CITADEL: An Icy Worlds Simulation Testbed

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Abstract

Icy Worlds present an exciting target for in-situ sample acquisition and analysis of surface samples for their potential to contain conditions necessary to support life. The unknown surface composition and topography of icy worlds present a challenging environment for which to develop effective sampling systems. Testing such sampling systems in a relevant environment is a critical part of validating and refining their design. We have developed the Cryogenic Ice Testing, Acquisition Development, and Excavation Laboratory (CITADEL) to enable sample acquisition and handling operations in an icy world or primitive body representative environment of <70K and 10-5 Pa.

CITADEL provides the unique capability of multiple load locks which can be separated from the main chamber to rapidly exchange simulant samples without disturbing the main chamber environment. This allows the use of surface simulants created outside the chamber itself to test a wide range of compositions and morphologies, while drastically increasing chamber throughput. The chamber serves as a platform for testing a variety of surface simulants, sampling tools, and end-end sample handling systems. CITADEL is equipped with 6DOF reaction load sensing, motor telemetry, multiple video cameras and other sensors. CITADEL allows for the investigation and discovery of unknown-unknowns when operating in this environment.

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1. INTRODUCTION

The NASA Jet Propulsion Laboratory (JPL) is conducting research for excavating, collecting, and transporting a sample from an icy surface for a future landed mission to Europa. Europa presents unique challenges in planetary sampling for a number of reasons. First, very little is known about the local surface topography and material composition of Europa's surface. Secondly, 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. Sampling on Europa requires a sampling system that is robust to local topography and chemicals that can become reactive at temperatures above certain temperatures. In addition, the sampling system has to maintain sample integrity throughout the collection and delivery to instrument process. Preliminary project requirements limit the collected sample temperature to a maximum of 150K to reduce volatile compound losses.

This paper provides an overview of the CITADEL testbed, some of the challenges related to developing a sampling system, and the testbed elements that enable investigations to understand these phenomena. In the future, an end-to-end sampling system will be integrated to validate the performance of elements that require surface interaction and sample handling in a representative mission environment.

The testbed consists of a vacuum chamber with cryogenic elements capable of maintaining externally generated simulant containers at cryogenic (70-100K) temperatures and a high vacuum (10^{-5} – 10^{-8} torr) atmosphere. The key elements that make this testbed an enabling technology for sampling system development include Load locks (LLCs), a robotic arm with 6DOF reaction load sensing and interchangeable excavation, collection, and transport tools, interfaces for a variety of sensors that can be tailored for specific test campaigns, and a software architecture for controlling the robotic system and aggregating telemetry.

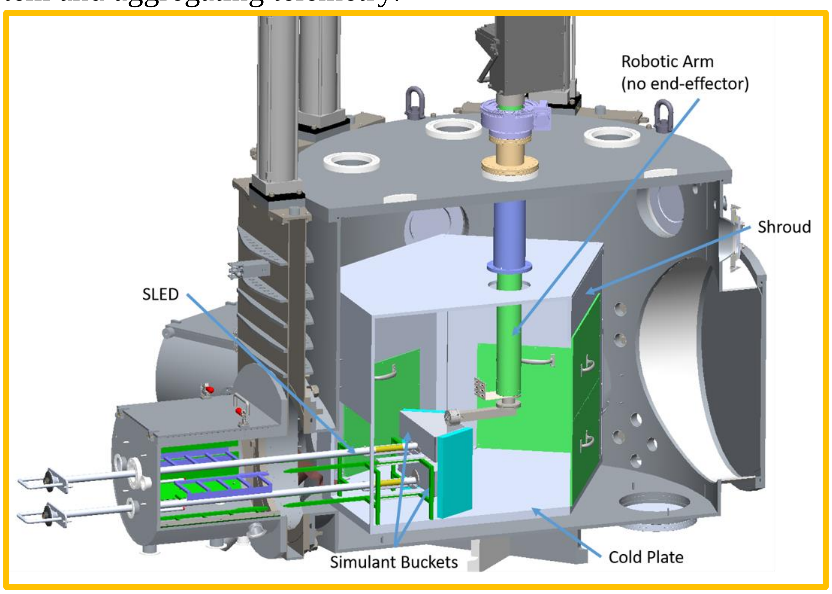


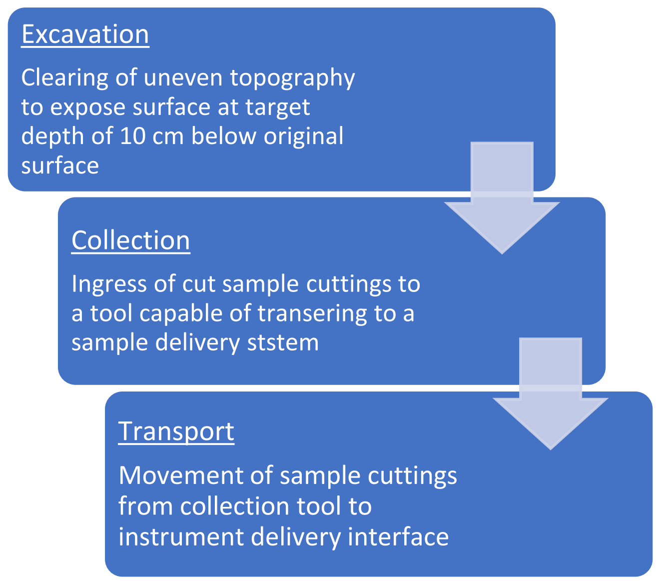
Figure 1: Overview of the CITADEL Chamber

2. PLANNED INVESTIGATIONS

Testing in relevant environmental conditions is required to fully understand the interactions between tools and the collection target surface. There are three major phases involved in the sampling chain: Excavation, Acqusition, and Transport. Each of these phases involves interaction with the undisturbed surface or the cuttings generated in a previous phase, and have poorly understood sensitivities to the material characteristics and environment. CITADEL is therefore intended to help characterize tool and system responses to a wide variety of surface simulants in each of these phases, as well as generally uncover unknown-unknowns relating the system performance.

Excavation (cutting)

Mechanical properties of ice change with temperature and composition, impacting the energy required to excavate a trench or other area clearing. Mass constraints on a flight system cutting tool design and time constraints on the excavation sequence in flight require an understanding of the range of energy budgets to excavate to appropriate depth. CITADEL's load locks enable tests of a single tool with a virtually unlimited number of simulants in a single chamber pumpdown to begin charaterization of surface composition and topography impacts on a proposed cutting tool's efficiency, power requirements, and reaction loads imparted to the lander interface.



Sample Collection

Environment-specific challenges for acquiring sample from excavated terrain must be characterized to satisfy high level science and engineering requirements. Collection mechanisms must minimize heat transfer into the sample to meet the science goal of keeping samples <150 K until processed by the instruments. The testbed provides the necessary elements and interfaces to verify this, as well as a test venue for a flight-like sample integrity verification system.

Dynamic behavior of chips/shavings will change in the absence of atmosphere, and will not melt and refreeze (as is typical on earth). These factors will affect debris pile-up and tool function in ways that cannot be effectively modeled or simulated in an ambient environment. Cameras, witness surfaces, and other inspection methods can be employed to understand these dynamic behaviors, the efficacy of current cutting tool designs, and feed forward into the next iteration of collection mechanisms.

Sample Transport

Sublimation rates drastically increase above 150K, along with potential reaction of volatiles. The lack of free moisture, both from low temperature and low pressure, may affect granular solid clumping behavior. These impacts to the sample handling behavior are not yet understood and must be tested in environmental conditions to both validate the system design and attempt to develop equivalent ambient simulants. CITADEL will be used for transporting sample using mechanical means, as well as pneumatic transport systems.

3. TESTBED ELEMENTS

The key elements that make this testbed an enabling technology for sampling system development include Load locks (LLCs), a robotic arm with 6DOF reaction load sensing, a thermally isolated sampling tool interface, and interfaces for a variety of other sensors. The software control architecture and preliminary results of a LIDAR system implementation will also be discussed.

Environmental Controls System

The environmental control system for CITADEL is comprised of the vacuum system and the thermal control system. The vacuum systems utilizes three dual stage rotary vane roughing pumps for pumping down the main chamber volume to 10^{-3} torr, and a turbomolecular pump is then engaged to reduce pressure to high vacuum levels, 10^{-5} torr and below. A fourth roughing pump is used for evacuating the load lock chambers (discussed below) before the gate valves opens to link them to the main chamber.

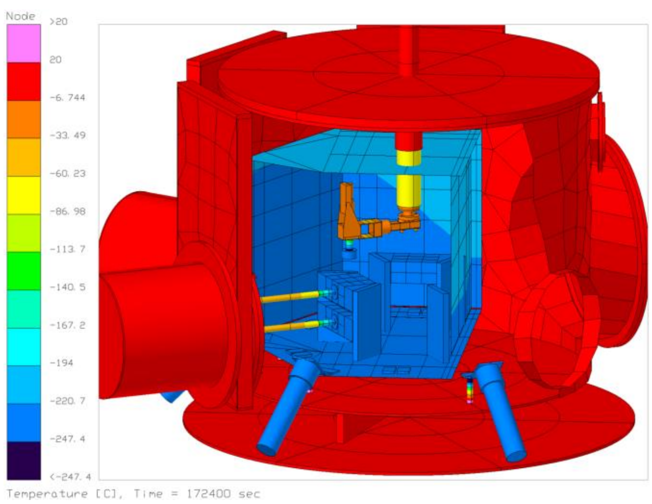


Figure 2: Thermal simulation of CITADEL at steady state cold conditions. The baseplate and sample buckets reach as low as 30 K.

The thermal system uses closed loop helium compressors feeding coldhead cryocoolers as a low cost means of achieving temperatures of 30-100 K inside the cold shroud. The cold shroud is a thermally isolated aluminum plate structure, outfitted with PRTs and heatsink structures known as backstops. The interior surfaces are coated with Aeroglaze Z306 black paint and the exterior is covered with single layer insulation (SLI). Four coldheads, operating at a steady state 30 K and 75W heat load capacity, use thermal straps to cool the shroud without the use of any LN_2 lines or other plumbing. The thermal gradients during steady state operation are show in Figure 2.

The coldheads normally function at 100% duty cycle, with heat leaks from the pressure vessel structure limiting the minimum temperature achieveable. Polyimide heaters located on the baseplate with a total heating capacity of 400W are used for returning the shroud back to ambient temperatures more quickly after the completion of a test series. The extremely low temperature of the cold plate precludes the ability to backfill the chamber with GN2 until all the shroud is warm enogh to prevent the formation of liquid nitrogen.

A secondary thermal shroud and heater system actively maintains the robotic arm and end effector assemblies at 250 K to allow the use of conventional materials and lubricants within the cryogenic environment for test purposes. An aluminum shell wrapped with SLI reduces the heat leak from the relatively warm assembly to the sample, cutting tool, and cold shroud.

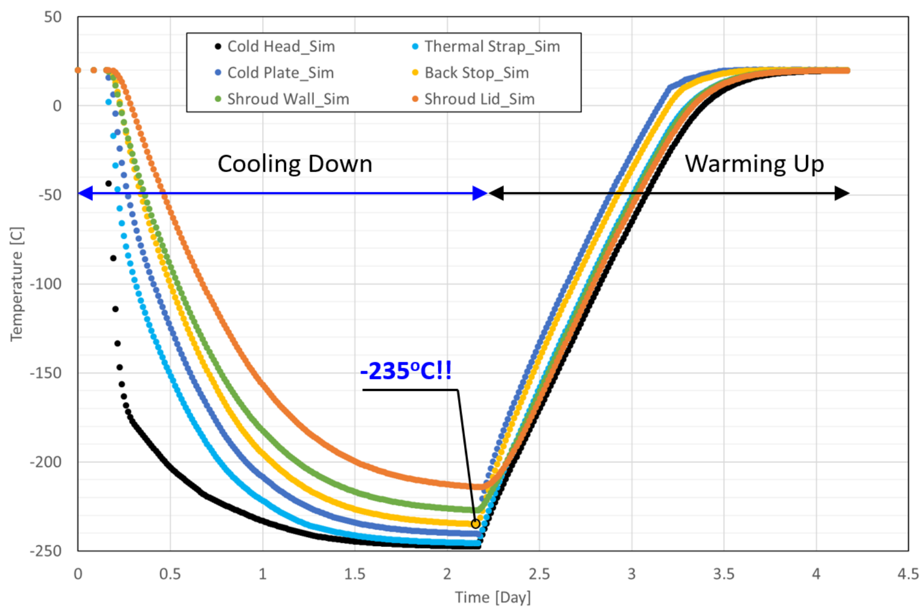


Figure 3: Thermal simulation results of time required to reach cryogenic conditions at the sample interface

Control of the environmental system elements is run through the Interlock control box, which uses a state machine to monitor and control pump status, pressure in all isolated volumes, valve state, and cryocooler state. This lockout system ensures operators cannot command the system into an unsafe state.

Load Lock Chambers

A key aspect of CITADEL is the presence of up to four Load Lock Chambers (LLCs) that enable samples to be loaded and removed from the chamber without returning to ambient temperatures. Tests and thermal analysis have shown the time required to reach cryogenic conditions at the sample bucket interface takes approximately 2 days of operation, shown in Figure 3. Testing a wide variety of surface topogrpahies and sample compositions to account for the unknown Europa surface requires the use of load locks to be able to load and remove samples in several minutes instead of several days.

The LLCs are volumes that can be manually loaded with samples in ambient pressure and then closed and evacuated by a roughing pump. A gate valve separates the LLC from the main chamber volume, which is able to be opened once the LLC pressure reaches 300 mTorr. With the gate valve open, the sample bucket can be pushed into the chamber by manually pushing a long tube through a linear motion vacuum feedthrough known as a Wilson seal. The sample bucket is preloaded against the backstops, where it will continue to be cooled until it matches the backstop temperature of ~70 K. Figure 4 shows a section view of the lower sample bucket being loaded into the chamber (note the LLC lid is not shown for clarity).

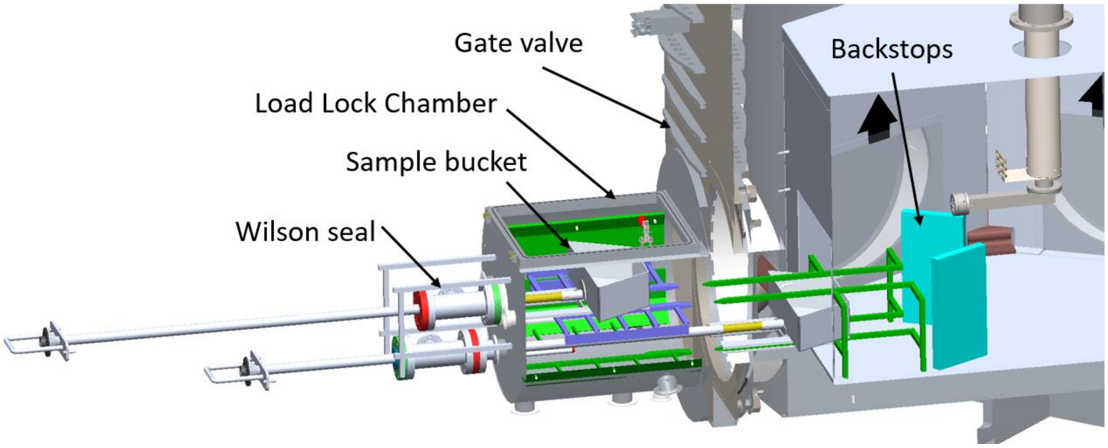


Figure 4: Section view of a load lock with sample buckets (lid not shown). The upper sample bucket is still in the load lock volume while the lower bucket is halfway between the load lock and the backstops.

Feedthroughs are located on the end of the sample bucket trays for passing thermocouple and other generic electrical signals through the Wilson seal. This allows samples to be instrumented with temperature sensors, or the use of a sample bucket as a platform for measurement equipment that can be installed and removed without breaking chamber.

Robotic Manipulator and End Effector

The robotic arm assembly mounts to the lid of the chamber and features two degrees of freedom, excluding the cutting tool motor. A vertical feed axis and rotational axis located outside the chamber are used for performing swept arc cuts and drilling activites. To reduce complexity, the only active elemenents on the robotic arm located inside the chamber are part of the end effector assembly shown in Figure 5. A rotarty/linear vacuum feedthrough allows conventional actuation equipment to be used outside the chamber while a structural extension with electrical feedthroughs for the end effector are inside the chamber.

A 6DOF force/torque sensor mounts between the end effector and the arm structure to measure reaction loads imparted to a spacecraft interface. The arm, F/T sensor, and end effector are capable of applying 500 N in any direction to envelope the capability of any proposed lander system interface.

With advanced cutting and collecting tool designs, material can be excavated, collected, and then transferred to an inspection station using only these three degrees of freedom. Future work includes plans to add another degree of freedom to the wrist to achieve scooping motions.

Inspection and Measurement Systems

Conventional means of evaluating the performance of sampling system often rely on the inspection or testing of material collected by the system under test. This is particularly challening in a low pressure and temperatur eenvironment where everything must be inspected remotely. Some of the baseline equipment being used in the chamber for evaluating system performance include lights and video cameras, F/T sensor readings, motor performance and current draw, and chamber pressure and temperature.

While these baseline measurements will be taken in all tests, the testbed is intended to be flexible for the inclusion of various inspection and perception systems depending on the needs of the test series being conducted, such as collected sample mass measurements or non-contact temperature sensing. One major area of focus is the implementation of a LIDAR system to quantify properties of granular solids produced during cutting operations. This will be discussed in further detail in Section 7: LIDAR Sensing.

4. THERMAL ISOLATION OF CUTTING TOOL

One challenge specific to sampling on icy bodies is the potential for phase change of the sample during acquisition and handling. Since many ocean worlds have extremely tenuous atmospheres, sample heated to temperatures above ~200K (-73ºC) will begin to sublimate. Thus, if a sample acquisition method requires a sample in the solid state, the heat flow to the terrain during the course of sample acquisition must be limited. There are two sources of heat transfer to the terrain: heat generated from friction between the cutting tool and the terrain, and waste heat generated by the tool actuator & transmission.

Because the working temperature of motors, gearboxes, and bearing lubricants is high relative to the sublimation temperature of water in tenuous atmospheres, it is necessary to thermally insulate the cutting tool from the electromechanical actuation system. CITADEL's end effector incorporates a novel design that can accommodate a >200K thermal gradient across the mechanical transmission at steady state, and higher thermal gradients in the transient condition. This allows the motor to begin operation at typical operating temperatures (~270K) and the cutting tool to begin cutting at temperatures near the sample surface temperature (~70K).

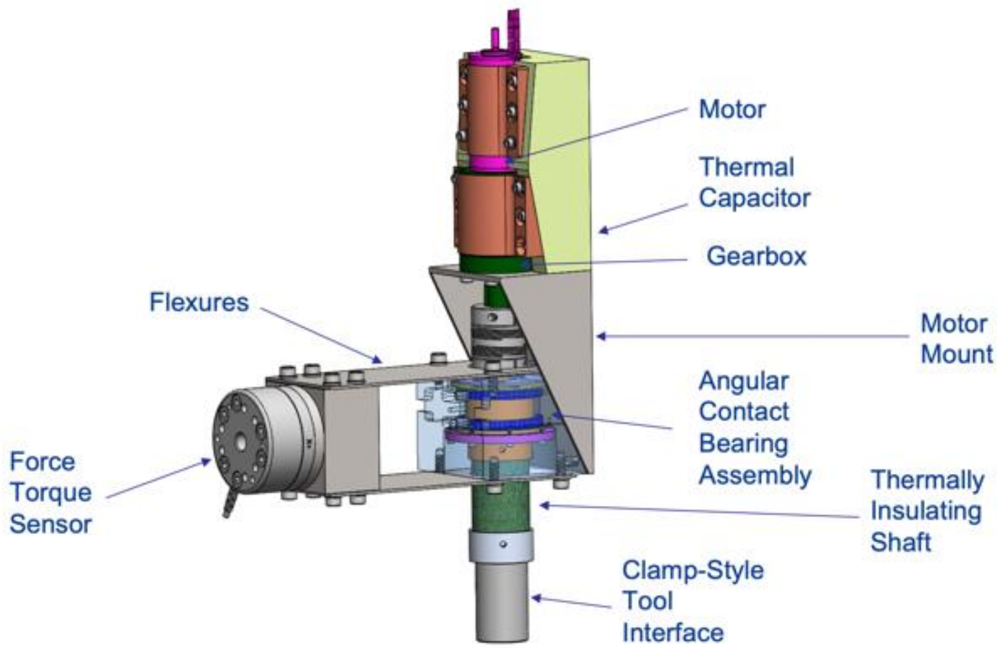


Figure 5: End effector components

The end effector actuation system can be broken into several subcomponents: encoder, motor, gearbox, bearing block, thermal insulation system, and cutting tool (see figure 1). Optimally, the operational temperatures of each of these subcomponents are distinct. Therefore, there are separate closed-loop heating systems for the motor/encoder, gearbox, and bearing block. The bearing block contains 440C stainless steel ball bearings with Braycote 600EF lubrication, which can operate reliably at -40ºC. In order to accommodate the effects of thermal expansion, the bearings, bearing block, and shaft are fabricated entirely from 440C stainless steel. Distal to the bearing block, the output shaft is then serially coupled to a G10 shaft, which is responsible for the bulk of thermal insulation.

This is accomplished via a cylindrical tongue and clevis fit between the G10 (tongue) and 440C stainless steel (clevis) as seen in Figure 6. The fit is installed as a free running fit on both cylindrical interfaces, but the volume is filled with Stycast 2850 24LV which acts both as a liquid shim and as a thermal interface material. The role of the Stycast as a thermal interface material is necessary to avoid uneven thermal contraction between the G10 and the stainless steel, which could lead to excessive clamping force on the G10 at cold temperatures. Once the bond is cured, radial holes are drilled through the material stack. This allows for the assembly to be riveted with 18-8 stainless steel rivets, which is the torque transmitting element. Because of the tongue and clevis fit, the rivet is loading between the innermost face and outermost face of the stainless steel clevis, which avoids issues of G10 relaxation under high local pressures. The coefficient of thermal expansion (CTE) of G10 is very similar to that of 440C stainless steel. The slightly larger CTE of the 18-8 rivets ensures that the assembly will tighten at lower temperatures, avoiding any loosening due to CTE mismatches. The same assembly is repeated on the output side of the G10 so that the output of the shaft will be 440C stainless steel. This allows for easily reconfigurable cutting tools, because it can accommodate a clamp style coupling. An 18-8 clamp style coupling has a larger CTE than the 440C stainless steel shaft, so the clamp strength will increase as the temperature drops. On the output side, the shaft can be any material with a CTE less than or equal to the CTE of 18-8 stainless steel. This includes a large design space of materials typically used for cutting applications. Furthermore, after assembly of the 440C stainless steel / G10 / Stycast 2850 24LV shaft, the output can match-machined concentric to the input, which can all but eliminate runout incurred during assembly. The runout of the output shaft was measured with a dial indicator on the CITADEL testbed to be less than .0002”.

Figure 6: Thermally isolating tool interface. This coupling maintains a >200 K thermal gradient while capable of transmitting over 100 Nm of torque.

The material properties of G10 are poorly quantified at the temperatures of the CITADEL testbed. In order to test the material properties at representative temperatures, and to validate the behavior of the assembly, a static loading testbed was built. A stainless steel shaft with a flange was rigidly fixed to an optical table with the notional shaft assembly installed above the steel base. Liquid nitrogen was piped through copper tubing fixed to the steel base, until the temperature of the stainless steel base piece reached a temperature of 110K. After 20 minutes, the temperature of the stainless steel on the other side of the G10 had increased by only 1.8K. This serves to corroborate a conservative thermal FEM that was performed (which does not account for the thermal inertia of the steel or tool or for convection), which suggests that after 20 minutes the temperature of the end effector would increase by 9.8K.

The base of the stainless steel shaft was then dunked into an LN2 bath and rigidly fixtured while torque was applied with a torque wrench. 100 Nm of torque was applied to the side of the shaft opposite the G10, and no signs of yield or movement were observed. The shaft opposite the G10 was also subjected to high shock loads with a hammer, and no structural concerns were encountered. These tests were repeated over 10 thermal cycles, all with identical results.

Tool Temperature Maintenance and Sensing

In order to maintain the cutting tool temperature near the sample surface temperature in the steady state condition during cool-down and during time between tests, end effector hardware distal to the G10 insulation must be thermally docked to the cold plate via conduction. The testbed includes a rigid thermal docking station with a compressible grafoil thermal interface material. The docking plane is normal to the allowable motion axis of the end effector flexures, which alleviates planar misalignments between the thermal docking surfaces. The thermal dock is equipped with PRTs and thermocouples, which will indicate when the tool has reached a steady state temperature. Because the end effector is designed to test multiple cutting tools of various geometries, the thermal dock is designed to mate to the clamp-style tool interface, which remains constant between tests. CITADEL thermal models suggest that the cutting tool temperature would reach steady state temperatures of 170K without a thermal conduction bath to the cold plate; the introduction of a thermal dock brings the steady state temperature of the end effector down to 70K. Additionally, because the cooling effects due to radiation alone are very slow, the thermal dock is designed to accommodate docking to the thermal capacitor that is thermally coupled to the motor. This allows for quicker cooldown times between tests, since cooling down adequately is essential for optimizing the allowable energy output of the motor for a single test

5. Control System

The CITADEL control system comprised of 4 main components: runtime controls, camera controls, environmental controls, and pressure interlock controls. The main control system components can be seen in Figure 7.

Runtime Controls

The runtime control system is responsible for sending commands to the sampling arm and tools and reading a large set of chamber sensors. This system hosts the operator interface used to sequence testbed sampling tests, initiates telemetry and video capture, monitors system faults, and coordinates functional autonomy behaviors for sample acquisition. More information on the software structure of this subsystem can be found in Section 6: Software System.

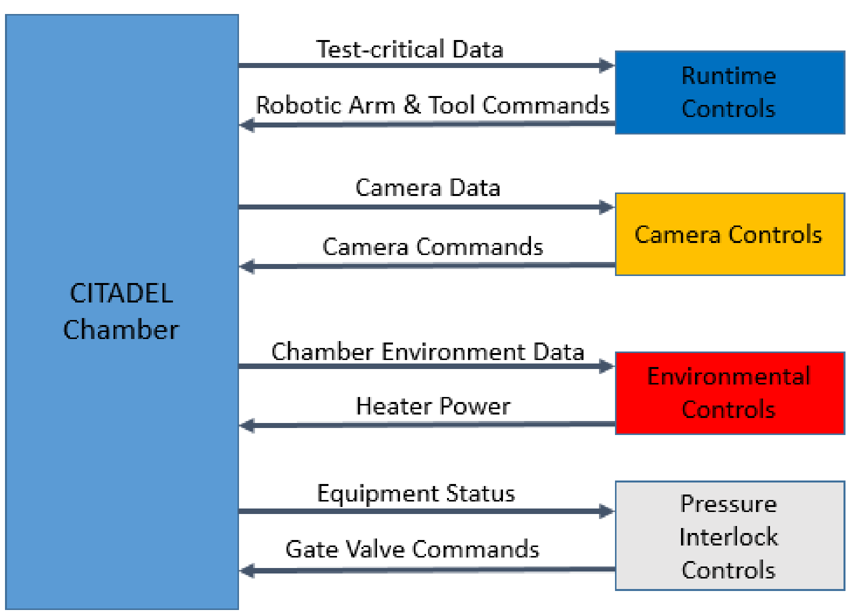


Figure 7: CITADEL Control System Components

Camera Controls

The camera control system is responsible for a set of up to 12 cameras that are located inside the chamber. The chamber itself has no viewports for operators to observe the interior of the chamber. This set of cameras is critical to monitoring operations in real-time and is capable of recording videos of chamber sampling operations. Video recording modes can be controlled by the runtime control system to ensure videos are synchronized with test sequences.

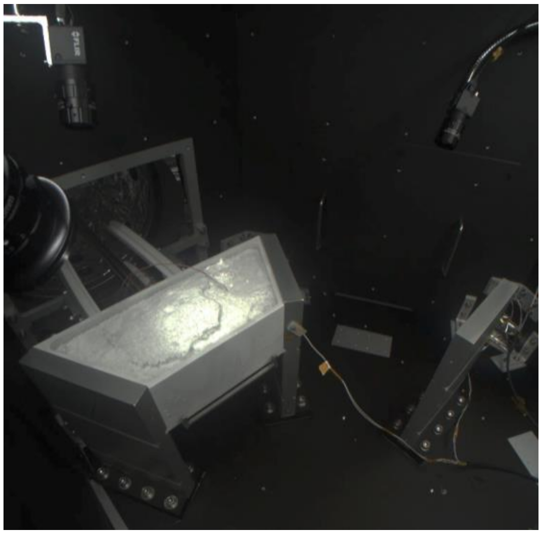


Figure 8: Camera image from inside the chamber

Environmental Controls

Environmental controls include electrical heating circuits, ambient lighting, and other always-on chamber electronics. The environmental controls system exists as a separate subsystem to ease system integration. Additionally, this subsystem is powered through an uninterruptible power supply to ensure sensitive equipment maintains appropriate temperatures even in the event of building power failure.

Pressure Interlock Controls

The design of the chamber allows for exchanging sample trays though load locks without requiring the entire chamber to return back to ambient temperature and pressures between tests. The advantage is test program velocity but increases safety risks to both testbed operators and equipment. The pressure interlock control system is responsible for monitoring chamber pressures and controlling testbed elements that could cause dangerous, rapid pressurization such as gate valves. Operators interact with the interlock though a human-machine interface that emulates the pressure system and prohibits unsafe actions. The nominal interlock operator interface can be seen in Figure 9.

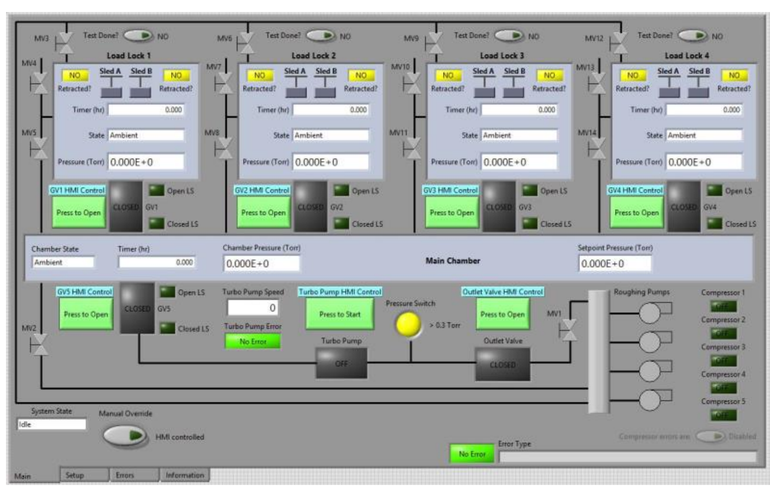
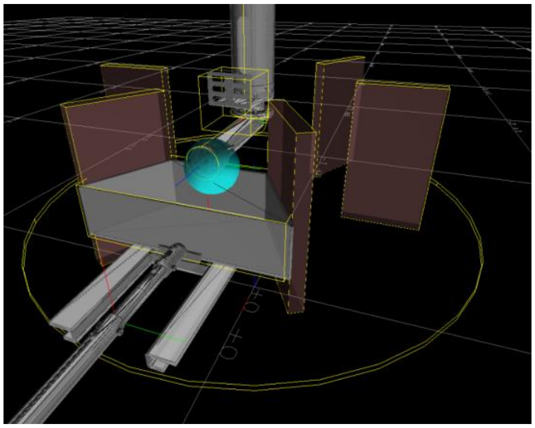


Figure 9: Interlock Operator Interface

6. SOFTWARE SYSTEM

The CITADEL software system is largely based off the JPL CASAH software system used successfully in early Mars 2020 sampling testbeds (Edelberg, 2018). The sampling software models the complicated internal geometry of the chamber to ensure hardware safety and executes robotic behaviors that can be composed together to perform sampling test campaigns.



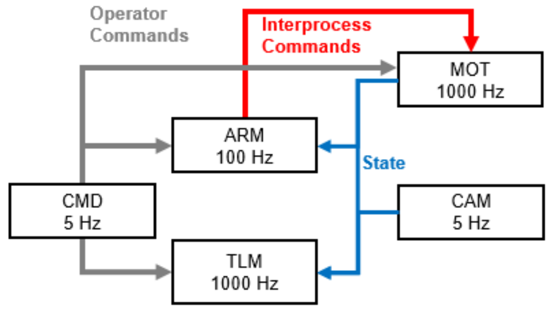


Figure 10 (Left): CASAH Visualization of the Citadel Chamber Model (Collision Detection is Demonstrated by the Teal Sphere)

Figure 11 (Right): CITADEL Software Modules

Simultaneous Force and Position Control

A unique contribution to the set of CASAH shared behaviors is a new manipulation behavior called ARM_MOVE_TASK_AXES. This behavior enables the operator to command specific tool-frame Cartesian axes in either force or position control mode, independently from each other axis. While tools are being developed and tested, this behavior enables rapid contact-based testing by operators as tools cut and chip into prepared sample blocks. For example, a rotary skimming tool could provide weight-on-bit force control in the vertical axis while translating across the surface using simultaneous position control in a lateral axis, allowing the tool to respond to uneven surfaces while acquiring sample.

7. LIDAR SENSING

A LIDAR (light imaging, detection, and ranging) system enables visualization of objects in three dimensions that would be otherwise difficult for a camera setup. For example, in imaging ices, the samples are often of a uniform white color making it difficult to correlate between images. A LIDAR system bypasses this issue by directly measuring the distance between a point on the sample and the sensor. Due to the small sample volume and single direction of measurement, a flash LIDAR with low physical profile is used for data collection, namely a PicoFlexx LIDAR (Figure 12).

To enable volume and volume change measurements of a sample (e.g. during sublimation), LIDAR point cloud data was processed using the open-source point cloud library (PCL), and two different methods were compared.

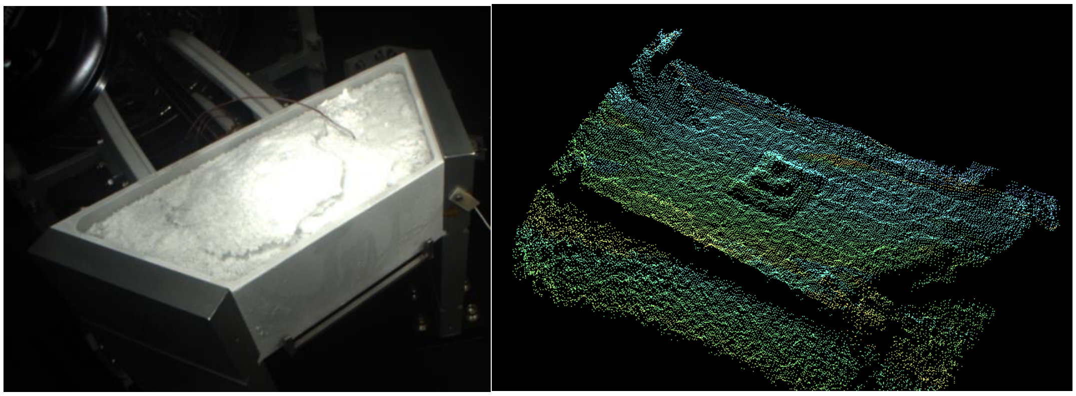


Figure 12: (Left) Visible light image of a sample inside the CITADEL chamber. The middle chunk is observably elevated with respect to the rest of the sample due to the shadows under the overhang. However, the rest of the sample topography is difficult to pick out. (Right) LIDAR image (three dimensional) of a calibration target (multilayered pyramid structure) in ambient conditionals. Color represents the distance from the LIDAR. Green points designate closer points. Blue points designate points that are farther away.

Data Collection and Plane Recognition

First, a stream of input point clouds are taken in-situ and the live data is filtered for data logging and later analysis. Next, plane recognition is achieved through the RANSAC sample consensus algorithm. After recognition, the sample is isolated in the cloud (Figure 13). The RANSAC threshold distance accounts for noise in the LIDAR measurement and is calibrated beforehand to better isolate the sample sitting atop the plane.

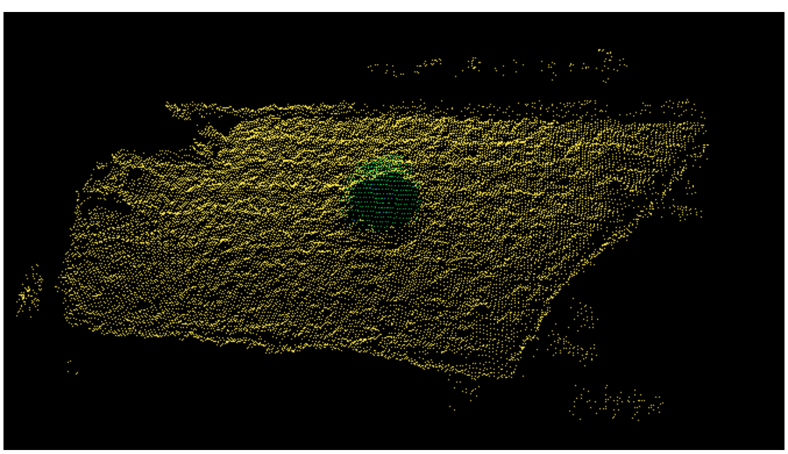
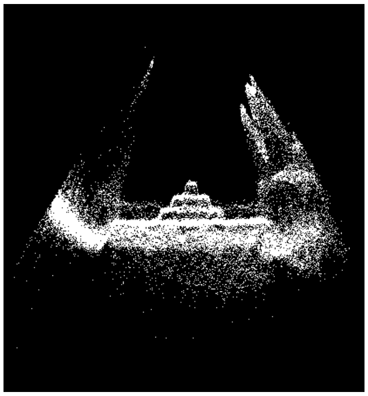


Figure 13: Recognized reference plane (yellow) with segmented sand sample (green)

Temperature Correction

A significant challenge of the project is data acquisition under harsh environmental conditions that simulate those of icy worlds. Although the LIDAR functions nominally at low pressures, the instrument was found to be far more sensitive to low temperatures (Figure 14). Moreover, there is a hysteresis in the LIDAR depth as the temperature cycles (Figure 15). As a result, the LIDAR requires thermal isolation to prevent loss of communications and preserve data fidelity.



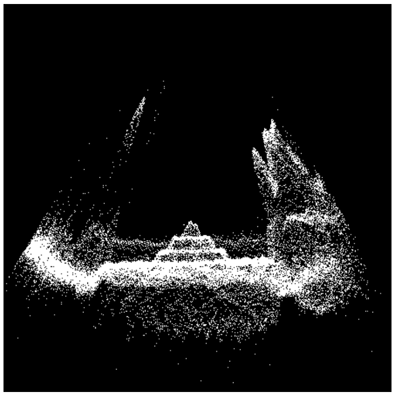


Figure 14: Drop in LIDAR depth with temperature: 25°C (left) and -65°C (right). Calibration target (step pyramid with three steps) is shown in each case. LIDAR is positioned at the top of the image with the calibration target aligned with the LIDAR viewing direction.

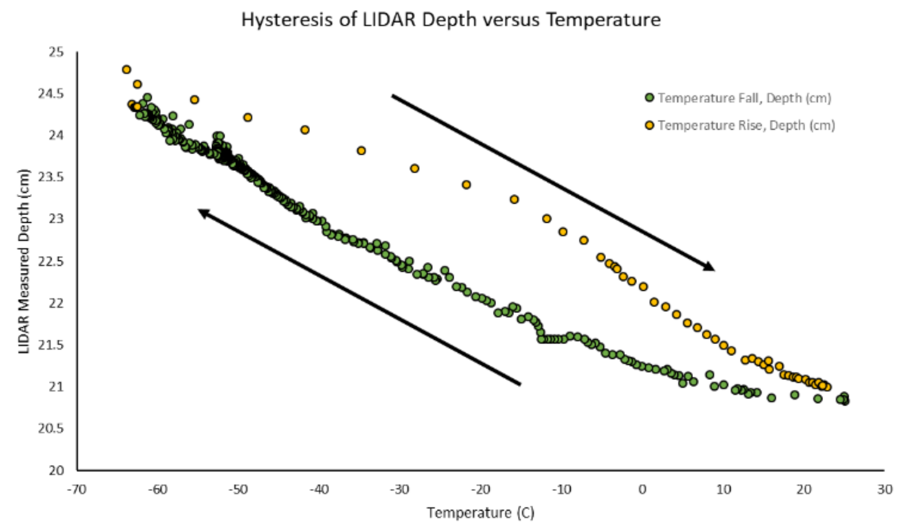


Figure 15: Hysteresis of LIDAR due to temperature variation. As the temperature dropped, the LIDAR detected the reference plane as moving further away even though no physical objects moved. As the temperature was returned to ambient, the LIDAR returned to its nominal measurement. Note that the temperature drop was far slower (over one day) than the temperature rise (only a few hours). This memory effect, dependent on the temperature change and rate of change makes it more difficult to compensate for thermal based depth measurements.

8. SUMMARY

The CITADEL testbed enables future studies on surface interactions of sampling systems for mission to icy bodies. Surface interaction dynamics, reaction load sensing, and partial or end-to-end system validation can all be performed within the CITADEL chamber. At this time of writing, the chamber has completed initial commissioning and is ready to begin conducting investigations for the Europa Lander mission concept sampling subsystem.

ACKNOWLEDGEMENTS

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