Introduction to Tools and Techniques for Surface Sampling on Europa

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ABSTRACT

The NASA Jet Propulsion Laboratory (JPL) is studying excavation and collection of a sample from an icy surface for a potential landed mission to Europa. Europa presents unique challenges in planetary sampling. Very little is known about the local topography and material composition of the surface. The environmental conditions of being cryogenically cold (80-130K), low gravity (~1/7th Earth), no atmosphere, low lighting conditions, and limited ground in the loop opportunities have forced JPL to look at sampling differently than past missions. Interacting with the surface of the Jovian moon requires a sampling system that is robust to local topography on the scale of the lander and/or the tool. In addition, the sampling system must be capable both of detecting faults and automatically adjusting to them to achieve the mission objectives without ground in the loop feedback. Presented here is an overview of a sampling system concept that involves a two-stage approach for collecting a sample. The first stage uses an excavation tool to prepare the surface site for sample collection by removing the top layer of irradiated material and clearing tailings from the hole. The second stage then generates and collects a sample for delivery to instruments on-board a lander. Also presented is an introduction for how autonomy and sensing technologies might be employed to enable mission success.

INTRODUCTION OF EUROPA AND WHY WE WANT TO COLLECT A SAMPLE THERE (MISSION CONCEPT OBJECTIVES):

The Galilean moons of Jupiter—Io, Europa, Ganymede, and Callisto—were the first satellites discovered orbiting a planet other than Earth. Europa in particular is of great interest to the scientific community. Based on data returned from NASA's *Galileo* spacecraft, Europa is known to be covered by a thick icy surface. This ice shell is relatively thin (<25 km deep), although that thickness may fluctuate over time and likely varies from location to location over the entirety of the satellite. While slightly smaller than Earth's moon, Europa very likely harbors a global, ~100 km deep liquid water ocean, which is likely in contact with a rocky, silicate seafloor. At that interface, water-rock interactions could lead to an ocean rich in the ingredients and energy sources needed to sustain life; as such, Europa is generally seen as one of the best places to find life beyond Earth within the Solar System. As a zeroth-order step towards determining whether Europa may be host to endogenous, extant life, we would first need to analyze samples of Europa's surface (in regions where scientists think the surface and the under-ice ocean may have interacted) using a suite of scientific tools on a lander.

The Europa Lander mission concept has three main objectives: 1) Search for evidence of biosignatures on Europa, 2) Assess the habitability of Europa via in situ techniques, and 3) Characterize Europa's surface and subsurface to enable future robotic exploration (Hand, et al., 2017). This mission concept traces back to the 2011 NASA Decadal Survey, and its objectives complement a subset of NASA's high-priority goals (as articulated in the agency's 2014 Science Plan) that motivate missions focused on planetary exploration: 1) "Advance the understanding of how the chemical and physical processes in our solar system operate, interact and evolve; 2) Explore and find locations where life could have existed or could exist today; 3) Improve our understanding of the origin and evolution of life on Earth to guide our search for life elsewhere".

UNIQUE CHALLENGES TO SAMPLING ON EUROPA

The potential Europa Lander would be the first surface mission to search for sign of life on an ocean world Martian rovers and landers such as NASA's 2007 Phoenix mission have focused on investigating the habitability and the surface chemistry of Mars. The forms of life that could be encountered on Europa might be very different from those known to exist on Earth. Europa's icy surface provides unique challenges with its low gravity, lack of substantial atmosphere, and cryogenic temperatures. Jupiter's strong radiation belts constantly irradiate the surface of the moon, driving the proposed sampling system to extract samples below the top layer of the icy crust. Planetary protection concerns and the low amount of sunlight in the outer solar system drive the baseline lander design to be battery powered with a mission life that would likely be less than 30 days. As a result, scientists would have less opportunity to communicate with the Lander, driving the system to be highly autonomous. Beyond the challenges of distance and communications, Europa's environment presents new challenges to sampling on an extraterrestrial body.

Relatively little is known about the actual surface conditions of Europa. Pictures from *Pioneer* 10 and 11, *Voyager* 1 and 2, and *Galileo* give some indication of the general surface topography. These images of the surface show craters, ridges, chaos terrains, and smooth plains. Overall, Europa appears to have a very smooth (i.e., few craters relative to nearby satellites like Callisto) and young surface that shows evidence of recent tectonic activity. The best images of Europa come from the *Galileo* spacecraft; however only a handful of images exist of the surface, and the majority of these images have a resolution no better than 100m/pixel which is insufficient to understand the topography on the scale of the lander, much less on the scale of a sampling system (Figure 1).

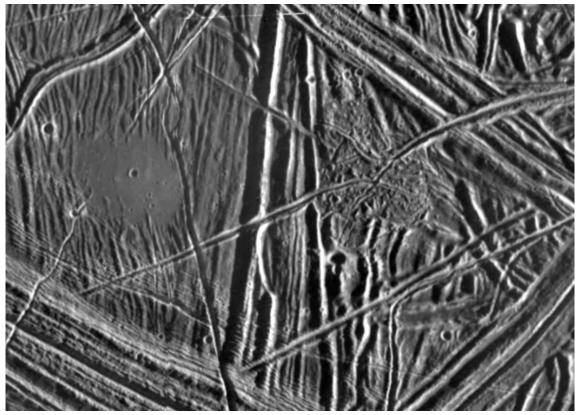

Figure 1: Close up of Europa from Galileo Spacecraft.

Image Credit: NASA/JPL/ASU

It is hypothesized that the surface of Europa could be analogous to the topography found at Devil's Golf Course in the Mojave Desert in CA (Figure 2).

Figure 2: Devil's Golf Course; Mock-up of Phoenix Icy Sample Acquisition Device (ISAD) (Peters, et. al, 2008) shown for reference.

Image Courtesy Lori Shiraishi, JPL

Other future missions to Europa, such as Europa Clipper, may provide more detailed images or other data that could aid in the selection of potential landing sites, though specific data would not be available prior to the lander's planned launch date in 2025. Therefore, the sampling system must be designed to be robust on all scales.

Europa has a gravitational pull of about 0.134 g's, or less than $1/7^{th}$ of Earth's (Pappalardo, et. al 2009). Past missions have utilized the gravitational pull of the planetary body they are landing on to excavate and collect sample (Phoenix, Curiosity, etc.) (Chu, et. al 2008). In addition, the sampling system would need to minimize forces transmitted back to the lander to avoid the possibility of shifting the lander position on the surface.

It is thought that the surface of Europa can range from <80 to 130K, which poses challenges to design of traditional sampling hardware. In addition, the detailed chemical makeup of Europa's surface is unknown. Europan ices may contain frozen sulfuric acid due that form from chemical reactions associated with the delivery of high-energy sulfur ions from Io to the Europan surface. Likewise, organic molecules—potentially from biogenic processes—and volatiles may be trapped in the ice. It would be the job of the sampling system to maintain sample temperatures below 150K prior to delivery to the instruments in order to preserve the integrity of such chemical species due to their significance in the characterization of the Europan surface and the search for biosignatures.

The material present on Europa's surface comes from both endogenic and exogenic sources, and it is important to try to differentiate between the two for sampling. Micrometeoroid impacts, thermal processes, radiolysis, and surface sputtering all affect Europa's surface chemistry and can erase or alter potential biosignatures. While the other processes are predominantly chemical in nature, micrometeoroid impacts overturn surface material in a process known as "gardening" which can mix exogenic and endogenic materials, resulting in a fluffy regolith (Hand, et al. 2017). The most widely accepted average surface composition of Europa is a mixture of water ice, magnesium sulfate, and sulfuric acid. The water ice is predominantly crystalline, but also could contain regions of amorphous ice. The surface may also contain traces of organics, other hydrated salts, oxidants like hydrogen peroxide, and an array of other minor chemical species. There could also be trapped gaseous or liquid pockets within the icy crust.

Europa's surface has tenuous O_2 atmosphere due to radiation sputtering of oxygen from the surface, leading to a surface pressure likely to be as low as 10^{-12} bar. Any atmosphere Europa does have is likely due to radiation sputtering of oxygen from the surface (Pappalardo et. al 2009). In order to keep a sample in its most natural state, a lander must operate in a way that resists sublimation and loss of trapped gasses during the collection effort.

One of the most difficult requirements for sampling on Europa is sampling at depth. Due to the high flux of high-energy radiation that bombards the europan surface, approximately 10 cm of material must be cleared away to get to pristine samples at most landing sites on Europa. The trailing and leading hemispheres near the apex points contain the most irradiated material, in which it would be more difficult to identify any potential molecular biosignatures (Hand, et al. 2017). Integrated together, these environmental challenges drive the sampling system concept to be highly robust to achieve the science objectives of a Europa Lander mission concept.

SAMPLING SYSTEM CONCEPT OVERVIEW

Due to the unique challenges presented with Europa and the nature of the mission concept, the JPL team is exploring new, more robust methods for sampling. Previous missions have typically utilized various combinations of drill type devices and/or scoops to collect samples (Bar-Coahn, Zachny, 2009). The current baseline for this mission separates the sampling into two operations – one to excavate the top layer material, the second to collect the material. The operations may be accommodated using one or two tools. For excavation, the team is currently baselining a device that uses a rotating blade such as a saw or drum cutter, while collection is exploring a number of different concepts including scoop and bucket type concepts.

SAMPLING SYSTEM FUNCTION 1 – EXCAVATION

The sampling system's first task is to clear a path through a layer of radiation-processed material for the collection tool.

Drilling has a long, successful history in planetary sampling, however one of the big limitations is the challenge of starting a hole. Optimally to start a hole, the drill needs to be place perpendicular to the surface and a sufficient amount of weight on bit (WOB) applied. Stabilizers (e.g. Curiosity rover drill) may or may not be used to help with maintaining bit alignment (Figure 3) (Baumgartner, et al., 2005).

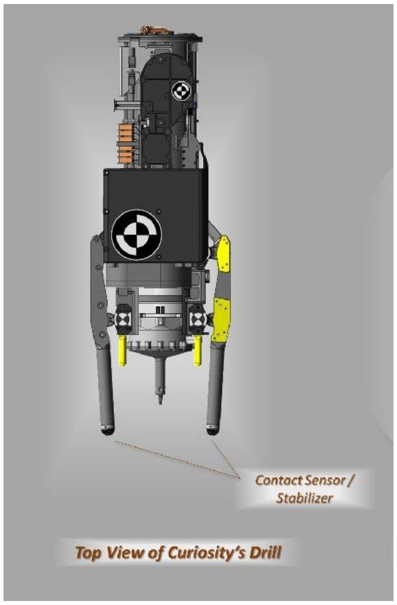

Figure 3: Curiosity Rover Drill

Image Courtesy of NASA/JPL-Caltech

Given the unknown topography, the possibility to have local terrain features on the scale of the lander, and the need for a high degree of autonomy, it is unlikely that a drill could be aligned properly to the surface to ensure a satisfactory hole start. In addition, given the low gravity on Europa, applying sufficient WOB to counteract the low friction contact between the bit and icy surface may not be possible. A saw type of device has numerous advantages over drills in this type of sampling scenario (Figure 4). First, a saw type device is agnostic to the surface topography. When the tool contacts the surface, it will remove material. If used on the end of a robotic arm that is configured to operate in a backhoe style motion, the arm only needs to counteract in plane reaction forces. Secondly, the saw type device is efficient at removing large amounts of material quickly which is advantageous for getting to the required sampling depth and preparing the underlying surface for sample extraction. Finally, the saw type tool can be used in combination with the robotic arm can quickly and efficiently clear tailings from the hole to ensure the bulk of the collected sample comes from depth.

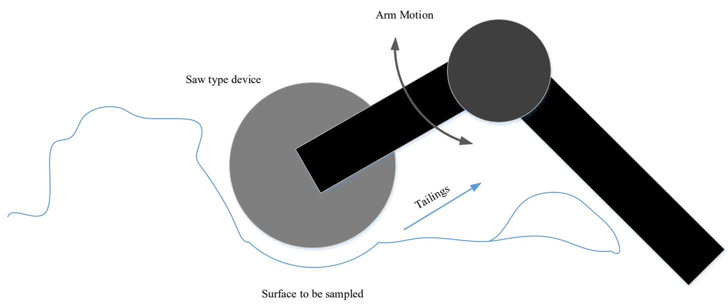

Figure 4: Saw Type Device Concept

SAMPLING SYSTEM FUNCTION 2 - COLLECTION

The sampling system's second task would be to transfer material from Europa's surface to the spacecraft. Work to date has identified key architectural branches and narrowed the trade space, and is evolving the more promising ones towards high fidelity testing while actively exploring new options.

At the coarsest resolution, the architecture of a collection tool must be as shown below.

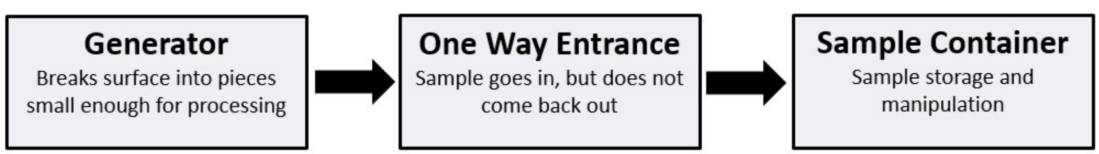

Figure 5: General Architecture of Collection Tools

Sample Generation
There are three key architectural options associated with the sample generator. First (and second) is the temporal (and spatial) separation between the sample generator and one-way intake. A general guideline is that the smaller the separation, the better the sampling system reliability, because opportunities for external factors to cause problems are reduced. Third is the size of the generated sample piece; size has thermal implications in maintaining sample integrity along with the basic 'will it fit' criteria for the collection tool, sample containers, and instruments.

One Way Intake
The second step in the collection tool architecture (Figure 5) is to pass the sample piece(s) through a one-way intake. This is a challenging step because almost all designs require interaction directly with the sample (not via an intermediary, such as a sample cup).

There are a limited number of principles by which the sampling system may physically interact with raw sample material to motivate it through the sample handling chain. These principles are summarized below (Figure 6), and a few described in more detail. A common theme is that since the sample material and the behaviors it will exhibit are unknown, care must be taken not to modify the sample. Starting the design process at this very fundamental level enables a potentially gigantic trade space of possible solutions to be pruned substantially.

Change the position of the sample (Motive) — **Preventing the sample from moving** (Holding)

Method of Interaction	Motive	Holding	Comments
Gravity	–	✓	Low magnitude on Europa
Magnets	–	–	Sample material unknown. Don't want to change it.
Electric fields	–	–	Sample material unknown. Don't want to change it.
Pneumatics (air puff)	✓	✓	Consumable mass vs. sample size? Thermal effects?
Contact: Transient	✓	–	Ballistic push, saw, rasp, oscillating bristles, etc.
Contact: Continuous	✓	✓	Geometry, plunger, wiper, brush, centrifugal, etc.

Figure 6: Collection Concept Space for Physical Sample Interaction. Checks indicate branches that are still active while slashes indicate areas that have been pruned.

Gravity: A notional requirement levied on the system is that gravity shall not be used to motivate the sample. Particularly in Europa's weak gravity, adhesion and cohesive forces on sample particles could easily dominate gravitational forces. The strength of these two forces will vary greatly due to the sample and tool materials, any processing done to the sample, and the ambient environment. However, gravity may be relied on to prevent sample movement. For example, a bowl filled with sample and left uncovered on the surface will retain the sample.

Pneumatics (Gas Puff): Although pneumatics raises concerns regarding consumable usage and thermal input to the sample, it remains as a potentially effective method of manipulating fine particles though further work is required to understand how well an pneumatic system needs to "seal" to the surface and to characterize performance on porous substrates.

Transient Contact: Sample may be motivated using transient contact, e.g. chip and debris stream from a saw blade. By definition, transient contact is incapable of holding the sample position constant.

Continuous Contact: Continuous contact is capable of both motivating sample movement (common examples include bulldozers, pistons, and drills) and preventing sample movement (geometric constraint, inertial forces).

Many concepts for one-way intakes exist under these guidelines. Examples include a bucket to catch the spray of chips off a saw, jawed scoops that close around sample material, and an air puff blowing sample material until it is snared in a filter.

Sample Container

The third element of the collection tool architecture (Figure 5) is the sample container(s). Getting sample into a container is a key risk mitigation factor for handling and preserving a sample. Once in a container, it is conceivable to cap the container to minimize the risk of spilling, sublimation, and other sample degradation due to environmental conditions. Additionally, once the sample is containerized, the manipulation system can handle and work with engineered surfaces. This minimizes the risk associated with handling and manipulating sample with unknown material properties and characteristics. To easily support a variety of automated manipulation steps, the current baseline is a test-tube-like shape, but this is subject to change as instruments are picked and the spacecraft design evolves.

Heritage

While there is no heritage sampling system that is suitable for use on this mission concept, a great many lessons can be extracted from prior missions and development efforts. As in previous missions, the sampling system would remove some volume of Europa's surface and after various manipulation steps, deliver it to instruments inside the lander for analysis (Bonitz, et al., 2001). What portion of volume is successfully manipulated by each step – the efficiency of that step – is of great concern. The scientific instruments require sufficient volume to complete their analyses and the system needs to allow for some degree of margin. If sample chain efficiency is low, huge amounts of sample may need to be initially collected. A low sample chain efficiency is not only problematic for scientific instruments, but also for the sample manipulation system: sample lost can potentially clog pathways and jam mechanisms. It is highly desirable to minimize the direct handling of sample and instead get it into an engineered container as quickly as possible. The sampling systems on past missions such as Phoenix and MSL (Mars Science Lab – Curiosity Rover) had greater knowledge about the materials expected at their mission sites, more time to be discriminating in choosing spots to sample, and Mars's stronger gravity (2.8x stronger than Europa's). These systems used gravity-motivated sample 'fluid' motion with the help of agitators and vibratory devices, but were still challenged by uncooperative sample, resulting in large sample chain inefficiencies and equipment jamming (Peters, et al., 2008).

Prototypes

To help develop a robust sampling the system, the development team must be prepared for a large variety of material *properties* and *behaviors*. Thus beyond obvious materials such as saltwater ice, the team is conducting testing in a wide range of materials including dust, smooth sand, pumice stone, pykrete, salt licks, mudstone, and nylon. While the mission would not expect to encounter these on Europa, these engineering materials exhibit a large range in behaviors against which the sampling system can be tested.

Several promising prototypes use saw type tools (blades used with rotation axis roughly perpendicular to the surface normal) that spray chips into a waiting cup. A series of scoop prototypes have refined that architecture and will help to explore its advantages and disadvantages relative to the other collection concepts. While hole start and auger reliability are risks for drill type collection tools, these have considerable heritage and thus continue to be evaluated by the team.

Prototypes of more novel collectors are being developed, including concepts which use inertial forces to move or hold particles, concepts which generate sample particles by pure impact (no rotation), and concepts which use puffs of gas to motivate sample particles.

OVERVIEW OF SENSING & AUTONOMY

The Europa lander concept's requirements and physical constraints drive the potential need for the highest degree of autonomy of any sampling mission undertaken by NASA and JPL to date. To preserve the Europa biosphere, planetary protection seeks to minimize any forward contamination from Earth. Due to the challenges of using an RTG (Radioactive Thermal Generator) and low solar intensity at Europa, the lander mission concept has baselined chemical batteries for power, resulting in an overall shorter mission life than previous sampling missions to Mars (Bonitz, et. al, 2009). The round trip time communications between Earth and the Europa lander is on the order of ~ 90 minutes not including processing time of the information on Earth. Coupled with the limited visibility of the Europa orbiter, Earth based communication is infrequent, ruling out human tele-operated type control of the lander such as used in the 2007 Phoenix mission to Mars. (Trebi-Ollennu, et al., 2009). In the current concept of operations, scientists provide the lander with desirable targets and then have the lander autonomously acquire a sample and processes it before the next uplink window for each of the planned five (5) samples.

The Europa lander concept sampling subsystem must satisfy a large set of requirements while operating in completely unknown environment, posing significant challenges to the autonomous sample collection system. The material properties and surface topology are expected to be unknown prior to landing, so the sampling subsystem would be equipped with a wide array of sensors to estimate the state of the lander and the properties of the environment in the sampling workspace. After choosing a sampling site the lander must excavate to a minimum depth of 10cm, acquire a sample, estimate the volume of the unknown material, and deliver it to science instruments internal to the lander vault for further analysis. During the sampling process the sample exposure of the sample to radiation is to be minimized, and the collection subsystem must maintain a sample temperature below 150K. To satisfy the various requirements imposed on the system, it must be able learn and adapt its behaviors to the environment in real-time to achieve these goals autonomously. Additionally, the system must be able to identify any internal system faults and attempt to finish the sample collection even under degraded sensing or actuation capabilities. As a result of these challenges, the autonomous sampling system will be a significant area of research as the mission technology matures. Technology areas being explored are detailed below.

Hardware and Sensors: The current design of the sampling subsystem concept consists of a robotic arm with an excavation tool, sampling tool, force-torque sensor, and perception sensors fixed to the end effector. The design of the robotic arm is under investigation to determine the number of joints and actuator design. The perception sensors have not been selected but would likely consist of cameras and LIDAR sensors. Additionally, the lander would be equipped with orientation sensors to determine body attitude.

Autonomy: The autonomy subsystem would operate as a Hierarchical State Machine (HSM) vs. the traditional human machine system (Tunstel, et al., 2005) to implement the various behaviors required to generate a sample. The HSM is chosen due to its ability to easily compose complicated system interactions yet limit the number of possible states and transitions to a manageable size. HSMs have been implemented with success on numerous flight missions to date.

The action set of the robot is implemented as a hierarchy, comprising of behaviors primitives at the lowest level to decision making logic at the highest level. The high level decision making flow is shown below (Figure 7). When called, each primitive will enforce required preconditions to be satisfied before executing. Optional preconditions can be specified to improve the performance or reduce the uncertainty of a given behavior primitive outcome, allowing for degraded modes of operation. The robot will also be equipped with probing actions that will be used to reduce environment uncertainty or learn environment properties. For example, the robot may probe the selected sample candidate area to verify the accuracy of the elevation map and get surface hardness measurements to better model the environment and adjust the initial excavation process parameters.

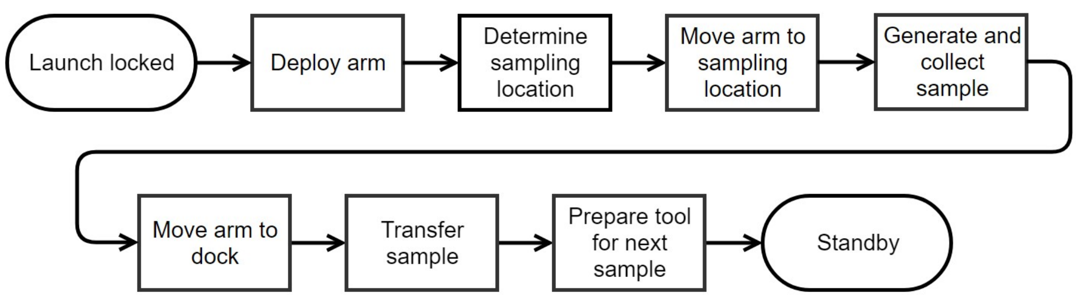

Figure 7: Europa Lander Concept Sampling Autonomy Process

Future plans and experiments

Over the last two years of development, a resilient set of tools for sampling unknown materials and topographies on Europa has been investigated. With the team focused on answering fundamental questions such as:

- Can a cryogenic, icy surface that is representative of Europa be excavated? [yes]
- What are promising methods of interacting with the potential Europan surfaces?

- Where do the bounds of a given concept lie; are there material behaviors or characteristics that are problematic?
- How can reaction forces and energy consumed be minimized during sampling?
- How can an excavation system be made resilient to the unknown surface topography, composition, and environment of Europa?

Development of the excavation and collection tools has steadily progressed through exploration of the interaction between the tool and sample material. As continued testing occurs on excavation and collection concepts, the focus will converge on finding designs that can fulfill the functional requirements of the mission concept in the most effective and reliable manner. To support this development, the team has commissioned several testbeds to support development.

StORM – Stiff Operationally Flexible Robotic Manipulator: To evaluate performance of excavation and collection methods, a testbed was designed that would isolate the behavior at the end effector and collect data on tool performance to inform future designs (Figure 8). The testbed consists of a KUKA industrial robotic arm mounted inside of a defined workspace. The KUKA arm works well with the requirements of the testbed as it is incredibly stiff and relatively easy to program to perform desired actions. The six degree of freedom KUKA arm is not intended to emulate a flight arm; rather, it serves a mechanism to actuate the desired tool in testing. This testing enables evaluation of excavation and collection tools on parameters that define the efficiency of the tool in use, such as current being drawn to power the tool.

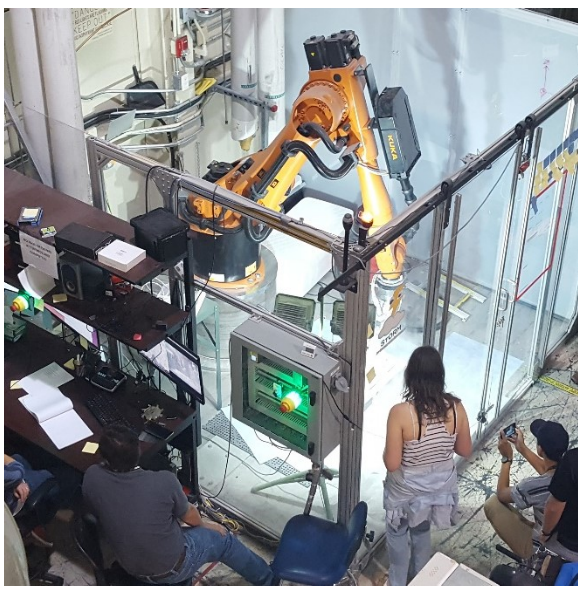

Figure 8: StORM Testbed in Operation

ELSA – Europa Lander Sample Acquisition Arm testbed

A five degree of freedom in-house arm will be used for software and autonomy testing. The arm is to serve as a flight hardware analog and will allow for development of autonomy and eventually higher level sample collection. The ELSA arm, which is designed to be compatible with preexisting drive and tool mounting serves as a useful tool to explore challenges, such as compliance, that do not exist during testing conducted with the KUKA arm.

ELSA DMC – Europa Lander Sample Acquisition Dirty Mid-size Chamber

The environment on Europa has been outlined as having a temperature varying between 80K and 130K and a pressure less than 10^{-9} Tor. As excavation and collection tools continue to develop, end-to-end testing of the sample acquisition and delivery systems in a relevant environment are key to validating designs. Planned to be operational in fall 2018, this thermal vacuum chamber introduces the opportunity to test tool concepts in an environment that will be representative of flight conditions. The chamber has an internal diameter of approximately 1.5m and a height of approximately 1.25m (Figure 9). It has been designed to pump down to 10^{-6} Tor and with four cryocoolers, it is estimated that is should reach temperatures between 70 and 100K. A unique feature of the chamber is that it has been designed with four load locks to allow for swapping of samples in and out of the chamber without having to open the main chamber. A robotic arm internal to the chamber will enable the end-to-end testing of tools and concepts from excavation to sample delivery in relevant environmental conditions. Initial pump down of the chamber is scheduled for late spring 2018. Pump down of the chamber at temperature is planned for the summer of 2018 and initial testing with one load lock is planned to start late summer 2018.

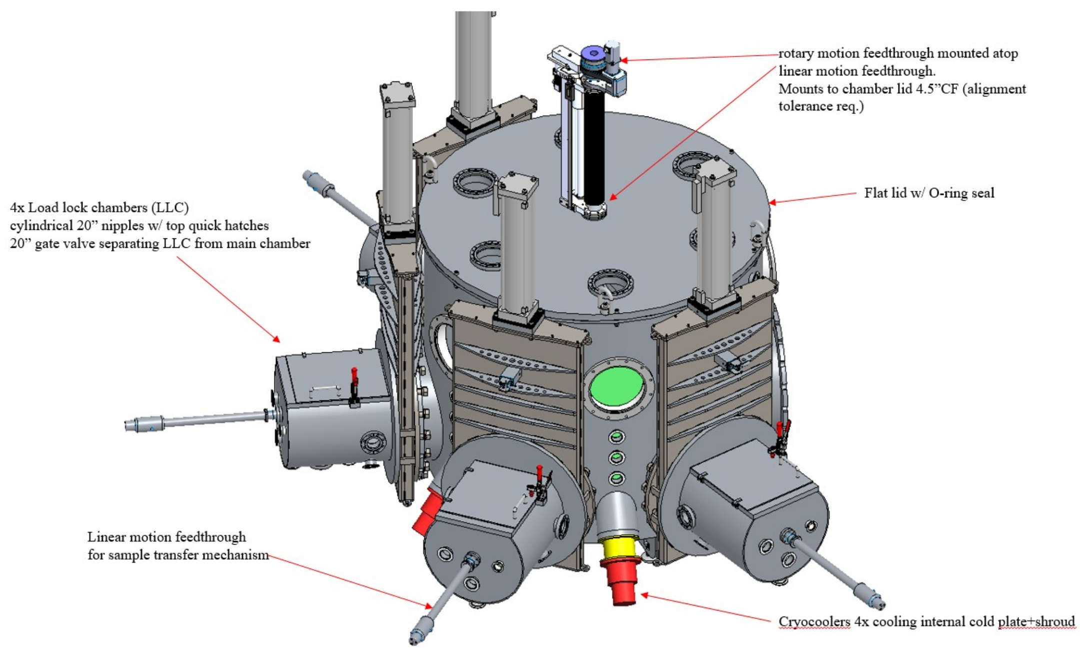

Figure 9: ELSA-DMC Testbed Design

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