Development of a Lander Autonomy Testbed for Ocean Worlds Missions

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ABSTRACT

NASA is developing platforms for evaluating autonomy technologies for lander-based robotic sampling missions to *Ocean Worlds*. As missions operate further from Earth under significant resource constraints and environmental uncertainty, autonomous technologies will have to play a greater role in their success. Significant advances have been made at academic, other government and industry research laboratories in recent years that could be leveraged for Ocean Worlds lander missions. Our goal is to facilitate the application of these technologies for NASA missions by making available the use of a testbed to physically emulate the operation of lander with a sampling tool in a low-gravity environment. The testbed comprises a lander, an instrument arm, and perception sensors typically found on lander missions. It will provide the hardware interfaces and low-level software infrastructure to allow commanding typical lander operations through a well-defined software interface. The testbed will model the environmental conditions and dynamic behavior of the lander on Ocean Worlds. It will also incorporate independent monitoring and data logging capabilities to evaluate the performance of the autonomy technologies.

INTRODUCTION

The term *Ocean Worlds* has been used to categorize bodies in our Solar System that have large quantities of water. Recent discoveries of liquid water below icy crusts [Porco et al, 2006; Kivelson et al, 2000] on satellites of planets in the outer Solar System has sparked interest in pursuing space missions to explore them. Two bodies in particular, Europa, a satellite of Jupiter, and Enceladus, a satellite of Saturn, are prominent among these [Frank et al, 2000] because 1) they have large subsurface oceans, 2) they have rocky cores in contact with the oceans that would provide salts and other chemicals needed for life, 3) they have energy fed into the oceans either from hydrothermal sources in the mantle or tidal activity, and 4) stable environments that could promote production of complex molecules and potentially life.

An orbiting mission to Europa, the Europa Clipper mission, is already under development and is expected to launch in the mid-2020s. Its cameras and spectrometers will image Europa's surface and its ice penetrating radar will map the icy crust. The mission to follow Europa Clipper is expected to be a lander to perform science operations on the surface [Hand et al, 2017]. Lander missions typically have instruments to collect and process in-situ samples in addition and sensors to monitor

the environment. One challenge in operating such a mission is the very long signal transmission times between these bodies and Earth. For Europa, the round-trip communication time will be up 1.5 hours. In addition, the extreme thermal and radiation environment and limited lander mass, the primary-battery supplied energy limits the mission duration to about 20 days. Consequently, on-board autonomy will be needed to handle many of the functions on the spacecraft.

NASA has set up the Applied Information Systems Research: Autonomous Robotics Research for Ocean Worlds (AIRS:ARROW) program to encourage and facilitate the adaptation of autonomy technologies for future missions to Ocean Worlds. The goal of the program is to develop autonomy technologies that would significantly increase the robustness and productivity for never-before-visited destinations, whose surface conditions and phenomena may be largely, or completely, unknown a priori at the time of landing at locations so remote as to require reacting to events without intervention from Earth. Two testbeds, a virtual software simulation testbed and a physical hardware testbed have been developed at the NASA Ames Research Center (ARC) and the Jet Propulsion Laboratory (JPL) respectively to test and evaluate candidate autonomy technologies. This paper describes the physical testbed, the Ocean Worlds Lander Autonomy Testbed (OWLAT), developed at JPL for the program.

LANDER-MANIPULATOR TESTBED

OWLAT, under development at JPL, will replicate the primary robotics components of a spacecraft lander system. This includes the lander platform itself, a manipulator capable of reaching and performing manipulation operations on surface materials, and a perception system. The primary components in the testbed are shown on Figure 1.

The approach we have taken in the development of OWLAT has been to:

- Use commercial off-the-shelf (COTS) component systems where available to meet the financial and development schedule constraints for this effort
- Add COTS sensors to have a highly instrumented testbed
- Build on prior software capabilities developed at JPL for operating OWLAT. This includes leveraging prior development of the CLARAty [Nesnas, 2005] and F Prime [Bocchino, 2018] software systems.
- Use a high-fidelity dynamics hardware-in-the-loop simulator [Jain, 2019] to assist in software development and set-up the control software to seamlessly switch between simulator and physical system
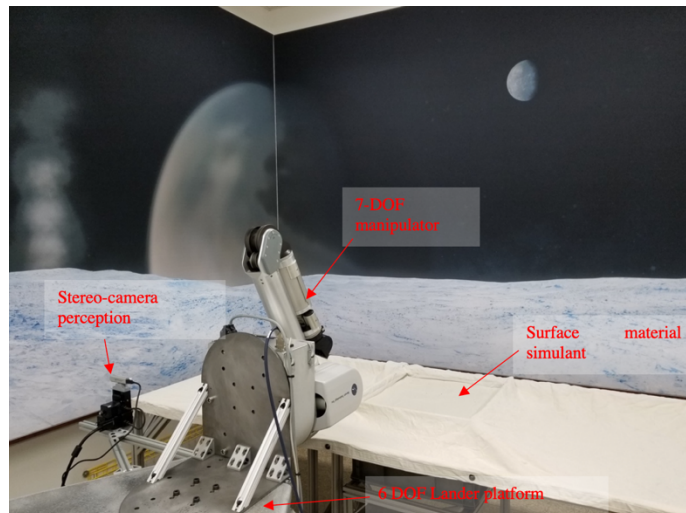
Figure 1 Testbed setup and major components.

- Use advanced robotics control algorithms to emulate dynamic behavior of lander systems on other bodies

- Use modular and interchangeable tools for a variety of science operations

Standard high-speed interface hardware and protocols are used to connect the primary components and an integrated software architecture drives the system. OWLAT has some unique capabilities that are reported in the following sub-sections.

Hardware

Lander Platform

The lander represents the base of the spacecraft that rests on the surface after touching down at the end of the landing sequence. Instruments, sampling systems, power systems,

Figure 2 E2M Technologies six DOF Stewart Platform representing spacecraft lander.

avionics, communication antennas, and all other spacecraft components are generally installed within or on the lander. One additional consideration for missions to Ocean World bodies was derived from the potentially very low gravity fields. Europa's gravity field strength at its surface is 1/8th that of Earth. On Enceladus, it is 1/100th of Earth. In these gravity fields, the lander has the potential to move in response to dynamic loads from the relative motion of components as well as from the interaction of sampling systems with the surface. The lander component in OWLAT was therefore chosen to be a 6 DOF Stewart platform that could be controlled to move to emulate the behavior of the lander on low-gravity environments. The COTS system selected was the E2M Technologies EM6-300-1500, shown on Figure 2, because it met the range of motion and load bearing needs for our application.

Manipulator Arm

The robot arm on the lander deploys instruments, performs manipulation operations and sampling procedures. To approximately emulate the lander arm on the Europa Lander mission [Hand, et al., 2017], the arm needs to have a reach of about 1 meter. We also required a dexterous arm to apply up to 10 N of force on the surface and have positioning accuracy of about 1 cm in order to perform sampling operations with tools and instruments attached to its end effector. In order to implement advanced control techniques on the arm to shape its dynamic behavior, we desired high fidelity torque sensing and control of the arm joints. Unfortunately, we were not able to find a COTS arm with all these features. A satisfactory compromise that met many of our

requirements was the 7 DOF Barrett WAM system. The arm was mounted to the lander platform as shown on Figure 3.
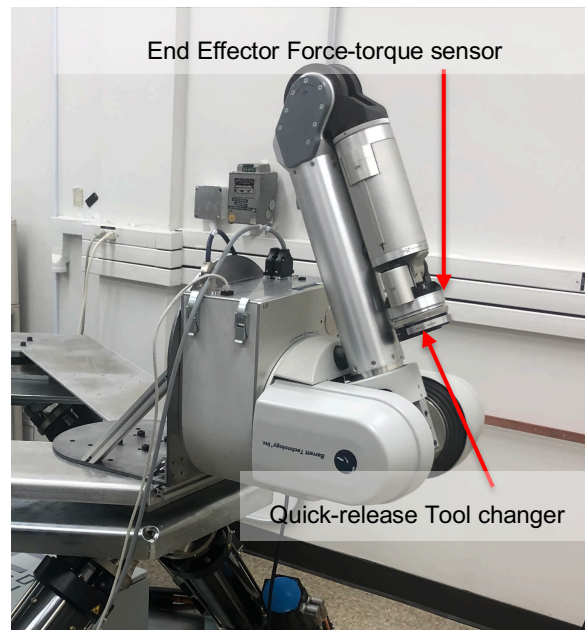
Sensors

The perception system consists of a COTS stereo-camera mounted on a pan and tilt unit that is attached to the lander. We use the Intel RealSense D415 camera. With a 65° field of view, 90 frames per second, an image resolution of 0.8 mega-pixel with a range from 0.44 meters to 10 meters proved adequate for our application. OWLAT makes extensive use of six-axis force-torque sensors (FTS) to implement its advanced capabilities for emulating dynamic behavior of the lander on other planetary bodies. The manipulator has an integrated six-axis FTS on its tool/instrument interface (see Figure 3) that is used to detect and measure manipulator interaction with the environment. In addition, three six-axis FTS are sandwiched between the top plate of the Stewart platform and a

End Effector Force-torque sensor

Quick-release Tool changer

Figure 3 Barrett WAM seven DOF manipulator arm mounted to lander with wrist FTS and tool changer.

Three 6-axis Force Torque sensors sandwiched between Stewart Platform and Interface Plate

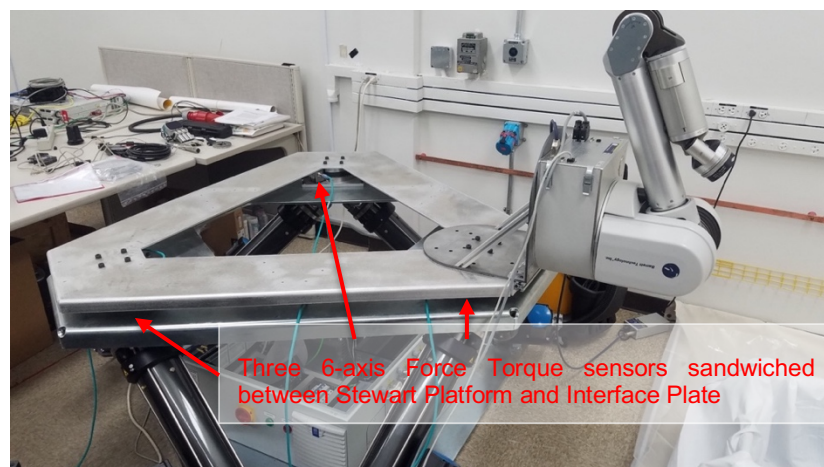*Figure 4 Three base FTS for measuring loads on lander.*

mounting interface plate on the lander as illustrated on Figure 4. They are configured to be used in combination to measure forces and torques on the lander.

Instruments

Several tools for performing geotechnical measurements and for sampling operations have been developed for use with the testbed. The suite of tools includes probes, a scoop and a drill. A COTS quick-release interface plate was adapted to mount on the manipulator end-effector to allow rapid manual change of tools on the robot. The probes developed include a pressure-sinkage plate, a shear ring and a cone penetrometer, commonly used instruments to measure soil strength and other geotechnical properties [Wong, 1980; Golob, 1981]. By pushing the plate into the

ground at a controlled rate and measuring the resultant forces, pressure-sinkage curves can be generated. This is useful information for determining terrain characteristics such as the bearing capacity of the ground. When pressing the shear bevameter against the ground and applying a torque until the material fails, the resultant torque can be used for

Figure 5 Modular instruments to be mounted on robot arm.

determining the shear strength of the material. A cone penetrometer with interchangeable cones of varying sizes was designed for determining bearing capacity as well as describing ground stratigraphy. A scooping device was designed for use as a sample manipulation tool to scrape, capture and transfer material for loose granular material on the ground. For sampling harder materials, a drill was designed with the capability of capturing swarf in a chamber and transferring it to a sample processing system. The tool interface and tools are shown on Figure 5.

Simulated Environment

Simulants at room-temperature are used to represent material anticipated to be found on the ground on Ocean World bodies. The simulants are used with the testbed for physically simulating interaction with the ground. In addition to having the appropriate material properties at room temperature and pressure (to circumvent the need to simulate surface temperature and pressures on these bodies – 100K and vacuum respectively), additional requirements on the materials chosen included being safe to work with and minimizing generation of dust and debris. We use two types of simulants: 1) white quartz sand to represent loose granulated ice that is expected to be on the surface of Enceladus [Schenk, 2018], and 2) highly porous concrete to represent fused ice that is expected to be found on the surface of Europa [Pappalardo, 2009].

Bins to contain the simulants were incorporated with white fabric to present a natural view of the surface to the perception system. An additional requirement was to have the "surface" be easily moved to allow access to the lander and arm for maintenance and upgrades. A collapsible structure, with the fabric draped over it with cutouts for the simulants, shown on Figure 1, was designed and was found to adequately meet these requirements.

Computing Hardware and Software

The computing architecture design for OWLAT is distributed between two computers as shown on Figure 6. Interfaces to the hardware components are at the bottom of the figure. A hardware-in-the-loop (HITL) simulator based on the DARTS physics engine [Jain, 2019] has also been implemented and is available as an alternative to the physical
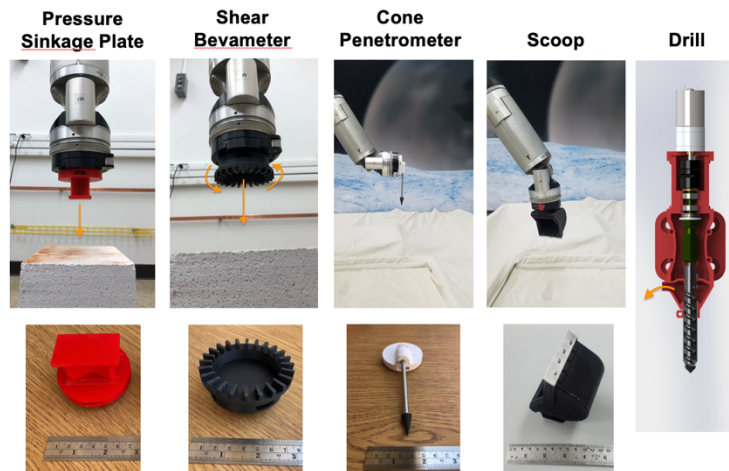
hardware. A software switch allows swapping between the hardware and the HITL simulator. This capability allowed development and testing of the control software while ensuring safety of the system. The real-time control software built on the reusable CLARAty package is implemented on an Intel NUC computer. The autonomy software, currently emulated with a browser-based operator interface, is implemented on a workstation and communicates with the embedded software through a ROS channel.

In parallel with the control and operations software packages, a safety and performance monitoring and evaluation software system, shown in the red boxes at both the workstation and the embedded
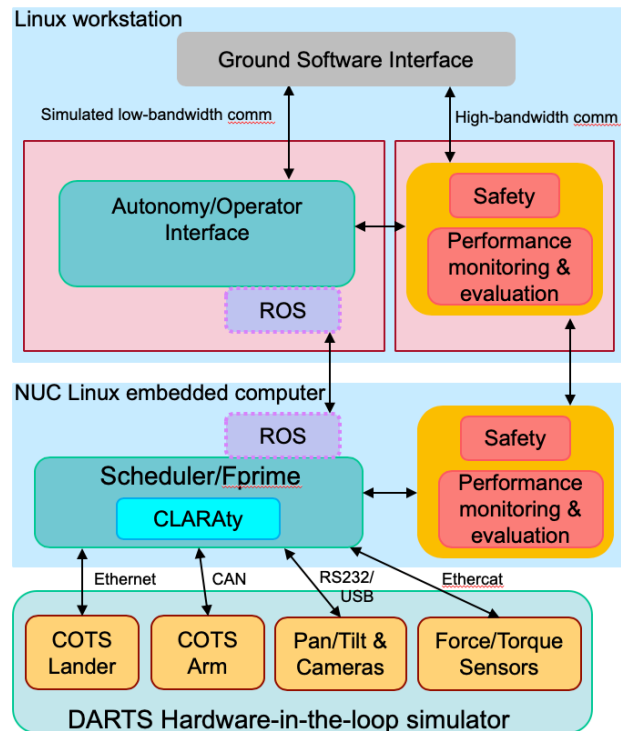

Figure 6 Computing and software architecture.

computer levels on Figure 7, will be implemented. The intended use-case of inviting external teams to deploy their autonomy software within this framework will require us take precautions to observe and place bounds on the autonomy software to prevent inadvertent damage of the testbed. In addition, when comparing autonomy packages, it will be useful to provide metrics on performance that may be used to evaluate and quantify alternative approaches. The design of this component of the software system is still in development.

Control System

A control scheme for the lander-manipulator, shown on Figure 7, was designed to exhibit some advanced behaviors typically not available in an Earth-bound testbed. The primary goal was to have the testbed respond to external interaction as a lander would in the environment of an Ocean World body. The generally low gravity fields on the surface of Ocean World bodies implies loads imparted to the lander could result in motion of the spacecraft. The autonomy software operating on the spacecraft needs to be robust to this possibility and it was felt that mimicking this behavior would be an important test for the autonomy.

Operator/Autonomy Interface

For our development and testing purposes, an operator interface was designed and implemented as a stand-in for the autonomy software. We used the Babylon.js 3D Web-GL engine to build the browser-based interface. A screenshot of the screen is shown on Figure 8. The interface displays the 3D point cloud of the surface scene in a window and allows the user to manipulate the viewpoint and select a point on the surface. To illustrate the use of this interface with the operator performing the function
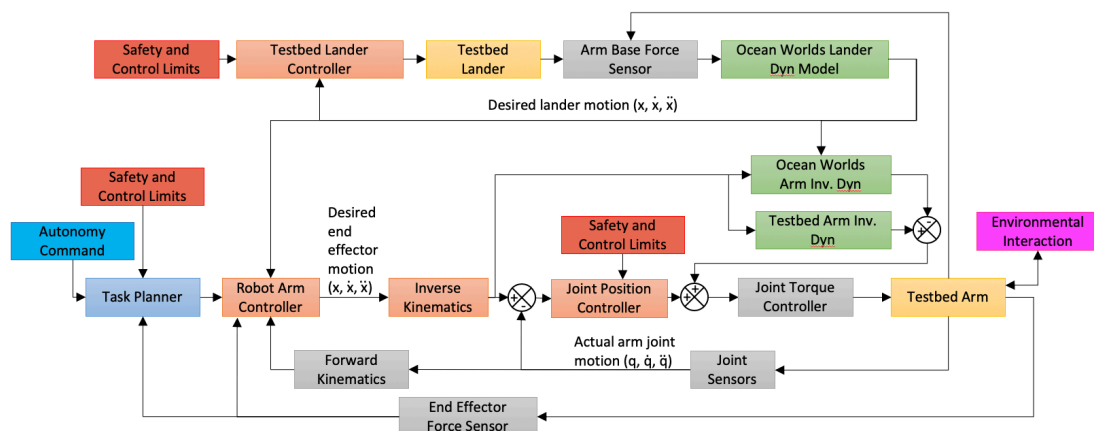
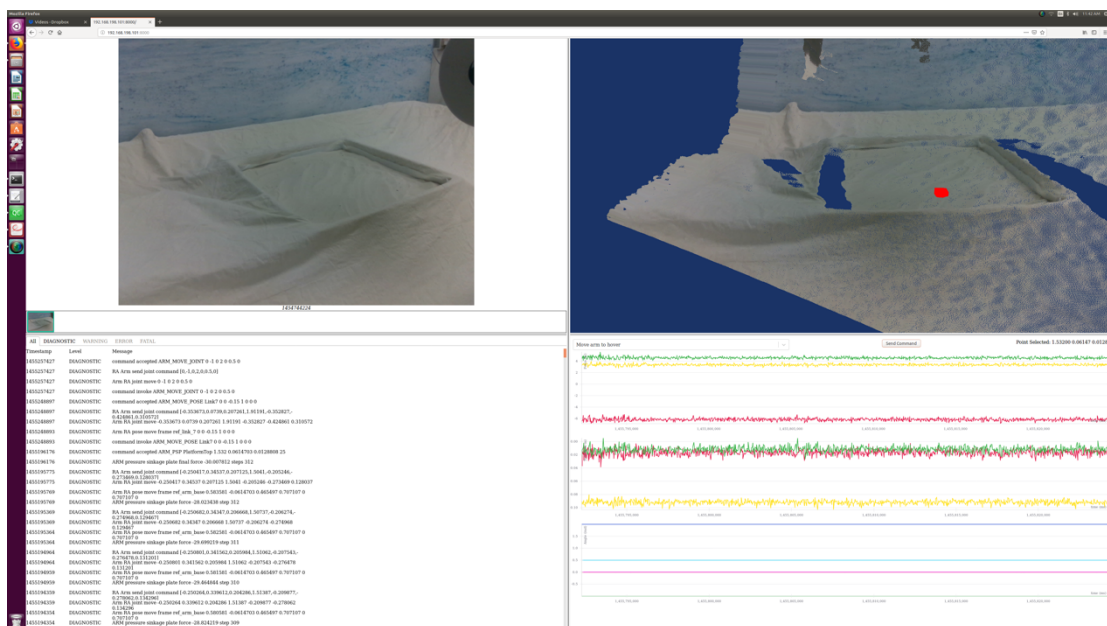*Figure 7 Control diagram for emulation of Ocean World body dynamics within testbed.*

Figure 8 Operator interface used as a stand-in for the autonomy software.

of the autonomy software, the selected point is sent as a command to the embedded control software to perform a manipulation operation at the selected point.

Dynamic Simulator

The HITL simulator was build using the DARTS software [Jain, 2019], developed at JPL and used on numerous research and flight projects over the last two decades. A dynamic model of all the physical components of OWLAT are implemented in the HITL simulator. In addition, the
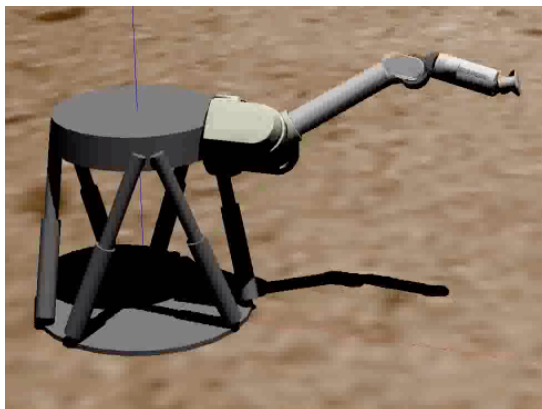

Figure 9 Screenshot of HITL simulator of lander and manipulator.

simulator was also configured to provide sensor measurements as would be obtained from the physical system. This includes FTS readings and camera images that may be then processed through the control algorithms or the stereo-image processing pipeline. The initial rationale for the use of the HITL simulator was to aid in the control software development. Development and verification of control algorithms when there is the potential for the algorithm to be not fully tested has the potential to catastrophically damage equipment. As a safety precaution, the control algorithms were developed and tested with the HITL simulator before deployment on the physical hardware. An additional rationale in our use-case for hosting external high-level software packages is to provide a means to ascertain that the external package meets a set of qualification tests before being allowed to access the physical hardware. A screenshot of the HITL simulator model is shown on Figure 9.

TESTBED OPERATIONS

There are currently five manipulation operations possible with the OWLAT system. They are 1) pressure sinkage test, 2) shear test, 3) cone penetrometer test, 4) scooping operation, and 5) drilling operation. The first three are geotechnical science operations to measure surface material properties. The last two are sample collection operations. A unique tool and specialized operational sequence is used for each of these operations. Figure 10 shows the execution of scoop and pressure sinkage test manipulation operations.
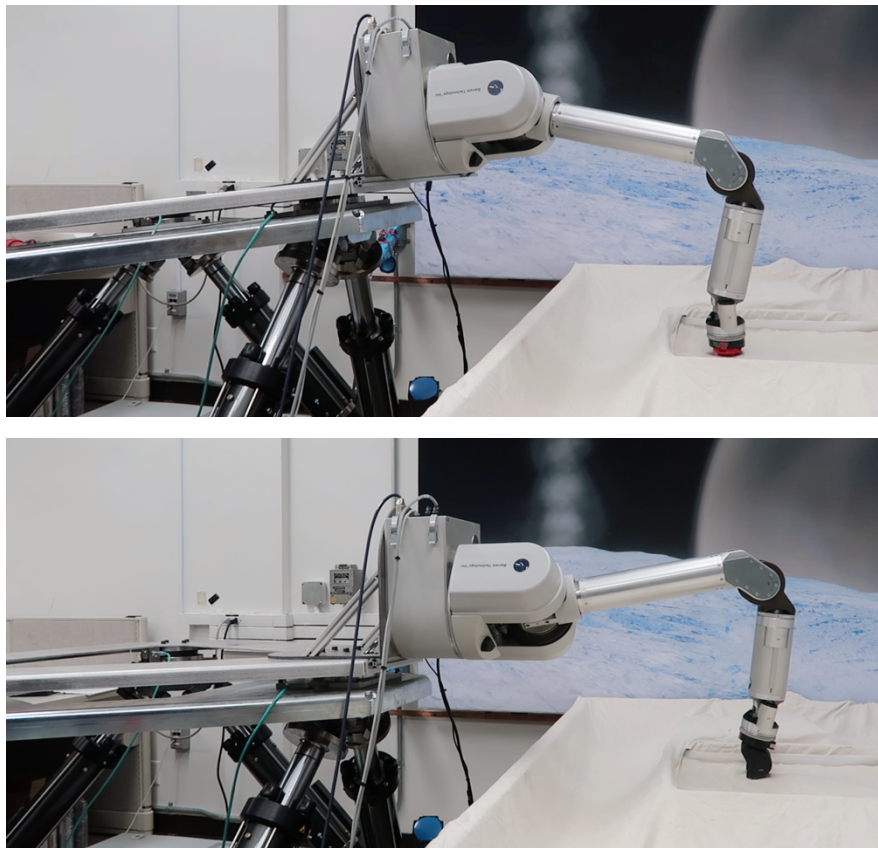
Figure 10 OWLAT performing pressure-sinkage test (top), and scooping operation (bottom).

CONCLUSION

The OWLAT system has been built with capabilities that will enable it to be a platform for evaluating lander autonomy technologies. The advanced control system implemented to emulate spacecraft dynamic behavior on other Ocean World bodies, the built in safeguards, monitoring software and software simulator will provide a realistic Earth-based testbed to provide a rigorous selection of autonomy technologies for future NASA missions. This testbed will be made available to the teams selected in the NASA ROSES ARROW solicitation. We expect to work with awardees to integrate, test and evaluate their autonomy frameworks and hope to facilitate the transition of the technology into future flight missions.

ACKNOWLEDGEMENT

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