Ground tests with Luna – 25 robotic arm in lunar like environment

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Abstract

In July 2022 Roscosmos plan to launch first near polar lunar mission Luna – 25. It will land at north of the crater Boguslavsky with coordinates of 43.544 degrees east longitude and 69.545 degrees south latitude. It is expected that lander will operate at least one year on lunar surface and will study lunar environment and properties of near polar lunar regolith including search for subsurface water ice. Luna – 25 is equipped with a multifunctional robotic arm designed to perform excavation (25 cm depth) and sample acquisition of lunar regolith. In this study we have presented results of ground tests conducted with robotic arm in lunar like conditions with frozen analog of lunar regolith doped with different concentration of water ice.

Introduction

Today, the lunar exploration moves to the lunar polar regions and permanently shadow regions (PSRs). PSRs do not see any direct sun light and exhibit a very low temperatures (<120 K) acting as cold traps accumulating volatiles delivered to the Moon by comets and asteroids. Therefore, they are considered as storehouse preserving relict records of the Solar system evolution gathered for the billions of years [see for example 1].

It is also discussed that water ice could be distributed outside PSRs at the partially sunlit polar and near polar areas where water ice layers could be preserved at some depth buried by dry regoilth. [see for example, 2]

It is widely discussed that Moon will be next permanent destination for human expansion outside Earth orbit. Thus, potentially water ice rich areas could be considered as a promising locations where future lunar bases could be built. The long-term presence and survival of astronauts on the Moon surface strongly depends on in-situ resource utilization (ISRU). Water ice is proposed as most significant resource because it could be used as water for various astronauts' needs. Its constituents oxygen and hydrogen will be used for breathing and for the rocket fuel production correspondingly.

Now many countries are developing own lunar programs and road maps and it is commonly accepted that the first step on this route should be done with robotic landing missions (landers and exploration rovers) to investigate polar lunar regolith and ambient environment at lunar poles. It is declared that search of surface or ground water ice, understanding its local distribution, origin and its accessibility for ISRU is considered as one of primary tasks proposed for these robotic missions.

Russia is also developing its own long term lunar program. Its implementation also starts from the robotic missions: Luna -25 , Luna – 26 and Luna -27 [3]. The first near polar landing mission Luna - 25 is already entered into the phase of assembling, testing and launch operations. Its launch is scheduled in July 2022 [3]. The landing site was selected in the southern hemisphere at the area located north of the crater Boguslavsky with coordinates of 43.544 degrees east longitude and 69.545 degrees south latitude [4]. Luna – 25 primary science goal is to study mineralogical, chemical, and isotopic composition of the lunar regolith, as well as search for volatile compounds (including water ice) in the top regolith layer at the high-latitude regions of the Moon [3]. To implement this goal Luna - 25 lander is equipped with gamma-ray and neutron spectrometer, laser ionization mass spectrometer, IR spectrometer, dust analyzer, ions and neutral particles spectrometer. To perform contact operations with lunar regolith it was developed a light and compact, but at the same time multifunctional robotic arm. It will be the second case (after sample return Chinese Chang’e-5 mission, successfully completed in 2020, see [5]) when robotic arm is being used for the excavation and sample acquisition of lunar regolith. In contrast with Chang’e-5 Luna – 25 will operate on lunar surface for at least one Earth year assuming multiple and long-term robotic arm operations.

In this study we presented a brief overview of the ground-based functional tests that have been conducted with the robotic arm to verify that all requirements were met, including requirements directly related with interaction with lunar regolith. For this purpose we conducted tests with analog of lunar regolith enriched with water ice under a low pressure and cryogenic temperatures. In other words we present results of test showing how robotic arm behave itself in lunar like conditions.

Luna – 25 robotic arm

The total mass of the robotic arm is less than 5.5 kg, maximum length is about 1.6 m, and it is capable to excavate lunar regolith to a depth of 25 cm. It has four actuators (azimuthal, shoulder, elbow, and wrist) to make it flexible for the navigation and excavation. It is also supplied with a sample acquisition unit to collect lunar probes (several cm^3), [6].

Robotic arm shall collect samples of lunar regolith (from the different depths each ~ 1cm) excavated from the different locations at the area around spacecraft and deliver them to the laser ionization mass spectrometer (LAZMA) for the elemental and isotope analysis [7], see Figure 1. To support contact operations and remotely to study lunar regolith a near IR spectrometer and stereo camera (LIS-TVRPM) is integrated on the robotic arm (Figure 1). It could be used to map IR spectrum of lunar surface in vicinity of spacecraft and to study excavated soil tails. The additional pair of stationary stereo cameras (STS-L) is also installed at the upper part of the lander to navigate and monitor robotic arm operations. It could provide a panoramic photo of the robotic arm working zone in front of the lander to select most interesting locations for the excavation and sample collection (see Figure 1). Since coordinate systems of STS-L and robotic arm were linked to each other during ground tests it is possible to navigate robotic arm for the excavation and sample acquisition from any local spot with the accuracy less than 1 cm [6]. All instrumentation involved in the contact operations with lunar soil is shown on the Figure 1(left). The working zone where robotic arm could excavate regolith and collect its samples is shown by grey color on Figure 1 (right).

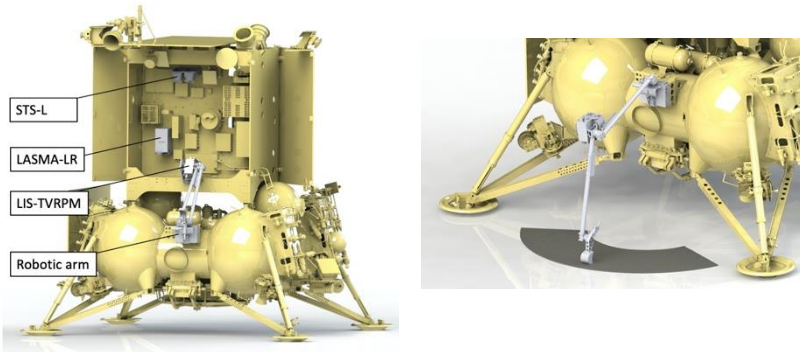

Figure 1. The 3-D view of Luna – 25 lander with the indication of science instrumentation involved in the contact operations with lunar regolith (LEFT). The illustration of robotic arm operations with the indication of available robotic arm working zone (RIGHT).

Ground experiment with analog of lunar regolith:

To conduct ground tests in lunar like conditions, a special cryogenic vacuum chamber was developed in Space Research Institute, Russia (provider of robotic arm for Luna – 25). This chamber (see Figure 2) allows

1) To allocate engineering model of robotic arm, as well as a container (up to 200 kg) with an analog of lunar regolith inside a chamber.
2) To keep pressure during operations with analog of lunar regolith as low as (~10^{-2} Torr.
3) To imitate space environment around robotic arm (nitrogen shroud with temperature of -190^{o}C)
4) To freeze analog of lunar regolith to temperatures -150^{o}C to imitate temperatures expected at the Luna – 25 landing site.

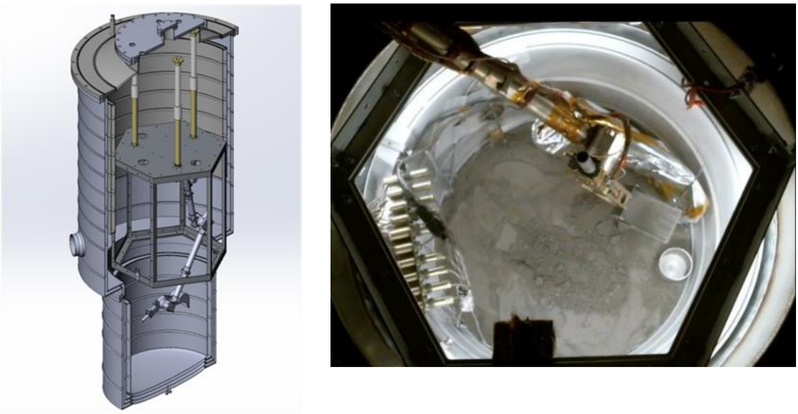

Figure 2. The concept of cryogenic vacuum chamber used for the robotic arm tests (LEFT). The photo of robotic arm operations in cryogenic vacuum chamber: excavation, sample acquisition and delivery to the special container (RIGHT).

Analog of lunar regolith for these tests was specially developed at Vernadsky institute, Russia. It imitates main physical and mechanical properties of lunar regolith including density, porosity, size distribution of lunar grains, their morphology, values of shear stress and internal friction angle [8].

During ground experiment a dry analog of lunar regolith was homogeneously mixed with the different content of water ranged from 0.05% up to 1.5% by weight. It was done because at the cryogenic temperatures the mechanical strength of lunar regolith significantly depends on the presence of water ice in the regolith pores. As a result, the strength of icy regolith could increase by several times even for a small concertation of water ice and as result significantly impact robotic arm excavation capabilities. The orbital observations demonstrate that average concentration of water ice at the Luna – 25 landing site could be estimated as ~0.1%. Such estimation is derived assuming that water ice is heterogeneously distributed with a depth. In lunar conditions at the Luna – 25 landing site water ice cannot survive on the surface but it could be preserved at some depth. The numerical simulations are showing that we may assume up to ~1% of subsurface water ice [9]. Therefore, the Luna – 25 robotic arm has a chance to meet with a buried icy layer (~1% of water ice) during excavation and sample acquisition of lunar regolith. It was decided to take it into account in ground test program of robotic arm and verify their capabilities to excavate lunar soil mixed with a tiny concentration of water ice.

To implement this task, we conducted several ground tests with increasing concentration of water ice in the analog of lunar regolith frozen to the temperatures -100C at the robotic arm's excavation zone. This temperature value was selected because orbital observations show that it is probable temperature that could occur at shallow depth of Luna – 25 landing site.

For each test with fixed concentration of water ice in the analog of lunar regolith we tested excavation of trench and sample acquisition. It was observed that while concertation of water ice does not exceed 0.5% the excavation of frozen analog of lunar soil was performed smoothly without any significant influence on robotic arm. At larger concentrations the frozen soil starts to form clumps and agglomerates indicating increased strength of analog of lunar regolith cemented by water ice in regolith pores.

During tests we continuously measured the torques on robotic arm actuators and analyzed how they were increased with elevated concertation of water ice. At the water ice concentration of 1-1.5% the torque of wrist (scoop) actuator approached to the maximal allowed value. It leads to the situation that robotic arm during excavation process stuck in the analog of lunar regolith and it was necessary to retrieve it to the initial position and repeat excavation again several times. It means that strength of lunar reogolith is dramatically increased (in comparison with a dry regolith) even if it contains a small concentrations of water ice. That is why any future excavation devices shall be ready for that.

Concluding, one can say that experimentally it was found that Luna – 25 robotic arm actuators are sufficiently powerful enough to excavate frozen soil and take sufficient sample volume (it was repeated several times to check if collected volume exceeds LAZMA requirements) if water ice content $\leq$1.5% by mass fraction. It corresponds with Luna - 25 requirements and has some margin to successfully work with polar lunar regolith in next future missions.

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