stabilization Boom
*SD2* = Sampling, Drilling, and Distribution Subsystem
*TAGSAM* = Touch-and-Go Sample Acquisition Mechanism

## I. Introduction

ASTEROIDS, comets, dwarf planets, and small moons (such as Phobos and Demos) all fall into the small bodies category. These bodies are remnants of the early solar system and carry information key to understanding its formation and how life began on Earth. To date 11 missions have been launched to study small bodies [9]. Only two have touched down on the surface to collect samples for investigation: Hayabusa and Rosetta. Hayabusa explored Asteroid Itokawa and planned to deploy impactors into the regolith to create ejecta for capture in a sampler canister. While the mission did not go as originally planned, the spacecraft did return to Earth with about 1mg of samples [4]. The Rosetta mission to comet 67P/Churyumov–Gerasimenko deployed a lander to the surface. The mission was to anchor the lander using harpoons, collect samples using the Sampling, Drilling and Distribution (SD2) subsystem (designed to drill up to 230 cm into the regolith, use a probe to obtain a sample, and deliver the sample to onboard instruments) for insitu analysis [7]. SD2 was deployed however no regolith was obtained.

Currently, two missions are under way to retrieve more samples from asteroids: Hayabusa 2 and OSIRIS-REx. Launched on December 3, 2014 JAXA's Hayabusa 2 mission will utilize an improved sampling mechanism for collection [10]. Scheduled for launch in September of 2016, the OSIRIS-REx mission will perform a sample return from asteroid Bennu [8]. The spacecraft plans to retrieve samples using their Touch-and-Go Sample Acquisition Mechanism (TAGSAM) instrument. Bursts of nitrogen are aimed to direct regolith into the sample compartments of the instrument.

If all goes well, by 2017 there will have been four attempts to collect samples from small bodies robotically. There is also interest to send humans to explore these bodies. NASA is planning the Asteroid Redirect Mission (ARM) in the 2020s, which will send astronauts to a captured Small Body for scientific research and sample collection.

Gravity on the Earth, the Moon and Mars allow for similar geology sampling tools and methods. However, this luxury does not extend to small bodies as they are by definition, milligravity to microgravity environments. Some of the difficulties include: no ground reaction force, debris clouds, body positioning, and anchoring.

With ARM planned to launch in the early 2020s and the Asteroid Redirect Crewed Mission (ARCM) planned for mid-2020s, a team of NASA engineers and scientists has been developing an asteroid centric tool suite. While the remainder of this paper is focused specifically on ARCM related tools and the requirements, most, if not all, of the work is extensible to other Small Body destinations.

## II. Science Requirements

To understand what geology tools are required for ARCM, it is first important to understand the scientific objectives. In support of ARCM mission planning, the Curation and Analysis Planning Team for Extraterrestrial Materials (CAPTEM) developed a list of investigations of interest to the science community. The "CAPTEM Findings: EVA Sample-Collection Operations Study" is focused around the baseline of performing two 4 hour Extravehicular Activities (EVAs). Table 1 highlights findings that directly impact geology sampling tool designs. [11].

**Table 1. EVA Tool Significant CAPTEM Findings**

| Finding | Description |
|---|---|
| 3 | Hand-held high-resolution cameras and supporting analytical instruments will be valuable for sample selection during EVAs. |
| 4 | Contamination control is vitally important. |
| 5 | We recommend the collection of at least 1000 g of material from two sites that sample the apparent diversity of the body. |
| 6 | We recommend the collection of at least one 5-cm diameter core sample of regolith from each of the two sites. |
| 7 | Preservation of volatiles is desirable, particularly if the sampled asteroid is of type C, P, or D. |

From these findings a list of tools was developed including items such as: cameras, sample tools, core drills, and sample containers that can preserve volatiles. To better understand each tools requirements, additional conversations were had with scientists in the Astromaterials Research and Exploration Science (ARES) Division at NASA JSC. Five different categories of samples were identified: Float, Chip, Regolith, Surface, and Core. In short, Float samples are rocks that are loosely adhered to the surface and can normally be retrieved via a grabbing action. Chip samples are small pieces forcibly removed from a parent body. Regolith samples are a loose conglomerate of fine particulate that can usually be retrieved via a "scooping" action. Surface samples are the fine, top layer (~1mm) of a surface. Core samples are cylindrical, hollow masses retrieved from the interior of a surface by "drilling". A list of the geology sampling tools necessary to obtain these sample types is captured in Table 2.

**Table 2. Tools to Meet Science Objectives**

| | |
|---|---|
| Chip Sampler | A tool for creating, containing chip samples. |
| Float Sampler | A tool for obtaining float samples. |
| Regolith Sampler | A tool for obtaining regolith samples. |
| Surface Sampler | A tool for obtaining surface samples. |
| Core Drill | A tool for creating, containing core samples. |
| Sample Containers | Containers to house the collected samples. |
| Stabilization Boom | A stabilization platform upon which to perform sampling tasks. |
| Anchors | Need a way to attach science experiments to the asteroid for long-term study. |
| Camera | A high-resolution camera to aid in sample selection and sample analysis. |

## III. History of Tool Development

Over the past five years, the Exploration EVA Tools Team at NASA JSC has been developing and testing tools and methods for geology sampling in a microgravity environment. Below is a brief look into the history of each tool's development, including a snapshot of key features and lessons learned. Additional history of the tool development and concept of operations can be found in "Extravehicular Activity Asteroid Exploration and Sample Collection Capability" [8].

### A. STABILIZATION

Body stabilization will be a key enabler of successful geology sampling activities on small bodies. Experience on the International Space Station (ISS) has highlighted the need for infrastructure to react loads during various tasks giving the crew a stable work platform. Current methods employed on the ISS were used as a starting point for Small Body EVA stabilization.

There are three methods of body stabilization currently used on the ISS: self-stabilization, Body Restraint Tether (BRT) Figure 1, and Foot Restraint (FR) Figure 2. Self-stabilization is achieved by simply grasping vehicle structure with an available hand. This method is limited to low load tasks and only enables one-handed tasks. Reach and access is limited to the crew members arm span and available handholds. The BRT however provides a method of local stabilization for tasks that require two hands. It is constructed of a flexible ball stack that has an end effector which interfaces with ISS handrails.

Finally, the FR provides the most reaction load capability. The crew member's boots interface with the FR providing worksite stabilization. The FR can be installed in numerous locations around the ISS. A more complex version of the FR is known as the Articulating Portable Foot Restraint (APFR) and enables additional body positioning options for the crew members.

Each of these methods was investigated as a potential stabilization method for geology sampling tasks. A baseline assumption was that ISS tethering protocol would be used to ensure the safety of the crew and hardware retention in a microgravity environment. Evaluations performed in the Neutral Buoyancy Laboratory (NBL) showed that it was feasible to obtain float, chip, regolith, and surface samples while only being loosely tethered at a worksite. A translation path, whether it be a rope or rigid structure, is still required to get to these sites of interest. In addition, body positioning options were limited and there was a risk for the crew member to contaminate samples due to lack of standoff capability.

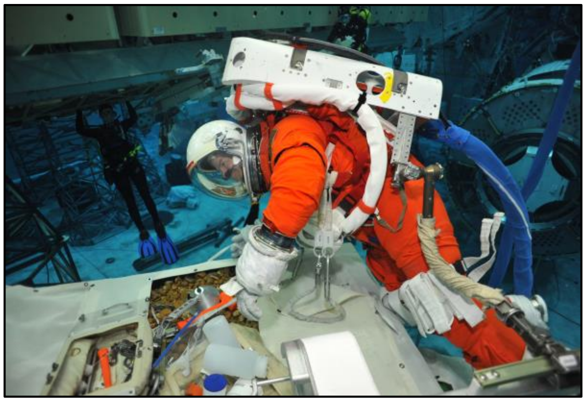

**Figure 1: Crew member wearing MACES stabilized with the BRT performing sampling tasks in the NBL.**

The BRT was tested in the NBL by crew members wearing the Modified Advanced Crew Escape Suit (MACES). It successfully enabled all sampling activities. The flexibility of a BRT like device for enabling two handed tasks and increased body positioning options, makes it a valuable asset for Small Body geology missions.

FRs have been evaluated in a number of different testing scenarios. On the ISS, they provide a stable platform for low, medium, and high load EVA tasks, however they are heavy for exploration type missions and rely on strong underlying structure to withstand workloads. One benefit for geology tasks is that FRs reduce the risk of touching or contaminating the surface due to increased rigidity over a tether or BRT.

Testing showed that most sampling activities could be adequately completed using the BRT or FR, with the exception of hand held core drilling. The potential high torque loads of hand held core drilling need be investigated more thoroughly before a stabilization requirements can be determined.

Other methods for stabilization have been investigated for small bodies. One concept is to anchor directly onto the body's surface. The Jet Propulsion Laboratory (JPL) designed a Microspine which uses surface irregularities to anchor itself to monolithic rocklike structures [6]. This technology is baselined for use as part of the asteroid capture mechanism for ARM. For the 20th mission of NASA Extreme Environment Mission Operations (NEEMO) this concept was adapted to be a crew deployed stabilization platform that provided a BRT attachment point. Additional investigations are necessary to understand the mission scenarios for this type of tool and its feasibility.

Regardless of the methods utilized, the vehicle used to approach the surface of the bodies must have all the necessary stabilization infrastructure on it. For science sampling around the immediate vicinity of the vehicle, handrails and foot restraints can be placed in certain locations. However in order to maximize the scientific return there will be the desire to explore tens of feet away from the vehicle's "landing" location. With current technology deployable structures are required to enable exploration of this nature. Having the crew translate using the existing surface elements is not recommended as the crew would end up contaminating samples and the surface will be unpredictable.

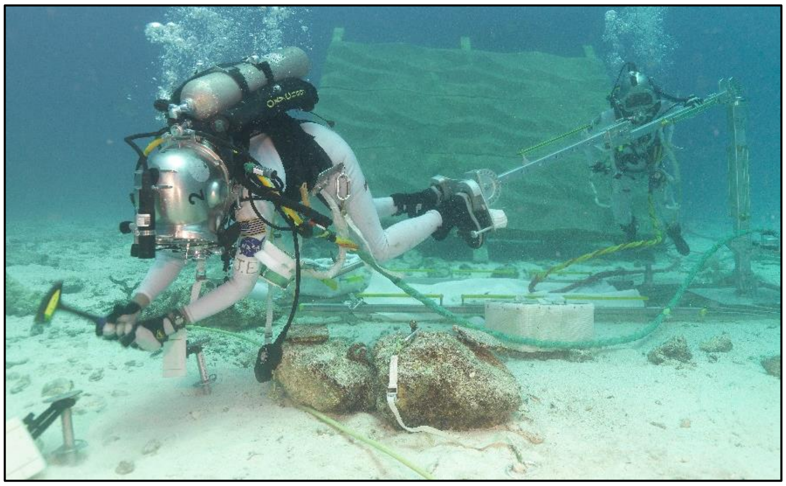

**Figure 2. Science Package Deployment, Body Stabilized with a Foot Restraint on a Boom during the NEEMO 18 mission.**

## B. FLOAT SAMPLE

Float samples are defined as individual units loosely adhered to the surface. In order to remove the sample from its original location one only needs to overcome the force of gravity. Here on Earth geologist may pick up these types of samples by hand or using a selection of tools: tongs, a scoop, or a shovel. In fact, the Apollo missions to the Moon utilized these same types of instruments [1]. In the low gravity environments (milligravity to microgravity) of small bodies the action of shoveling or scooping would eject the sample into space, making it unobtainable and creating a debris hazard to the crew and vehicle. Grabbing the sample by hand or using tongs are the only methods which are gravity independent as they capture and contain the sample in a single motion.

Retrieval of a sample by hand was investigated within the scope of these potential missions and the science requirements therein. Having the crew member directly grab samples with their gloved hand was ruled out as the suit materials create avenues for sample contamination and there is an increased risk in glove puncture. One solution that has been developed is to use a soft bag and place it over the gloved hand of the crew member. First, the bag would be removed from its storage location. Second, the crew member would have the bag gripped in one hand and use the other hand to manually invert the bag over their grabbing hand. Third, they would reach out and carefully grab the sample of interest. Finally, upon grabbing the sample, they would then unfurl the bag, enclosing the sample within. The bag itself could have a method to seal the sample or could be placed into a larger container that provides sealing for multiple bagged samples. This method was deemed feasible though material selection for such a bag is still an open question.

Tongs are a simple mechanism by which the user squeezes the handle and the opposing grabber tongs open up. The user would place that over a sample of interest and undo their squeeze, trapping the sample. Apollo astronauts utilized tongs to retrieve multiple float samples. This tool acted as an extension of their arm, preventing them from having to bend down to get their samples. These tongs were multiuse, meaning a single unit was used to retrieve many samples from multiple different areas. Contamination between samples sites was not part of the science requirements. The tongs were used to obtain the sample, which would then be placed into a sample bag.

Commercial Off The Shelf (COTS) solutions that simulated these tongs were evaluated to determine how well this type of tool worked in microgravity. Overall, the concept proved feasible though there were a number of comments from the crew. Tool stiffness needs to be considered. Comments from NEEMO 16 and Apollo missions expressed frustration with flimsy tools. Additionally, a clamshell design was preferred to the tong design as the clamshell was better at containing floating rocks. From a science standpoint, enabling the crew to perform sampling tasks at a further distance from the surface is preferred because it reduces risk of contamination from the surface, as seen in Figure 3.

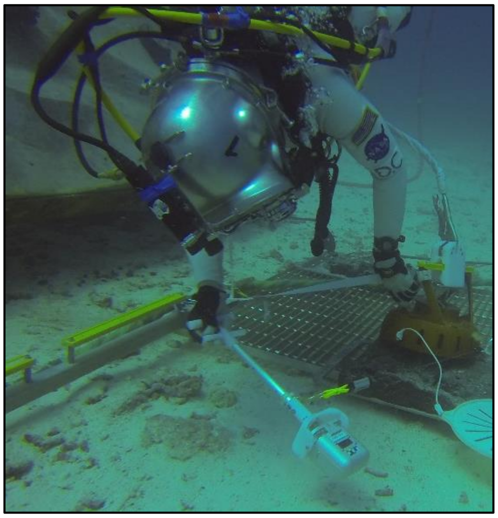

**Figure 3. Float Collection at NEEMO 20 using a Microspine for Body Stabilization**

## C. REGOLITH SAMPLE

Regolith is defined as a loose conglomerate of fine particles. Similar to a float sample, this sample is loosely adhered to the surface, though depending on how packed the regolith is, may take more force to remove. On Earth, regolith collection is normally accomplished using a shovel or scoop. However, as previously described, this method is not viable in the low gravity environment of small bodies. For that reason, a similar strategy can be employed for regolith samples; tongs that enable the crew member to retrieve and contain the regolith in a single action would prevent the sample from flying away. For these types of tongs to work they would have to be solid all-around to prevent the sample from getting out. Because of this, the same tool could be used for collecting both float and regolith samples. This tool would have a clamshell gripper to contain the sample and any other debris.

### D. SURFACE SAMPLE

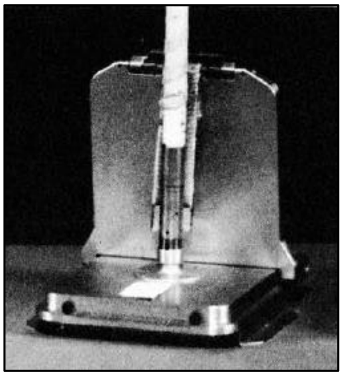
**Figure 4. Apollo Stamp**

A surface sample consists of the top layer of the surface. It is of scientific importance as the particles have been directly exposed to the space environment for many years. For instance, surface samples are of interest in the field of space weathering. Space weathering is how the space environment alters the surfaces of airless bodies through various physical and chemical processes [3]. The Contact Soil Sampler, Figure 4, was designed for the Apollo missions to obtain the uppermost layer of lunar regolith [1].

More specifically, the goal was to sample undisturbed regolith. This was accomplished by obtaining the sample from the far side of a boulder many feet away from the Lunar Lander. A similar methodology should be considered for obtaining the sample on small bodies. A translation aid could be used to get away from the vehicle and a location could be selected on the far side of an obstacle, such as a boulder. The microgravity environment also drives this sample to be the first one that is collected. Other sampling activities create a risk of disturbing regolith, ruining the quality of the sample.

Two versions of this tool were created; one with a velvet cloth as the sampling method, the other with beta cloth. The door was opened manually, sample pad lightly touched to the surface of interest, and then the door was manually closed, capturing the sample for return. As this heritage tool meets the requirements laid out for Small Body EVA, no additional concepts have been imagined. To evaluate this tool in the microgravity environment and a functional demonstration unit was created. Aluminum foam was used as the collection surface. This was tested as part of the NEEMO 20 analog mission. It was an operational requirement that this tool were to be used to obtain the first sample. This was confirmed as viable and good practice. Crew feedback indicated that the method for opening and closing the door should be relocated, as the current design creates a potential for sample contamination due to accidental interactions between the sample collection material and the astronaut's gloved hand. A recommended solution is to put a lever by the handle that would be actuated by the crew member to control the opening and closing of the door. The results of the evaluations to date indicate obtaining a surface sample is viable.

### E. CHIP SAMPLE

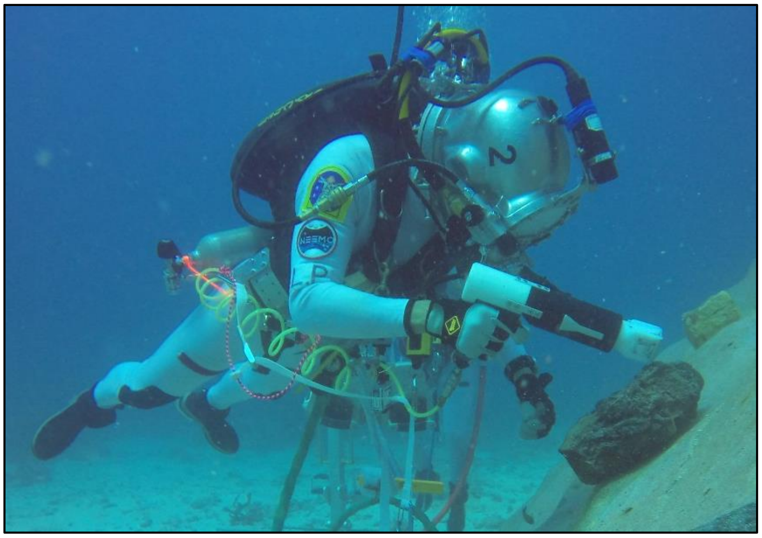
**Figure 5. Chip Sample Collection at NEEMO 20**

A chip sample is defined as a piece of debris that has been forcefully liberated from a parent body. On Earth a chip sample is obtained through the use of a hammer and a chisel. In Earth's gravity the liberated chip simply falls on the ground for easy retrieval. However, in low-gravity environments this becomes more difficult.

A number of concepts for obtaining chip samples have been investigated. One idea was to cover the rock with a clear blanket which had embedded chisel points throughout. The blanket's function was to prevent debris and samples from flying away. However, this method proved to be difficult to attach to the surface and actually collecting the chip samples was difficult. The next iteration evolved into a hard shroud, or bell, that was mounted around a chisel. The operator simply pressed the bell against the surface providing more control, however it was difficult to aim because of its large size. Furthermore, it did not fully address how the chips would be captured for sample return. The most recent iteration was designed around a removable end effector that contains a chisel, two windows and a sliding door. Figure 5 shows this hardware being used during a NEEMO mission. This design helped to eliminate cross contamination between sample sites by allowing for a new, clean chisel and collection container to be introduced at each sample site. One of the challenges encountered is the size of the Chip end effector. It needs to be small enough that a crewmember can easily position the chisel for sample collection, large enough to collect the chips created, and also small enough to stow easily.

### F. CORE SAMPLE

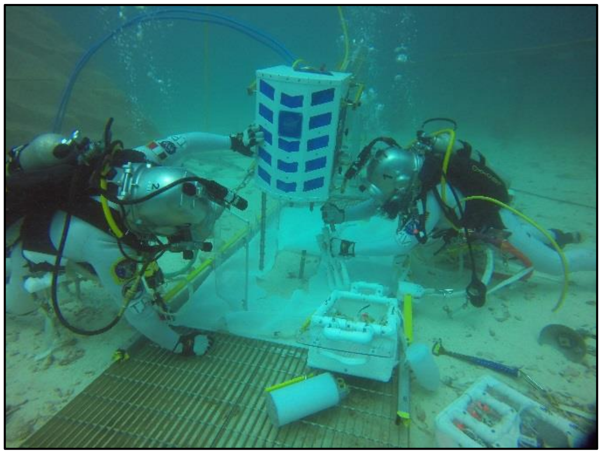

**Figure 6. NEEMO Deep Core Drill**

Obtaining core samples on Earth has been mastered in even the most extreme environments like that of Antarctica and the bottom of the ocean. During the Apollo mission, crew members even obtained a core segment 5m deep into the Moon. Lessons learned from these experiences will inform core drilling techniques for small bodies. There are some unique challenges presented in this new environment such as: reacting the drilling loads, storing the samples and length of drilling time. CAPTEM indicated their interest in a core at least 4cm deep (shallow core), however deeper cores, 1m or more, would also provide value [11]. Work through an ARM Broad Agency Announcement (BAA) focused on a shallow core drilling and caching system that utilized a unique break-off tube design [5] providing an initial concept for obtaining a shallow core in microgravity.

During NEEMO 18 and 19 a deep core drill was tested. The main goal was to better understand the concept of operations and capability requirements of future deep coring systems. The NEEMO Deep Core Drill, Figure 6, was designed to be deployed on the end of the Stabilization Boom, reacting the loads back into the spacecraft (in this case the Asteroid Retrieval Vehicle). The crew deployed the drill and then controlled the rotation speed and feed rate. The design utilized removable core strings that the crew was responsible for inserting and removing. Consideration should be given to automating the coring process. Since this is expected to be a slow process, the automation would enable crew to make efficient use of their EVA time by performing other tasks.

### G. SAMPLE CONTAINERS

Once samples are obtained they need to be placed in a container for the trip back to Earth. The curation process back on Earth will drive the requirements of these containers. Sample containers can range from plastic bags to knife-edge vacuum sealable canisters, both of which were used during the Apollo mission [1]. Crew members would obtain a sample with a tool then transfer that sample into a container, using the Moon's gravity to aid in the transfer. The low gravity environment of small bodies has driven an architecture where the sample container is integrated into the collection tool. This eliminates the need to perform sample transfers in microgravity. This system is explained further in Section IV. Furthermore, testing has reiterated the need for a set of contingency bags. These extra bags allow for samples of interest to be collected, and preserve options for sample collection if there are any hardware failures. Regardless of the architecture contingency sample bags are vital to ensure a successful mission. As these missions develop, it is important that the science and engineering communities stay integrated.

### H. CAMERAS

An important aspect of sample collection is understanding the context of the surrounding environment. This context can be captured through verbal descriptions, however it needs to be supported by high resolution photographs or video. During the Apollo missions this was accomplished through a hand held 35mm camera and a gnomon which allowed for size and color calibration after the fact [1].

## IV. Integrated Sampling Solution

The scientific desire to minimize cross contamination and the microgravity environment are drivers for a new sampling architecture. This architecture is one in which each tool is one-time use. This method prevents material from one sample site getting mixed with a different sample site. Unfortunately, the mass and volume of this system becomes unfeasible. A compromise has been developed where the collection end of the tool is one-time use and can be removed from the parent tool. This also prevents the need to transfer samples from the tools to sampling bags, which is risky in microgravity. A first iteration of this architecture was developed and tested during NEEMO 20. Figure 7 shows the various types of End Effectors (EE) that could be housed in the Sample Briefcase, Figure 8. Each end effector was designed to obtain one of the aforementioned samples desired by the scientists. In this version the Sample Briefcase contained two chip EE, two core EE; two Float/Regolith EE and one Surface EE. A set of six contingency/sample-of-opportunity bags were also provided. Two drivers were designed to interface to the end effectors. A manual driver enable collection of float, regolith, and surface samples. Samples that required additional force interfaced with a powered driver, seen in Figure 5. The briefcase can be designed to hold different quantities of each EE depending upon unique requirements of a given mission. Long term, the system could be designed to be modular allowing for in-situ reconfiguration prior to a sampling EVA. Currently, the system is designed to restrain each EE using two opposed ball plungers. The plungers provide adequate restraint during translation activities, and still allow for easy removal once a Driver has been attached. This design minimized the potential for cross contamination however it does significantly impact the mass and volume of the sample collection suite. This initial water-compatible prototype provided a good first look, however future iterations are needed to hone flight appropriate EE's and to minimize mass and volume.

**Figure 7. Integrated End Effectors**

**Figure 8. Sample Briefcase**

## V. Conclusion

Human exploration of small bodies is inevitable. Their scientific value is great and their reduced gravity environments are beneficial from a cost standpoint. Presently, the space exploration community has imagined human missions to Ceres, Phobos, and asteroids. This paper outlined an initial framework for performing geology sampling on these missions. This field is still in its infancy and further development is required. As mission architecture decisions are made, additional requirements will be levied. Decisions about exactly what samples will be taken and the mass limit of the samples will need to be made.

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