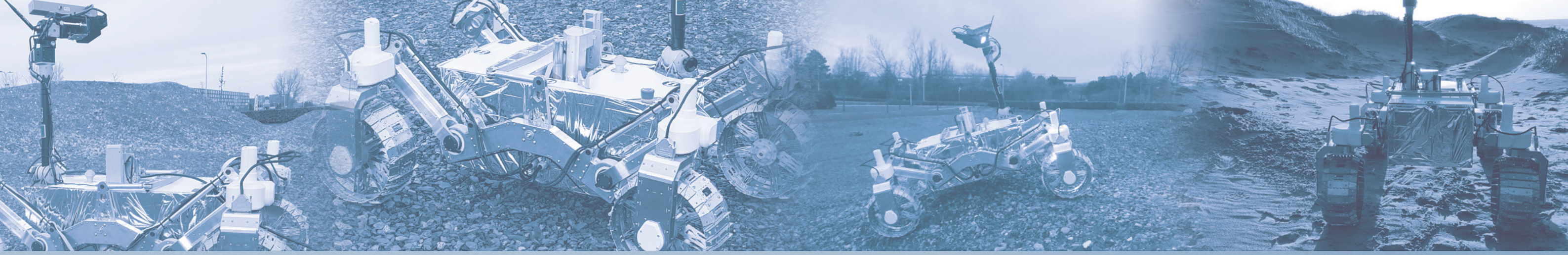

Prototype Moon Rover tested in Noordwijk

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In December 2018 a team of European space companies and universities came to Noordwijk to test a new, compact prototype Moon rover equipped with a suite of instruments aimed at measuring lunar volatiles, such as water, hydrogen and methane. The trials marked the end of a first development phase, the results of which are now being used in a follow-on activity.

The project named LUVMI, for 'Lunar Volatiles Mobile Instrumentation', is an undertaking of a consortium of Belgian, German, and British space companies and universities, and is co-funded by the European Commission's Horizon 2020 programme. The consortium leader, Space Applications Services NV, a Belgian SME, has offices in Noordwijk just opposite of ESTEC, and the 'Mars yard' terrain of neighbour DECOS BV, as well as the sandy dunes at the beach, offered the perfect location for various outdoor trials.

Background and Motivation

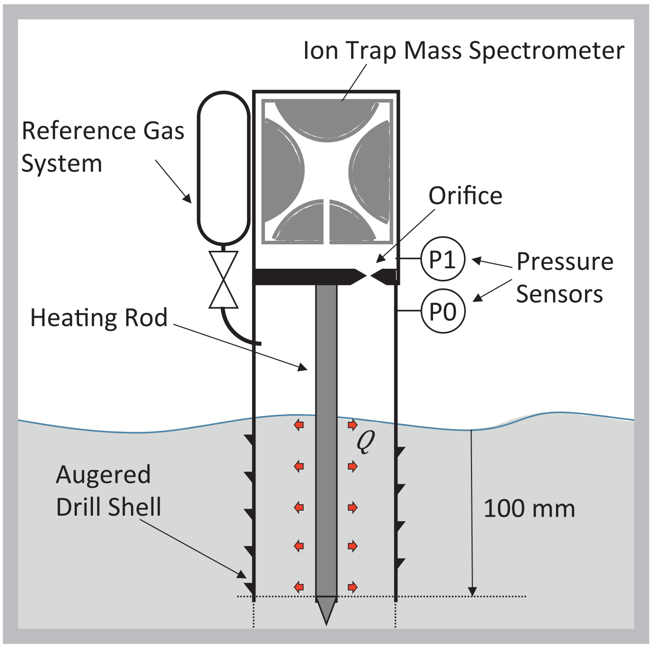
One of the currently most debated questions in lunar science is the amount of water and other volatiles in the lunar regolith. This is of particular interest due to their possible utilisation as an in-situ resource for future exploration missions, and because of wide-ranging implications for solar system science. Lunar volatiles have been theorised to exist in frozen form in Permanently Shadowed Regions (PSRs) and in chemically or physically bound states inside surface particles. Various remote sensing missions were conducted in lunar orbit in recent decades and provided encouraging results. Bistatic radar observations, infrared spectroscopy measurements and neutron-spectroscopy data from Clementine, Lunar Prospector, Cassini, Deep Impact, Chandrayaan-1 and the Lunar Reconnaissance Orbiter missions suggest the existence of water on the Moon, with diurnal changes in the signal and increased concentrations towards higher latitudes. This data is complemented by the results of the LCROSS (Lunar Crater Observation and Sensing Satellite) impactor mission, which indicated 5.6 +/- 3% water in the ejecta plume of the Cabeus crater. However, only a surface mission can provide ground truth data and investigate the actual state and distribution of lunar volatiles on the surface.

Previous surface missions to the Moon or Mars have mostly been either very large and costly, with complex drill and sample handling mechanisms, or very small with rather limited scientific capabilities. The LUVMI project and its follow-on LUVMI-X is attempting to find a solution in between that can provide almost as much scientific output as a large platform, yet is sufficiently compact and lightweight to be carried to the Moon as a secondary, 'piggyback' payload rather than needing its own dedicated mission. This can be achieved by the combination of an autonomous, 4-wheel rover with active suspension and an innovative instrument package.

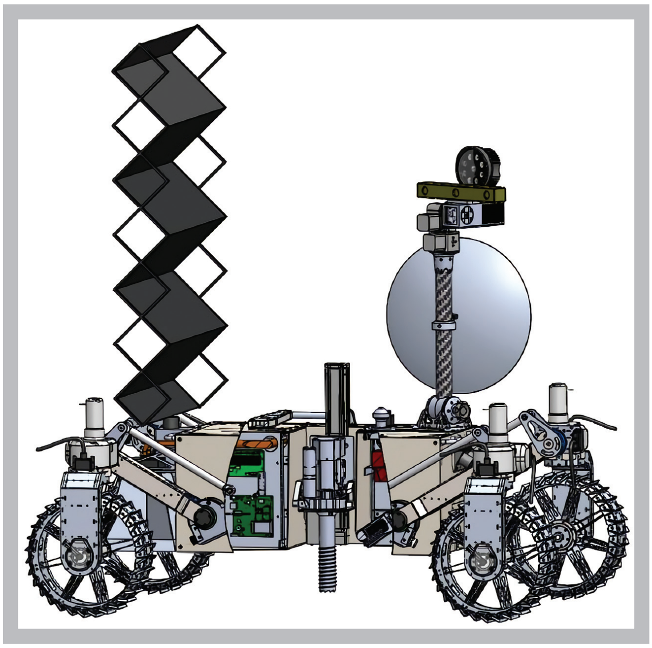
Lunar instrument package

The scientific payload consists of a combined Volatiles Sampler (VS) and Volatiles Analyser (VA), which enables drilling into the lunar soil and direct sensing of volatile constituents without complex (and therefore fault prone) sample handling or transfer mechanisms. The sampler is a joint development of the Technical University München and OHB System (Germany). It uses the core drill principle, as applied in terrestrial geology, to obtain cylindrical core soil samples, and combines that with a central heater element. After inserting the hollow auger drill up to 20 cm into the ground, the enclosed sample is heated to release volatile components. The released gas is led to a quadrupole ion trap mass spectrometer, developed by the Open University (UK), which allows measurement of a wide range of ion species (mass range of m/z from 10 to 200) with a parts-per-million sensitivity. This would enable the detection of all volatiles species that were identified in the LCROSS ejecta plume. A similar type of spectrometer was flown on the Rosetta mission's Philae lander, which measured the organic composition of the nucleus material of comet 67P/ Churyumov-Gerasimenko.

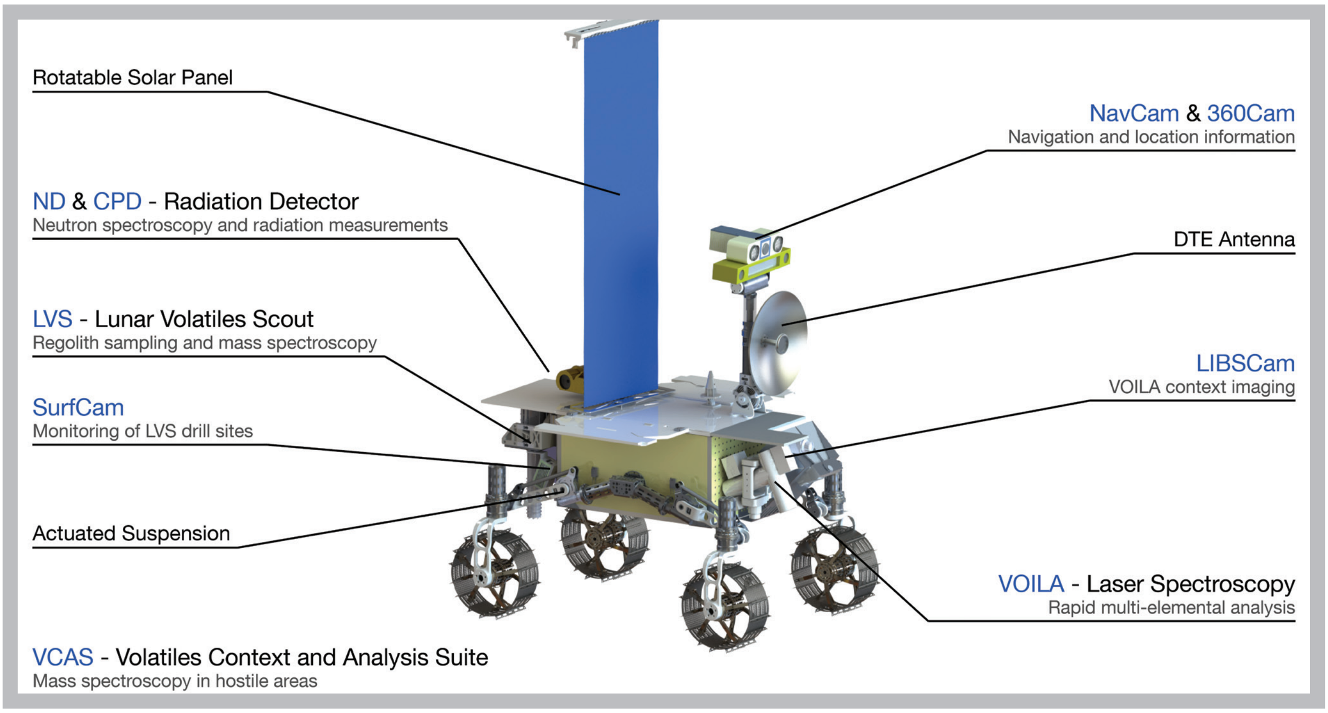
The instrument package is complemented by a novel set of cameras based on the light-field technology, which offers a simple and robust 3D imaging solution with no moving parts. This is used both for the supervision of drilling operations and in support of the navigation of the rover. The cameras with light-field optics are developed by Dynamic Imaging Analytics (UK). The Surface Camera (SurfCam) can provide depth information of the drill sites and rover tracks, as well as an overview of drilling operations. The Navigation Camera (NavCam) will be used to generate point clouds of the surrounding environment, enabling the identification



Principle schematic of the volatiles sampler and analyser (VS/VA).



Cut view of LUVMI.



The LUVMI-X concept.

of hazards and possible points of interest. These data is fed into the on-board computer, which allows partial or fully autonomous driving to short distance waypoints.

Rover platform

Since mapping of the spatial distribution of volatiles on the lunar surface, and their correlation with existing remote-sensing data, are among the prime objectives of LUVMI, the mobility of the system, including the possibility to take measurements inside and outside of PSRs, is essential. A rover platform with supporting subsystems (power supply, thermal control, communication, on-board computer with locomotion control and navigation software, illumination units) is therefore the second key element besides the instrument package. It is developed by Space Applications Services (Belgium), which has the lead also on systems engineering and overall integration.

The rover is based on a 4-wheel drive train with deployable, adjustable suspension. It offers the possibility to adjust the chassis height from 0 to about 300 mm from the ground. This is used to deploy or stow the rover (then fitting in a volume of 95x85x40 cm) and also allows adjusting the ground clearance to improve navigability on hazardous terrain. The same mechanism is exploited for on-spot drill positioning where the platform needs to touch the ground as to obtain maximum depth with the drill. In addition, a passive rocker-bogie mechanism provides the rover with a high obstacle clearance (up to 0.3 meter) compared to its size, while limiting the overall mass compared to a six-wheel rover with similar capabilities. A rocker-bogie system allows the rover to adapt the wheel positions passively so that contact of the four wheels with the ground is maximised at all times.

Space Applications Services has a long track record of robotic systems development for space and terrestrial environments – as well as experience with the operation of such robotic systems. For instance, in the ESA METERON programme, robotics devices were controlled from the ISS by Danish astronaut Andreas Mogensen in a tele-operated mode, under the supervision of the Space Applications Services operations team.

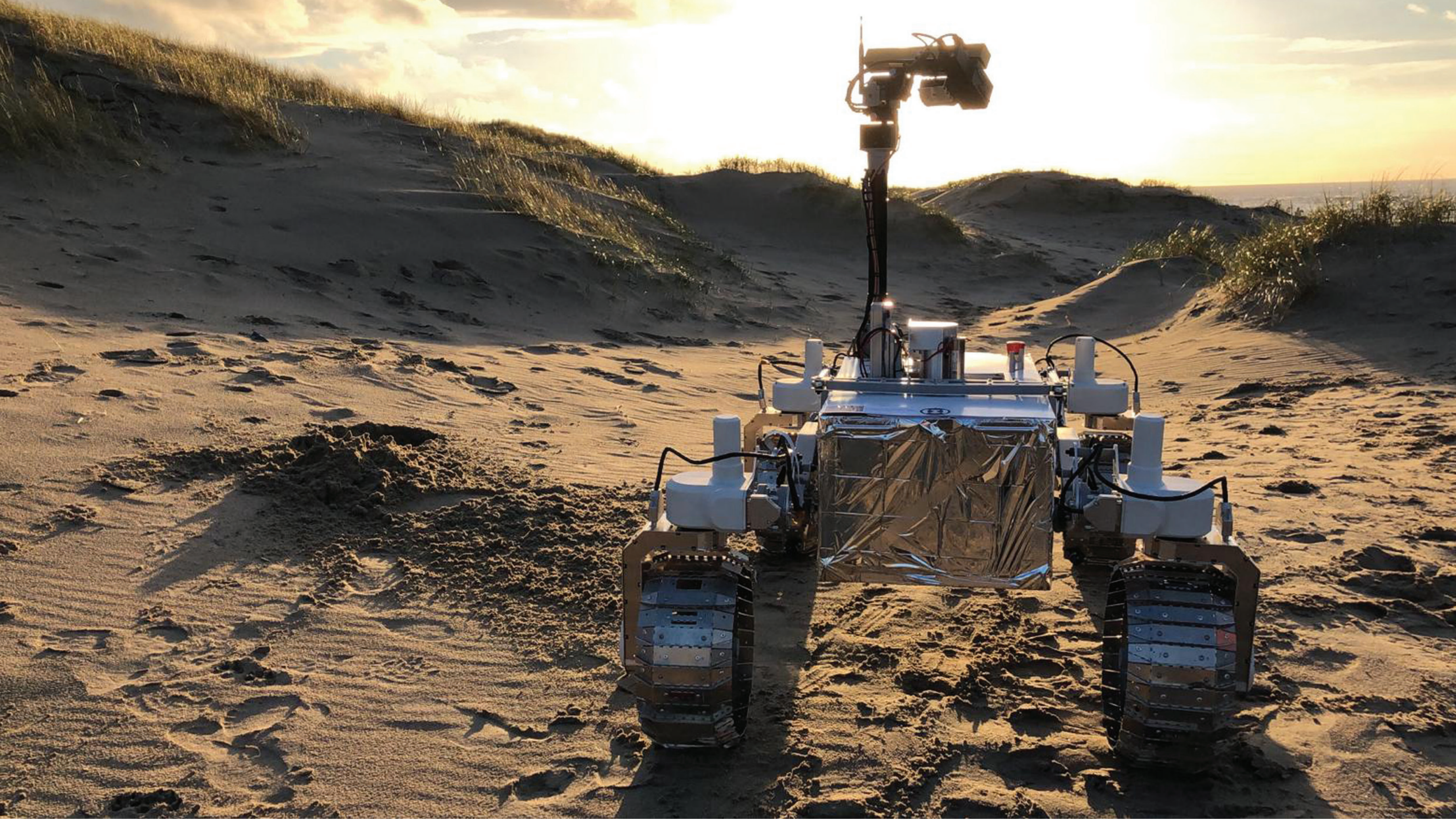
Testing in Noordwijk

The rover is capable of driving on slopes of 20 degrees (targeting up to 30 degrees) while carrying a payload of up to 30 kg, and this was one of the points to be tested in a realistic environment. The gradeability, traction and steerablility was put to the test first in the Mars yard terrain of DECOS BV, which has rocky soil, followed by similar tests on sand at the Noordwijk beach. The individual control and steering of each wheel allows various modes of movement, including forward, backward, diagonal ("crab" move) and rotational (spot-turn), which were all tested.

The rocky soil at the Mars yard posed an unexpected challenge for the drive train. The traction on pebbles gave rise to repetitive shocks, eventually stressing the wheel suspension, and small deformations were detected in lateral attachment plates that were not anticipated during design and simulation.

The second part of the tests, in sand dunes by the beach, covered a notional end-to-end scenario of operations, including a traverse of 50 meters, stopping and performing drill operations, and driving back to the starting point. This sequence was conducted in tele-operated and partial autonomous mode, without line of sight control.

The trails included operations in darkness and unknown terrain, thereby testing also the collaboration of the rover's lighting units, cameras, and onboard computer with its mapping and autonomous navigation software. The design is aimed at a short 14-day mission, i.e. a full lunar day, since the rover is not designed to survive the lunar night. Nevertheless, short excursions into dark craters, shadow areas, or beyond the day/night terminator will be of great use to achieve the scientific objectives. It was therefore important to demonstrate this capability, which is required as part of the operations concept.



LUVMI testing near the beach at Noordwijk.

...and back in the lab

Not included in the Noordwijk campaign was the functional and performance testing of the VS and VA, since volatiles release and detection can only be tested under vacuum conditions. These were therefore tested separately prior to integration, and then together in a purpose made thermal vacuum chamber in Munich. One of the challenges of that test was the preparation and conditioning of a representative frozen regolith simulant, which has significant impact on drill forces and behaviour, as well as measurement characteristics. The simulant was doped with up to 5% water and frozen to below -50°C. After drilling and heating with 15W of power, the VA sensor readings identified water, as well as small amounts of residual nitrogen and CO_2.

Another test performed prior to the outdoor trials was a 'partial gravity drilling test'. To validate that the required force and tilting stability for drilling can be achieved in the reduced gravity on the Moon (1/6th of Earth), an offloading setup (pulley system) for the rover was developed and installed in Space Applications Services' lab. It included placing the rover wheels on regolith simulant, in order to have realistic friction forces when the drill engages the ground. The test showed that the target drill depths were achievable even with an offloading level as on the lunar surface, and the rover stayed stable under all conditions while torque was generated by the drill.

An overview of LUVMI activities has been presented at the 15th Symposium on Advanced Space Technologies in Robotics and Automation 'ASTRA 2019', 27-28 May 2019, at ESTEC, Noordwijk, as well as the International Astronautical Congress IAC, 21-25 October 2019 in Washington DC.

LUVMI-X

Meanwhile the innovative concept developed and tested with LUVMI has been leveraged such as to extend the overall approach into a platform that can host a greater variety of scientific and eventually even commercial payloads. This resulted in a new EU-project called LUVMI-Extended (LUVMI-X).

Besides enlarging the instrument package with a laser induced breakdown spectroscopy (LIBS) instrument, a neutron detector (ND) and a charged particle detector (CPD), LUVMI-X will be able to accommodate a variety of payloads with standardised form factor and interfaces, similar to the ICE Cubes facility onboard the ISS, also developed and operated by Space Applications Services. These cube size payloads can be mounted in different locations on the rover, including the mast. Furthermore, it foresees the option of having payloads dropped on the surface, or even propelled (soft catapulted) into hard-to-access locations of interest. In this way the payload complement can be tailored and configured for different missions targeting polar regions as well as equatorial regions of the moon. LUVMI-X will further optimise the rover mass-to-payload-mass ratio, to make the concept economically viable also as a commercial service.

LUVMI and LUVMI-X are both potential candidates for upcoming robotic missions to the moon with a time horizon of 4 up to 6 years.

The authors would like to acknowledge LUVMI consortium partners for the excellent work done in the project and the test campaign performed in 2018 in the Netherlands.

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