A SPHERICAL ROBOT UNDER SIMULATED LUNAR SURFACE CONDITIONS: E. Patrick[1], L. Xie[2], K. Le[3], ([1]Southwest Research Institute®, 6220 Culebra Rd., San Antonio, TX 78238 epatrick@swri.edu), [2]Louis Brandeis High School, San Antonio, TX 78249, [3]Ronald Reagan High School, San Antonio, TX 78258.

Introduction: The discovery of volatiles at the lunar surface has ushered in the era of in situ resource utilization (ISRU)—a concept for "living off the land" on such celestial bodies as the Moon and Mars by making use of local resources for sustained human presence beyond the protective confines of Earth. To make ISRU possible on these worlds, analytical instrumentation is essential during the sensing, discovery, and processing of local resources, and for monitoring outgassing signatures from robots, humans, spacecraft, and processes taking advantage of these precious local resources.

Laboratory space environment simulation (SES) is an essential part of characterizing the performance of prototype lunar instrumentation necessary for monitoring ISRU activities and the native lunar environment, and it must be conducted under analog conditions mimicking those expected during lunar surface operations. Working with unconsolidated materials that simulate planetary surface conditions is an important method used in SES, as is the ability to introduce and control the release of volatiles into the surrounding vacuum system. Combining these two methods would show much promise for the programmed evolution of volatiles from samples by exploiting grain-on-grain interaction.

Two Space Simulation Methods: One previous method used at SwRI for processing gases involved the use of quartz tubing for producing Titan-like "tholin" chemistry. Fittings appropriate for sealing the quartz tube allowed for use of either a closed-end-tube like a test tube, or for using an open tube with vacuum fittings affixed to both sides for additional gas handling or system diagnostics manifolds.

A second method relevant to this project was the discovery that grain-on-grain interactions were a means for producing volatiles[1] from a sample inside the SES system. Using a tiny metal flag, quantities of gas released through this grain-on-grain interaction were greater than could be produced by illumination from outside the chamber, and also faster and easier than methods for heating the sample volume from outside.

An Idea Forms: The next logical step in a method for releasing volatiles inside a vacuum system analogous to what is expected at the lunar surface was to find a means of placing the lunar simulant or lunar sample inside the chamber and then finding a way to disturb that sample. Quartz tubing would not only hold the sample, but would also allow it to be observed from outside. "Tilting" the quartz tube would allow the ball to roll back and forth over the sample to release its native gases. The inside diameter of quartz tubing we used for Titan atmospheric experiments was only 38.1 mm, but we were able to find commercially-available quartz tubing with an inside diameter of 50.8 mm which would allow the use of an object with a diameter equal to that of a golf ball (42.7 mm) and with clearance for the sample.

After a search for numerous spherical objects in this size range that could be "rolled" across simulant in vacuum, a commercial off-the-shelf (COTS) robot was discovered in which one of the models incorporated an outer shell like that of a golf ball and with the same diameter. Such a textured surface would provide better traction in the powdery simulant sample, so several of these were purchased for evaluation purposes in the lab.

Initial Test Plan: Before the robot sphere could be introduced into the vacuum chamber, we had to verify that it could be controlled through the quartz tube. Consequently, a stand was constructed with appropriate hardware both to elevate and capture the quartz tube on both ends, and to permit ease of insertion of the robot. Communication was then established with the robot through Bluetooth® from a smart phone and the robot commanded to roll back and forth from one end of the quartz tube to the other.

After this test, the question was whether or not the robot would survive in vacuum. Certain electronic components such as electrolytic capacitors are known to burst in vacuum and consumer electronic products are not manufactured with a view toward operations in anything resembling a space environment. For this reason, we had no expectation that the COTS robot would survive in vacuum, but it would at least make for an interesting test.

A vacuum system was assembled and attached to the quartz tube using a diaphragm pump to pull a "rough" vacuum into possibly a few tens of Torr and monitored with a convection-enhanced Pirani gauge. Because the expectations for successful operation were low, the system was assembled from spare parts using only the essential components required for testing. The exception was the additional plumbing in KF50 vacuum flange format to accommodate the much larger diameter quartz tube. The tube was supported at the end opposite the vacuum manifold with a KF50 compression fitting and a KF50 blank flange. Though awkward and difficult to tighten, the KF50 blank flange acted as a loadlock for insertion and removal of the robot.

1st Test: Rough Vacuum: The robot was tested repeatedly inside the quartz tube at atmospheric pressure prior to evacuation by communicating to it, observing operation of its LEDs, and then commanding it to move end-to-end inside the quartz tube. Though there was no expectation that the robot with commercial electronics should survive vacuum, we at least verified that operation was nominal prior to the test and the robot was communicating through the walls of the quartz tube.

For evacuation, the diaphragm pump was started with the isolation valve in the closed position. Once ready for evacuation, command of the robot was initiated and the valve slowly turned, but using an inexpensive KF isolation valve in place of a precision leak valve meant that it was difficult to control its opening. As a result, when the valve opened, the pressure plummeted from the 760 Torr of atmospheric pressure to around 100 Torr, but the robot continued to operate and roll end-to-end inside the quartz tube. Once fully opened, the diaphragm pump was able to achieve a base pressure of 3.8 Torr, or about half the surface pressure of Mars (99.5% vacuum).

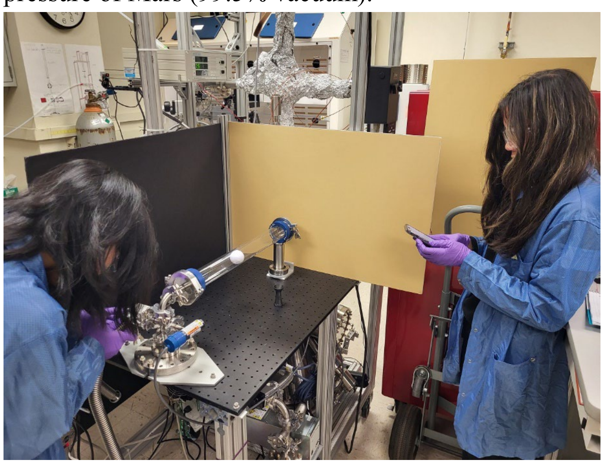

Figure 1. Student Lucy Xie (left) makes her vacuum connection to the diaphragm pump while Kathy Le (right) tests her phone's Bluetooth® connection to the COTS spherical robot.

In this first vacuum test, the robot continued to operate until a final roll in which it struck the KF50 blank flange at the end of the tube and the outer shell of the robot broke in two. Though it could no longer propel itself, communication continued with the robot as its LEDs remained illuminated and it could be felt vibrating inside the tube.

2nd Test: Longevity in Vacuum: The robot's operation in vacuum was a surprising success, and immediately forced the necessity of further experiments. At 99.5% vacuum, there was no reason to believe that it would not survive vacuum conditions at the surface of Mars or the Moon, but it would be necessary to determine its ability to operate longer term. Consequently, another vacuum system was assembled with better components and a better location in the lab permitting easier access and photography.

No new vacuum pumps were used in the assembly of this second test system, so several turbomolecular pumps were tested before one was found that was ideal for adding to the new system's capability. Once the "roughing" pump—a 2-stage diaphragm pump—had achieved rough vacuum, then the turbopump could be started in order to bring the system to high vacuum.

In the second test of the robot, the quartz tube system once again achieved a base pressure of approximately half that (3.7 Torr) of the Martian surface. The robot was operated and rolled back and forth inside the tube and kept in the middle of the tube for the balance of the day. Every day for one week, the robot was activated and tested successfully and returned to the center of the quartz tube.

3rd Test: Hard Vacuum: After one week (168 hours) under rough vacuum, the robot was still operational and without recharging. To test its operation at even higher vacuum, we started the turbopump and further reduced the background pressure to 9 mTorr, or about 10 ppm of sea level atmospheric pressure. After several hours of this high vacuum test, the system was brought back to atmospheric pressure and the robot removed for photographing and recharging.

The Path Forward: Future tests will include:

1. incorporation of a mass spectrometer to monitor outgassing from the COTS robot,
2. tests of various "shells" to improve propulsion over simulant samples, and
3. monitoring of gases evolving from the sample as it is disturbed.

Co-authors of this work, Kathy Le and Lucy Xie (Fig.1), were students in the Southwest Research Institute® 2022 Young Engineers and Scientists (YES) summer program and subsequently requested a mentor for independent study during their senior year in high school. Along with further testing of the spherical robot as part of their independent studies, they are also currently fabricating components for the assembly of a prototype ion gauge for lunar surface operations.

References: [1] Patrick et al. (2015) *Icarus* 255

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