German Aerospace Center – Program Space

Lunar Exploration Roadmap

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Motivation

Aerospace contributes to fundamental human questions for more than 60 years. After focusing on research in the first decades, first institutional and commercial services were provided for communication (since 1960s), weather forecast (since 1970s) and navigation (since 1990s). Currently, space exploration undergoes a dramatic change mostly due to "New Space" economy opening novel business models, e.g. in Earth observation, communication/ navigation, launchers, ground stations, even in manned space flights. This development is unthinkable without decades of government-funded research.

The research communities need to accompany this transition process, to take advantage of new opportunities, to support the development of space technologies and services and also to re-define their roles in the field of aerospace. Subjects as space science and planetary exploration, protection from space threats and resource utilization will stay non-commercial for the next decades.

DLR, the largest space agency in Europe, needs to answer these challenges. From the authors' point of view it is important to bundle R & D activities to develop and offer powerful contributions to international space missions. For doing so, the extraordinary experience of several DLR institutes shall be used as a nucleus. Following several international space exploration strategies and considering own capabilities and experiences, the authors propose to focus on the field of robotic exploration of the Moon as a strategic goal of the DLR space research.

Starting with this motivation and with a chapter describing DLR's heritage on robotic exploration missions, this paper lists scientific research questions and mission scenarios. The subsequent chapters describe the robotic, sensors and communication technologies needed for moon missions. The paper concludes with an analysis of the research environment and first draft ideas for a technological roadmap.

The explicit goal of the authors is to contribute to a DLR-led robotic exploration mission in 2035.

Heritage in Robotic Exploration

DLR has a long tradition in managing, designing and operating payloads and equipment for space exploration. Recent examples are Philae, the first lander on a comet, MASCOT, an asteroid lander with DLR-provided camera (MASCam) and radiometer (MARA), the "mole" as part of the HP^3 experiment aboard InSight on Mars, and the DLR-contributions to the ExoMars rover's mast camera "PanCam"

As robotic elements in space e.g. ROKVISS has demonstrated its capabilities aboard the ISS. There is significant experience in rover wheel interaction with planetary surfaces at DLR. Currently a rover for the Mars Moon Phobos is developed together with CNES and shall be part of the JAXA MMX mission.

The involvement or lead in these missions is a sound basis, also for the implementation of lunar missions, despite of a different gravitational and thermal environment.

In the following paragraphs, DLR's past and current involvement in space in situ missions is described:

ROSETTA

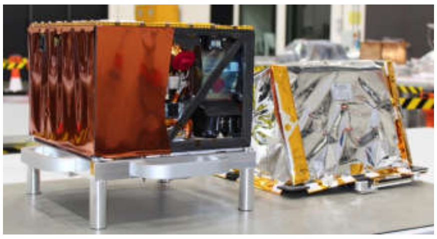
Rosetta was a Cornerstone Mission of the ESA Horizon 2000 program. Launched in March 2004, it arrived at its final destination, comet 67P/ Churyumov–Gerasimenko, in August 2014, following a 10 year cruise. After detailed study of both its nucleus and coma the Lander Philae, provided by an international consortium under DLR lead, has been placed on the surface of the nucleus. Although, the lander could not be anchored to the surface, Philae was operated from the DLR Lander Control Center for about 60 hours and a suite of ten scientific instruments brought unprecedented results, enlightening our understanding of cometary physics and helping to understand the role these bodies for the evolution of the solar system and the formation of life. There were significant payload contributions to this lander by DLR institutes, e.g. the Rosetta Lander Imaging System ROLIS, which was later the basis for developing MASCOT's MASCam, or MUPUS, the „Multi-Purpose Sensors for Surface and Subsurface Science".

InSight

In 2018 NASA has launched the Insight mission, in which a lander is carrying out geophysical measurements directly on the surface of Mars to explore the planet's inner structure and thermal balance. DLR has contributed to this mission the HP3 instrument, which comprises two elements – a mole and a radiometer. The electromechanical 'mole' is equipped with an active and a passive Thermal Measurement Suite as well as a combined accelerometer and tiltmeter (STATIL). The mole uses an internal hammering mechanism to penetrate through the ground. The thermal probes are located on a five-meter long flat ribbon cable, which measures its temperature and gradient through to its maximum length. The radiometer will characterize thermal properties of the Martian surface.

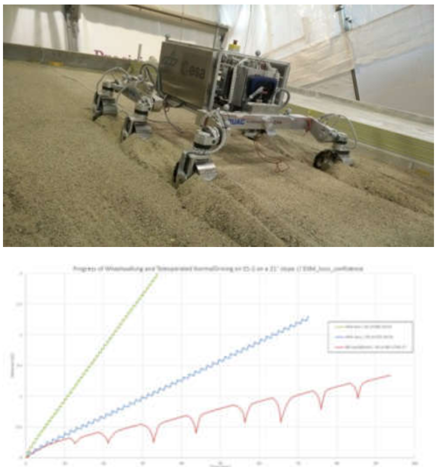
MASCOT

The Mobile Asteroid Surface Scout (MASCOT) is a lander for the Japanese asteroid sample return mission Hayabusa2, which was launched in 2014 and reached the near-Earth asteroid Ryugu in 2018. MASCOT was built by DLR in collaboration with the French space agency CNES. The aim of the Hayabusa2 mission is to learn more about the origin and evolution of the Solar System. MASCOT was operational on the surface of the asteroid for over 17 hours, performing uprighting and re-location maneuvers and collecting unprecedented data from the asteroid's surface. DLR also provided the lander camera MASCam (e.g. Jaumann et al, 2016, 2019), and the radiometer MARA (e.g. Grott et al, 2019).

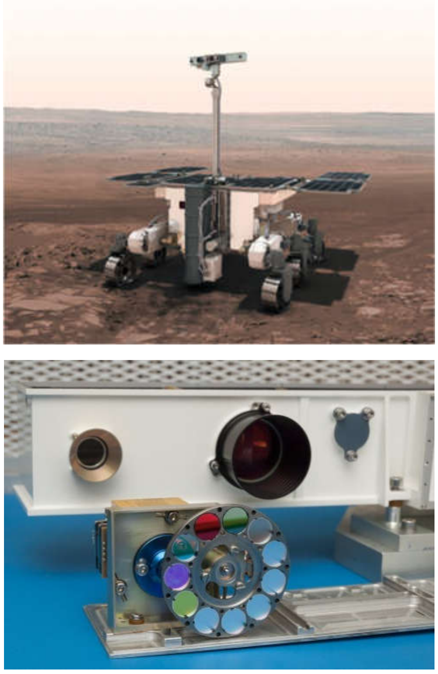

MASCOT lander flight model in the cleanroom

ExoMars

The 2020 mission of the ExoMars programme will be mainly formed by the European rover and a Russian surface platform. After a nine-month journey these two elements will be delivered to the surface of Mars and the ExoMars rover will start its journey across the Martian surface searching for signs of life and collecting and analyzing samples. During the early project phases a strong contribution to the development of the locomotion subsystem (2008-2010) has already been made and the development of the actuator concept, the evaluation and simulation of the operational performance and the testing and validation of the locomotion requirements have been covered extensively. Based on these experience and knowledge and to strengthen participation, the project has been rejoined as an associated project partner in 2016. During the Rover Confidence Tests in 2017 and in close cooperation with ESA, RUAG Space and Airbus Defence & Space, the refurbished ExoMars rover BB2 breadboard was successfully used to demonstrate the gradeability performance and limits on Martian soil simulants. On those sandy slopes conventional driving strategies, advanced driving strategies and the outstanding capabilities of the wheel walking mode have been demonstrated. During the test campaign, the gradeability limits of the rover could be significantly improved by a combination of appropriate driving operations. Next, it has been demonstrated that these limits can be further improved by deploying the optional wheel walking mode. This combination of wheel rotation and appropriate pivoting of the leg also results in a more efficient and faster uphill motion.


Exomars Rover in the DLR Testbed, plot of the wheel walking modes (green, blue) in comparison to the common drive standard way.

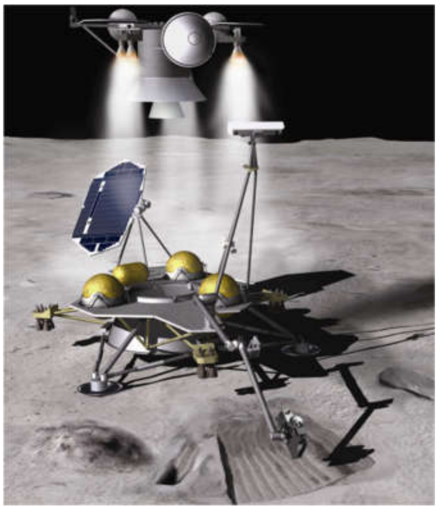
Together with the UK space agency (UKSA), DLR is also providing the rover’s panoramic camera, PanCam. DLR’s part is the provision of the high resolution channel (HRC). PanCam consists of two wide angle cameras with a filter wheel (provided by UKSA) and DLR’s High Resolution Camera (HRC) [Coates et al., 2017].


Artist’s conceptio of ESA’s ExoMars rover with PanCam on top of the mast, flight model of ExoMars Panoramic Camera „PanCam“, including DLR’s HRC

MMX

The JAXA Mars Moon Explorer (MMX) mission, will bring samples from the Martian moon Phobos back to Earth, but also study both moons from orbit and deliver a small (29 kg) rover to the surface of Phobos. This rover is going to be provided by CNES and DLR. DLR will be responsible for the scientific payload (a radiometer and a Raman Spectrometer), the locomotion system and operations during rover mobility and science sequences. This rover clearly profits from the heritage of Philae and MASCOT. MMX will be launched in 2024, MMX rover operation on the Phobos surface is foreseen for 2026.

In general, DLR’s cross-programmatic activities will support the ambitions for robotic Moon exploration. DLR programs in transport and energy will contribute to relevant technological research questions, e.g. in autonomic driving and batteries. Digitalization is one of DLR’s major research areas which is of outstanding importance for such a challenging undertaking.



Artist's conception of the MoonRise lander concept with PanCam/MCI on top of the lander's mast.

Other contributions

DLR is also involved in NASA's Mars 2020 mission, with a scientific contribution to the rover's mast camera Mastcam-Z. DLR will provide stereo processing (and subsequent geological analysis) of Mastcam's images, based on DLR's previous developments of stereo processing software, and derived products such as geomorphological base maps. The involvement also includes pre-flight and in-flight activities, in-mission operations and testing, E/PO, and data archiving.

For the Russian mission Luna-27, ESA will provide the Package for Resource Observation and in-Situ Prospecting for Exploration, Commercial exploitation and Transportation. DLR is involved with a member of the science team in the „Imaging, Surface Modelling and Spectral Analysis" team, and supports the definition, development and calibration of the PROSPECT cameras (context and drill camera ProSEED, sample camera SamCam) as a part of the membership in the PROSPECT User Group.

In the past , DLR and partners have performed several studies to adapt the ExoMars PanCam to be compatible with the requirements of a lunar robotic exploration mission, such as MoonRise MCI (MoonRise Context Camera) and „Lunar PanCam" for ESA's Lunar Lander:

- The robotic mission concept „MoonRise" was proposed in 2009, and 2017, respectively, as a New Frontiers mission. Major objective was the return of samples from the Moon's South Polar Aitken Basin (SPA) (Jolliff et al., 2011). In 2010, the team received funding for a Phase A study, which included the „MoonRise Context Imager", a slightly modified version of the ExoMars PanCam. The mission was not selected, and again proposed in 2017 (again with MCI/ PanCam on board). The lander concept also included a DLR-PF-provided descent camera and arm camera, both based on Rosetta Philae/ROLIS. The MCI's pan-tilt unit was proposed by DLR-RMC, based on ROKVISS.
- For ESA's first Lunar Lander concept, the PanCam consortium studied how the ExoMars PanCam could be modified for deployment on the lunar lander (Coates et al, 2012).

Science

Scientific Background

The Moon is the single most important planetary body to understand not only Earth but all terrestrial planets in the Solar System in terms of planetary evolution and processes. Building on earlier telescopic observations, our knowledge about the Moon was drastically expanded by the wealth of information provided by Apollo and other missions of the 1960s and 1970s, as well as several recent space missions, including SMART-1, Chandrayaan, SELENE, the Lunar Reconnaissance Orbiter (LRO), LCROSS, GRAIL and recently Chang'e-1-4. The analyses of lunar samples returned by the Apollo and Luna missions, and lunar meteorites found on Earth are key sources of information that were used to develop and test various hypotheses and models that were subsequently applied to other terrestrial bodies. Remote sensing using passive sensors in the optical wavelength range, as well as active laser and radar measurements supported by in-situ field work allow the entire lunar history to be studied with respect to its geological, compositional impact-related, volcanic, tectonic, and space weathering evolution. Spectral measurements in all wavelength ranges from high energy gamma-rays to the mid infrared provide the overall surface composition and major mineralogical content of rocks, whereas geochemical details and the origin, differentiation and evolution of the lunar rocks have been deduced from the returned samples and geophysical data. The vast amount of knowledge gained from samples brought to Earth by the Apollo and Luna missions, the lunar meteorites, and the in situ geophysical measurements made by the Apollo Lunar Surface Experiment Packages (ALSEPs) demonstrate how valuable the Moon is for understanding the Solar System. Today, the Moon is unique in that we have a rich data base for geology, geochemistry, geodesy, mineralogy, petrology, chronology, and internal structure that is unequalled for any planetary body other than the Earth. These data are crucial for our understanding of planetary surface processes and the geologic evolution of a terrestrial planet. They are also essential for linking these processes with the internal and thermal evolution. Because its surface of this one-plate planetary body has not been affected by recycling through plate tectonics, an atmosphere, liquid water, or even life, the Moon recorded and pre-served evidence for geologic processes such as impact cratering, magmatism, and tectonism that were active over the last 4.5 Ga Since most of these activities occurs during the first (approximately) 1.5 Ga of the Moon's geological history, this opens a "window into the past", offering the unique opportunity to look back into geologic times for which evidence on Earth has already been erased. Thus, the Moon is the easy-to-reach "Rosetta Stone" for understanding the fundamental processes that drive planetary formation and evolution (e.g. Jaumann et al., 2012, Hiesinger and Jaumann, 2014).

With respect to impact processes the Moon allows us to study, for example, the depths of excavation, the role of oblique impact, modification stages, composition and production of impact melt, ejecta emplacement dynamics, and the role of volatile-element addition. The lunar samples returned from known geological units provide the calibration of crater size-frequency distribution chronologies for the entire Solar System. These data are important to further understanding the importance of impact cratering in shaping planetary crusts, particularly early in Solar System history. For example, crater counts indicate that the impactor flux was much higher in the early history of the Moon, the period of the "heavy bombardment," which lasted until ~3.8 Ga ago (e.g. Jaumann et al., 2012, Hiesinger and Jaumann, 2014). The Moon also allows us to study planetary magmatic evolution and volcanic activity in its purest form, that is, without the influence of plate tectonics, atmosphere, and life. We have detailed knowledge of many aspects of lunar plutonism (intrusion) and volcanism (extrusion), and can assess the role of magmatism as a major crust-building and resurfacing process throughout history. For example, the ages, distribution, and volumes of volcanic materials are indicative of the distribution of heat-producing radioactive elements from the times of lunar formation and therefore mantle melting processes in space and time. In addition, the detailed magmatic record coupled with the samples permit an assessment of the processes in a manner that can be used to infer similar processes on other planets. These data have provided a picture of the role of magmatic activity during the heavy bombardment (intrusion, extrusion, cryptomaria), and more recently in lunar history, the mare stratigraphic record, the distribution of basalt types, and the implied spatial and temporal distribution of melting. Stratigraphic information and crater ages also provide an emerging picture of volcanic volumes and fluxes. In addition, the Moon allows us to assess a wide range of eruption styles, including pyroclastics, and their petrogenetic significance (e.g. Jaumann et al., 2012, Hiesinger and Jaumann, 2014).

The Moon is also a type locality for tectonic activity on a one-plate planet. Tectonic processes and tectonic activity can be understood in the context of the complete lunar data set, including the internal structure and thermal evolution. The distribution of grabens illustrate deformation associated with mascon loading, and wrinkle ridges appear to document the change in the net state of stress in the lithosphere from initially extensional to contractional in early lunar history. Finally, small-scale scarps formed by thrust faulting probably indicate a global shrinking and a change in diameter and can be linked to the lunar thermal evolution, i.e., the cooling of the planetary body.

In summary, the Moon is a complex differentiated planetary object. Many open questions need to be answered, and much remains to be explored and discovered, especially regarding the origin of the Moon, the history of the Earth-Moon system, and processes that have operated in the inner Solar System over the last 4.5 Ga. The Moon remains an extremely important and interesting target, both scientifically and technologically, because although the current data have helped to address some of our questions about the Earth-Moon system, many questions remain unanswered. Returning to the Moon in the near future is therefore the critical next stepping-stone to further exploration and understanding of our planetary neighbourhood (e.g. Jaumann et al., 2012, Hiesinger and Jaumann, 2014).

The lunar regolith represents a major source of all the chemical elements and compounds we may use to build structures on the Moon, exploit resources, and support manned missions. The regolith layer is completely covering the surface of the Moon, except perhaps on some very steep-sided crater walls and lava channels, where the bedrock may be exposed. The thickness of the lunar regolith varies in mare areas compared to highlands. In mare areas there is a 4-5 m and in highlands 10-20 m of regolith (McKay et al., 1991; Lucey et al., 2006). In mare, regolith is mostly composed of basaltic rock fragments rich in pyroxene and olivine, whereas in highlands anorthositic rocks with more than 90% plagioclase are the major component of the regolith layer. Below the regolith layer, there is mega-regolith which is a fragmented layer of impact crater and basin ejecta above fractured bedrock. Its thickness has been suggested as ~2–3 km based on geologic and seismic data (Head 1976). The regolith layer has a high porosity (~83% (Hapke & Sato, 2016)) and the average grain size, based on Apollo samples, ranges between 60 and 80 µm (McKay et al., 1991). The formation of regolith is a continuous process which resulted in a global resurfacing rate of about 2 to 5 millimeters per million years.

Ancient regolith layers buried by e.g., lava flows and fresh ejecta are termed paleoregolith (Fagents et al., 2010, Fa et al., 2015). As younger lava flows are superimposed on older ones,

We may expect to find layers of paleoregoliths sandwiched between these lava flows. The paleoregolith have an undisturbed record of composition and evolution of the Sun, ancient asteroid populations, and probably interstellar dust particles, which could complement our knowledge about the formation and early evolution of the solar system (Crawford et al., 2013).

Priorities for Science of the Moon

Increase the diversity of lunar rocks in the sample collection

New rock and dust samples should include new samples of mare basalts, especially those that appear 'younger than 1 billion years based on crater counts, those associated with surfaces of different ages including the oldest impact basins, those with diverse lithologies, plutonic samples (e.g. the Mg suite). Dating these samples and analysing their composition and mineralogy will:

- better constrain the cratering rate throughout Solar System history
- better understand the formation and evolution of the Moon
- to investigate the global distribution of volatile loss and isotopic fractionation.
- to unreveal the lunar mantle composition and evolution
- to investigate paleoregolith trapped between basalts.

Improving the calibration of the cratering rate would be of great value for the whole of planetary science including the science of the early Earth. Lunar chronology is poorly constrained at ages older than 3.9 Ga. Thus, sample return and/or in situ radiometric age dating of well-understood samples (e.g., impact melts) could fill this knowledge gap. Similarly, there is no data point in the lunar chronology from sample analysis between 3.2 and 1 Ga. Chang'e 5 will sample young basalts NE of Mons Rümker that can provide parts of the required information. The ages of Copernicus, Tycho, North Ray, and Cone craters are less certain than one would prefer and need to be augmented/replaced with samples from a better understood geologic context. Despite these caveats, the crater size frequency distribution method works well and can accurately reproduce model ages.

The method could be further improved by getting additional data points to the chronology curve, preferentially outside the 3.2-3.9 Ga time period. Thus, sampling of old (>3.9 Ga), well-understood terrain or basalts that are 1-3 Ga old is of the highest priority because the lunar chronology is extrapolated to date any surface in the Solar System. Priorities should be placed on establishing geologically well understood landing sites and the accomplishment of a few scientific questions rather than accessing highly optimal and complex landing areas for which interpretation of samples would be too challenging.

Deploy geophysical stations and build up a global geophysics network

Deployment of such instrumentation and an eventual network would constrain models of the lunar interior — in particular evidence about the existence of a metallic core – and address questions on present day seismic activity. Both seismic and heat-flow measurements are required with global coverage.

Return samples of previously unsampled regolith and pyroclastic deposits

After the detection of water in pyroclastic deposits sampled at the Apollo 16 landing site, new samples of this type could constrain the thermal evolution, and the volatile inventory of the lunar interior. Samples would also provide insight into the processes of regolith formation and maturation and the diversity of the mantle-rocks that were the source of materials. There is also synergy between science and exploration as scientific understanding of these will increase their potential as resources.

In situ characterisation of water and other volatiles at polar locations

These measurements would constraint the sources of these volatiles and their evolution. Both ice on the ground of permanently shaded craters at the north pole and south pole and the hydrated regolith apparently identified in Mangalayaan M3 spectroscopic data at high, but not permanently shad-owed, latitudes should be included. In both cases the physical and chemical state of the water, its concentration, and its vertical distribution within the uppermost few meters need to be determined, as well as the presence of other volatiles and potential organics. Special attention should be paid to the possible synthesis of organic molecules in polar ices by cosmic-ray irradiation as this is potentially a natural 'Urey-Miller experiment' of astrobiological relevance.

In the following we have identified three major tasks for lunar exploration all requiring mobility, autonomous operations and sophisticated energy handling.

Sample Return Mission from the Moon's South Polar Aitken Basin (SPA)

The evolution of the Solar System during its first 500 million years is poorly understood, but it is of critical importance because it was a time of formation of habitable environments on Earth and Mars, and the emergence of life on Earth. The Moon, formed shortly after the Earth's early differentiation and is the planet's companion since that time, lacks plate tectonics, oceans, weather, and experienced erosion only through external forces like the bombardment of the solar wind and meteorites of all sizes. Thus, its ancient surface records the timing and effects of the Hadean Eon, the final period of heavy impact bombardment on Earth and throughout the Solar System. This chronology, only partly known from Apollo samples, is the key to understanding what caused the late heavy bombardment – possibly caused by a dramatic inward-migration of the giant planets that destabilized primordial asteroidal and cometary populations, reshaping the Solar System and delivering volatiles to the young Earth. The 2,300 km-sized South Pole-Aitken (SPA) basin, on the southern lunar farside, is the Moon's largest and oldest impact basin, and as such, anchors the heavy impact bombardment chronology. Rocks melted by the impact uniquely preserve the record of onset of this cataclysmic bombardment, allowing us to test theories of how the early Solar System worked and how its present-day configuration came to be. In addition, the impact that formed the SPA basin probably excavated material from the young lunar mantle and therefore probably is the only location where this material can be sampled, which would complement the sample collection towards the most pristine and 'primitive' lunar rocks. In addition, SPA shows an iron anomaly and a paleo-magnetic field anomaly. Hence, South Pole-Aitken basin is a high-priority science target for Solar System exploration, and, in particular, for a sample return mission.

The major objectives for SPA sample return are (Jolliff et al., 2011):

- Determine the SPA-basin impact chronology: When did the impact event and other large impacts within the basin occur? What does this imply for the late heavy bombardment of the inner Solar System? How does it constrain giant-planet orbital dynamics?
- Characterize giant basin-forming processes: How deeply did the SPA impact penetrate? How were the excavated materials distributed? How did the Moon's crust and mantle respond?
- Elucidate the lunar crust/mantle/core structure and evolution: What processes controlled the differentiation? When was the core dynamo active?
- Determine the lithologic distribution of thorium and other heat-producing elements, and the implications for the Moon's thermal evolution: How are heat-producing elements distributed in the lunar interior?
- Investigate basalts as farside mantle probes: Why are lunar maria more abundant on the nearside? What is the reason for the lunar crustal nearside/farside dichotomy? What is the origin and distribution of indigenous volatiles recorded in the SPA basalts?

In order to target on required sample types, the landing/sampling site should be in the deep interior of the SPA basin (because large, post-SPA impacts move and mix materials laterally, so ejecta from external basins are more concentrated in outer zones of SPA).

Rock components in regolith at a given landing site should include:

- original SPA impact-melt rocks and breccia (to determine the age of the impact event and what materials were incorporated into the melt);
- impact-melt rocks and breccia from large craters and basins (other than SPA) that represent the post-SPA Large Heavy Bombardment (LHB) interval;
- volcanic basalts derived from the sub-SPA mantle; and
- older “cryptomare” (ancient buried volcanics excavated by impact craters, to deter-mine the magmatic (mantle) and volcanic (crust/surface) history of SPA basin).

All such rock types are sought for sample return. The ancient SPA-derived impact-melt rocks and rocks that crystallized from melt that formed later are needed to determine the chronology, and thus address questions of early Solar System dynamics, lunar history, and effects of giant impacts. Surface compositions derived from remote sensing are consistent with mixtures of SPA impactite and volcanic materials, and near infrared spectral data distinguish areas with variable volcanic contents vs. excavated SPA substrate. Estimating proportions of these rock types in the regolith requires knowledge of the surface deposits, evaluated via morphology, slopes, and terrain ruggedness. These data allow determination of mare-cryptomare-nonmare deposit interfaces in combination with compositional and mineralogical remote sensing to establish the types and relative proportions of materials expected at a given site. Remote sensing compositions and concentrations, e.g., FeO, also constrain the relative abundances of components. Landing-site assessments use crater and boulder distributions, and slope and terrain ruggedness analysis. Using these criteria, many potential landing regions exist, concentrated near the center of the basin.

Successful mission implementation requires at least two mission elements: a communications relay satellite (farside!) and the lander with a sample-return unit. The mission would enormously benefit from the addition of a small scouting and sampling rover, which would be able to reach outcrops in the nearer vicinity (e.g. ~100 m radius) with the ability to transport samples to the sample-return lander.

The mission scenario can be summarized: The mission will land in the SPA basin and document the landing site and workspace with multi-spectral imaging and IR spectroscopy. Selected outcrops and regions of interest (out of the range of the lander’s robotic arm) will be further investigated by a small scouting and sampling rover. Lander and rover will collect rock and regolith samples using a robotic arm and a mechanical end-effector. The sample material collected by the rover will be transferred to the lander’s sample storage system. Finally, the samples will be returned to Earth via a sample return capsule for analysis in terrestrial laboratories. The returned samples would first be transferred to a tbd location/lab for curation and for preliminary examination, and would then be distributed to the scientific community for more in-depths analysis.

Top priority for a sample return mission is the careful documentation of the geologic context. For this purpose, lander descent imagery and multi-spectral imagery on the surface would be correlated with orbital data to document the landing site.

For context documentation on multiple scales, and selection of sampling sites/areas, the lander shall be equipped with a descent imager, and a multi-spectral stereo imager as a mini-mum (360° coverage around lander). Desirable additional payload would be a (N)IR spectrometer. The rover needs to be equipped with a navigation camera for autonomous driving, a scientific multi-spectral stereo camera, and a (N)IR spectrometer as a minimum.

The mission objective would be to obtain no less than 1 kg of lunar material, including bulk, un-sieved regolith. These samples will provide critical ground truth for orbital data and context for interpretation of rock types and mineralogy across the basin.

The approach for sample collection could be a mix of grab-and-go sampling (lander), supported by targeted sampling performed by the scouting and sampling rover. For this, the sample acquisition system on the lander and rover combined must be able to collect >1 kg including sieved rock fragments of sizes sufficient for multiple analytical techniques and age determinations.

To maximize the diversity of the collected sample and rock fragments the sampling system needs to be able to scoop within the work volume in such a way as to maximize rock fragment diversity, and then concentrate rock fragments by sieving in the range of 3-20 mm (tbc).

Priority requirements for the scouting and sampling rover would be autonomous navigation, the ability to drive and sample on slopes, to trench a profile and sample inside, and to transfer the collected sample material to the lander's sample storage and return system.

Lunar Geophysics

The low mean density of the Moon (3,344 kg m–3) indicates that iron is much less abundant than in the Earth or any other terrestrial planetary body. If the Moon were fully differentiated with a pure iron core, the core radius would occupy less than 1/4 of the lunar radius. However, the existence of a small lunar core could not be confirmed or rejected on the basis of the on-ground seismic data acquired by the Apollo missions. Lunar laser ranging data show that the rotational state of the Moon is consistent with internal dissipation in a partly fluid central region. Furthermore, remnant magnetization of the lunar crust and the paleomagnetic record of lunar regolith even suggests the possible existence of an early lunar core dynamo, depending on the early differentiation of the lunar interior subsequent to the Moon's formation.

Robotic exploration of the lunar surface using mobile rovers from which in-situ instruments can be deployed would considerably help to improve our present knowledge of the formation and early evolution of the Earth-Moon system. Whereas geophysical instrumentation would better characterize the present state of the lunar environment and interior, geochemical instrument payloads would resolve critical timing issues of the evolution of the Moon.

A mobile ground-penetrating radar (GPR) system is useful to reveal the subsurface structure of the lunar regolith near the landing site and along rover transects with high spatial resolution. These measurements would substantially improve knowledge on deposition and erosion processes in the absence of an atmosphere. In-situ capabilities for Raman-LIBS and Mössbauer spectroscopy are required to determine the mineralogical composition and iron contents of rock and regolith samples along the pathway of the rover with confidence (e.g., in the SPA impact basin where lunar mantle rock may be locally exposed). Magnetic field sensors are important to determine the magnetization of rocks.

The deployment of an instrumented 'mole' would provide the opportunity to derive physicochemical properties of the lunar regolith as a function of depth. In particular the usage of a permittivity probe (PP) together with ground penetrating radar (GPR) offers synergies that are well known from borehole geophysics on Earth. A tethered instrumented mole, equipped with additional temperature sensors, would allow to determine the subsurface temperature gradient and to infer the local heat flow lunar provided the thermal conductivity is known. This is an important constraint for thermo-chemical models of the lunar interior (e.g. for the KREEP1 terrain in Oceanus Procellarum, enriched in heat-producing radioactive elements and isotopes).

The deployment of seismometers as part of a lunar seismic network would be required to better characterize the structure and seismicity of the lunar interior. Most of the deeply situated lunar quakes are induced due to tides exerted by Earth. Measurements of key tidal parameters using an extremely sensitive seismometer or gravimeter would provide important clues on the constitution of the lunar interior, augmenting the Apollo seismic, and GRAIL gravity data record, respectively.

In-situ instruments for the determination of exposure ages of lunar regolith and crystallization ages of lunar rocks are essential to address the timing of the lunar bombardment history. In-situ dating capabilities using key isotopes are further needed to quantify the local abundance of heat producing elements and to decipher the volcanic history in order to better constrain the thermal evolution of the lunar interior.

Titanium Oxide in the Lunar Regolith

The origin of the Earth's Moon is one of the major open questions in planetary sciences. The giant-impact theory is now generally accepted as the preferred explanation for the formation of the Moon (Hartmann and Davis, 1975; Cameron and Ward, 1976; Wood, 1986). However, the nature and chemical composition of the impactor, the evolution of the Moon's interior structure, its gross chemical composition, and the origin of water in the Moon's interior are still unclear and debated. The materials on the surface of the Moon are originated from the lunar crust and mantle (Wieczorek et al., 2006; Wood, 1972); therefore, constraining the distribution and abundance of various minerals within the lunar regolith is essential for under-standing its evolution. In addition, analyzing the surface material in situ is the most effective approach to constrain the chemical composition and to measure the isotopic ratio of the sur-face and shallow-subsurface materials.

The lunar regolith is rich in minerals and oxides which are highly valuable for addressing these open scientific questions as well as for future mining and economic purposes. One of these oxides is titanium oxide (TiO2), which is abundant in the lunar regolith and can be estimated in situ and remotely. Constraining the lunar TiO2 concentration is crucial for classifying the mare basalts and comprehending the geology and evolution of the crust of the Moon. The mare basalts are richer in TiO2 than the highlands (0-5%); however, the mare basalts are as well divided into low-Ti (<1-7.5%) and high-Ti (7.5->10%) (Taylor et al., 1991; Giguere et al., 2000; Hiesinger, 2010). It is still unclear what caused the high abundance of titanium on the Moon's surface and this sort of distribution between the highlands and mare basalts. The lunar mare basalts are samples of the interior composition of the Moon, thus their composition indicates the conditions of the Moon formation and its mantle evolution.

Ilmenite (FeTiO3) is one of the minerals which have been detected widespread on the surface of the Moon. Ilmenite is a valuable titanium ore, and can also be used as a worthy source of oxygen production, in addition to iron. The abundances of ilmenite in high-Ti basaltic lava are higher (9-19%) than in high-Ti mare soil (<10%) (Heiken and Vaniman, 1990). The extracted oxygen can be used to investigate the effects of space weathering and the solar winds on the lunar regolith and regolith in general. Ilmenite minerals also trap solar wind hydrogen very well; therefore, processing ilmenite will also produce hydrogen, a rare element on the Moon that can be used for in-situ water or rocket-fuel production. Ilmenite may as well be an efficient trap for 3He with potential use as a fuel for fusion energy generation. Extracting the solar-wind isotopes and gases implanted in the minerals of the lunar regolith enable us to better understand the space weathering and maturity of the lunar regolith.

Technologies

Robotic Technologies

The next future robotic missions will focus on the exploration of the Moon, Mars and small celestial bodies. Meanwhile the Global Exploration Roadmap (NASA, 2018) foresees three steps in the next decade, starting from Earth orbit to the Moon orbit, continuing with Moon surface operations and applying these approaches later on to the Martian environment.

As described in the first robotic mission on the Moon might be a precursor mission with the objective of operating robots to install, maintain and operate permanent bases. As ISRU (In-Situ Resource Utilization) is a key aspect of permanent operated bases on Moon or Mars, many precursor missions, are planned in the near future.

In general, initially starting with full robotic driven missions while later resuming with human/astronaut cooperative mission is the common roadmap. Only NASA aims at a human return to the moon as soon as 2024. All other agencies use robotic precursor missions. These focus on enabling the operation of single robotic assets to demonstrate the achieved capabilities. Subsequently, cooperative robotic systems comprising heterogeneous capabilities will be the next step to complementarily solve the challenges necessary for permanent operated installations, such as energy farms, oxygen generators, scientific networks or outposts or even the visionary lunar village coming from ESA.

As noted above, a lot of scientific questions concerning the Moon are still under investigation. Therefore will the robotic tasks of the next science missions be the inspection, in situ analyses, collection of samples, and sample return. The robotic challenge common with all these tasks will be the mode of operation from a distance, but also from an orbit and surface based stations. However the mode of operation can vary from the tele-operated case, with the human in the direct loop through supervised autonomy towards the common goal of highly autonomous robotic systems (see section 5 operational aspects).

The robotic systems therefore will start with surface missions, as scientists have high interests in lower areas such as gullies, lava tubes and craters, as well as to reach permanently shaded areas and unchanged environments. For the establishment of permanent bases, the aspect of shielding and covering the bases against cosmic radiation inside these natural structures and shelters is needed.

Currently several European activities focus on the development and enhancement of technologies for such missions. The H2020 space activities in the Peraspera framework (Compet-4) seek for the common development of base technologies for orbital space robotics and planetary exploration with the common goal of serious demonstration missions in relevant environment. In the ESA METERON (Multi-Purpose End-To-End Robotic Operation Network) framework, several sub projects are and will be established as experiments addressing validation of technologies needed to operate robotic assets on the surface of the Moon or Mars from a Lunar/Martian orbital station. The experiments in METERON will also serve as baselines for the HERACLES scenario, which has the target to use the Deep Space Gateway (DSG) to deliver samples to scientists on Earth

Meanwhile ESA, DLR and its partner Agencies look for Mission opportunities with e.g. the Japanese space agency JAXA and the Russian Roscosmos for common activities. For the HAYABUSA-2 mission DLR in collaboration with CNES provided the small MASCOT lander to the JAXA mission to the Asteroid RU-1999, Ryugu. A follow-up cooperation will allow

DLR and CNES to contribute a small landing element to JAXA's MMX mission, which aims to land on the Mars moon Phobos.

During the ARCHES project the scientific question of the deploying and maintaining a radio telescope infrastructure on the planetary surface will be in focus as well as scientific relevant surface exploration, sample selection and collection. The aspect of in-situ inspection and analyses will be furthermore a new aspect in this large research project. To achieve this objective for a more widespread area and a longer period, autonomous cooperative robotic assets will be used and heterogeneous robotic systems will cooperate together (see section 4). With the probably biggest robotic ESA Mission coming up, EXOMARS will underline Europe's role in planetary exploration with the landing of the rover element in 2020.

In and outer Space Manipulation

CAESAR: Space Robotics technology for assembly, maintenance, and repair

Currently, there is a worldwide increasing interest in orbital services. This is not only driven by national agencies or defense organizations but also by private companies. E.g. Orbital ATK is developing the Mission Extension Vehicle (MEV). In 2019 it will dock an IntelSat asset in GEO providing life-extending services by taking over the orbit maintenance and attitude control functions. Space robot services are going far beyond that. Space robots are performing exploration, assembly, maintenance, servicing or other tasks that may or may not have been fully understood at the time of the design.

The Institute of Robotics and Mechatronics at DLR is developing the space robot system CAESAR (Compliant Assistance and Exploration SpAce Robot). In the mid-nineties DLR developed a new generation of light weight robots (LWR) with an excellent power to weight ratio as well as impressive control features, which made the system easy to use and safe for terrestrial servicing applications. The same hard- and software technology was verified in the ROKVISS (RObotic Components Verification on the ISS) experiment, on a platform on the outside of the Russian Service Module of the ISS from March 2005 to November 2010.

With the development of the space-qualified robotic system CAESAR, the Institute of Robotics and Mechatronics at DLR is continuing the work on on-orbit servicing that began with DEOS. The seven degrees of freedom (DoF) robotic system is intended to be capable of catching satellites in LEO/GEO, even ones that are in tumbling, and/or non-cooperative states. The dexterity and sensitivity of CAESAR enables the assembly, maintenance, and repair of satellites.

The key to CAESAR's high performance is intelligent impedance and position controlled joints. Each joint is a building block for setting up diverse robot kinematics depending on the different mission goals. The scalability of the robot is determined by the number of joints and the length of the links. CAESAR's seven DoF enables it to meet the dexterity and the kinematic redundancy requirements. Extending the impedance controller, the CAESAR arm can behave compliantly, while maintaining TCP position. The compliant behaviour is triggered if any part of the robot detects contact with the environment. Compliance is a significant safety feature in dynamic environments or in close vicinity to the astronauts.

TINA Small Arm for Planetary or Indoor Manipulation

The aim of the research project TINA is to have a modular concept technology needed for a small, force-controlled robotic arm for use in exploration missions. This allows different kinematics for many applications of the arm, with only small changes in the mechanical- and electrical design. By selecting specific components, it is possible to use the TINA modules in microgravity conditions as well as on Earth.

The design of TINA follows the 'qualifiable' philosophy of DEXHAND (Chalon. Et al, 2011), which uses industrial-grade components with a similar performance to their space equivalents and follows the ECSS guidelines closely, or uses the industrial-grade versions of radiation-hardened electronic components. This philosophy ensures that the transition to a fully qualified design can be achieved with a minimum number of changes. It also provides an almost perfect version for thermal and EMI modelling. Another big advantage is the low price compared to the fully qualified, radiation-hardened version, which allows the construction of multiple test arms for grasping, object handling and many other applications.

Docking-Interface between Manipulator and Payload Carrier

The leading aim of the design team “Docking & Interfaces” is the definition and development of reliable docking interface systems with the capability of defining a new interface standard. With respect to the requirements of the deep sea- and space domain, corresponding prototypes have been constructed and validated during laboratory and analogue field tests. The various mission tasks conducted autonomously by the LRU during the space analogue mission required an extension of the rover’s capabilities by a modular robotic docking interface and a payload carrier to enclose scientific mission equipment that could be docked by the interface.

To this end, the docking interface was designed for autonomous or tele-operated docking procedures with the aim of enabling mechanical connection, the transfer of electrical power, data communication and fluid transport among the docked systems.

However, during the analogue mission campaign the docking requirements have been reduced to connect mechanical loads with a high degree of reliability. To enable mobile measurement capabilities, the scientific carriers have been equipped with durable internal batteries and a COTS-based wireless LAN communication device.

In order to increase the safety of the mission in such extreme environment, a dedicated, robust docking process has been thoroughly designed that enables a high degree of repeatability and high docking success rate. The process’ reliability is complemented by the simple geometry of the coupling components as well as the modular and scalable design. With respect to the design, the rotational symmetrically shape of the passive coupling partner and the mechanical mating mechanism provides high misalignment tolerance.

Mobility, Perception, Navigation, Autonomy Capabilities

Small Scout Rover

Based on the Space Research project MPE which was performed in 2012 as contribution to the ESA Lunar lander mission the mobile payload element (MPE) concept has been evaluated. The MPE concept aimed to be lightweight (10-14kg), and focused on the task to deliver samples for scientific analyses in a range of approx. 100 m back to the lander. The ESA lunar lander mission has not been continued. Yet, follow up projects have been funded. One is the contribution and participation to the PTScientist Audi lunar quarto rover development, which also aimed for a lunar roving vehicle with the weight of ~30 kg to be delivered to the Moon surface in the Apollo 17 area. PTScientists are a new space company from Germany, initially founded as one team of the lunar X-price competition, now fully financed by private investors. Additionally to this two external projects, DLR internal small scout rover Light Weight Rover Unit (LRU, Wedler, et al 2015) has been developed, aiming to proceed the developments of this external space projects with internal funds and enables research on the relevant topic of mobile robotic planetary exploration.

During the ROBEX project, we extended the capabilities of the LRU, our rover prototype for planetary exploration missions. This area of application poses many challenges to the design of a robot. It has to be lightweight to allow economic transportation to another planet. After its arrival on the planet’s surface, all sensors and actuators are required to work under these alien conditions. Heavy communication delays and blackouts between the robot and operators on Earth are to be expected. A ground station team thus must be able to interact with the rover on a high level. As large communication delays render teleoperation inefficient, the rover has to solve most tasks autonomously. It needs to navigate previously unknown, rough terrain in order to explore the area and arrive at scientifically relevant locations. There, the rover can employ its manipulator to take samples or to assemble technical equipment.

We considered these challenges during the design of the LRU: Its unique construction is lightweight (approx. 40 kg) and thus economic to transport into space. Further, the LRU solely relies on sensors (stereo cameras, inertial measurement units) that work in alien conditions and are used in current space missions. We designed its locomotion system for rough terrain and high maneuverability with four independent wheels, each being equipped with individual steering and driving motors. A force-controlled manipulator on the back of the rover can be used for pick and place tasks and to assemble objects. The autonomous capabilities of the LRU stem from a variety of software components. We developed and integrated modules for on-board self-localization in GPS-denied environments, local and global mapping, fast obstacle avoidance, path planning, object detection and pose estimation, manipulation, inter-process communication, high-level autonomous task control as well as a ground station mission control to overview and control the processes, and interact if necessary.

All these rover prototypes consist of different kinematic aspects, based on constrains of the mission and the transporting assets. Inside all scout rover concepts, the locomotion subsystem and the perceptions functionalities has been considered key elements of the robotic institute.

Smart Scout Systems for Extreme Terrain

While wheeled rovers do have obvious advantages over legged locomotion, e.g. the design simplicity and need of just a few actuators, their mobility is limited to somewhat smooth terrain. Many objects of interest for science and sample return are inaccessible because of rocks, steep slopes (crater walls) or too soft soil. Furthermore the search for present and past extra-terrestrial life requires to go to “safe havens” like lava tubes or other types of planetary caves. These caves feature extremely harsh and hazardous terrain and may often only be entered through skylights.

Small 10-30kg scale agile scouting rover for extreme terrain and planetary caves) based on rimless wheels

For such extreme terrain DLR is currently investigating the concept of a rimless wheel. As its name suggests the idea is to remove the rim of a wheel and drive directly on the spokes (normally just a few, ranging from 3 to 6).

While the idea is not new, DLR’s small scout rover with rimless wheels introduces several new concepts, the most important being that the spokes are made of compliant material in order to profit from energy storage and release during locomotion. In addition, the rover is modularly built out of three segments with two wheels each that are connected via flexible parts. Another aim of the system is to be as simple as possible to reduce failure points and the amount of qualification work. The simplicity of the system together with the simple compliant components allows a high system robustness. It has been shown that the technology demonstrator survives drops of 1.5m height on Earth, which will equal to >9m on Moon. Therewith the system becomes capable of entering skylights or taking the risk of falling into smaller vertical drops and shafts in planetary caves.

A first prototype/technology demonstrator has been built in 2018 and currently further development is ongoing for example regarding control and locomotion schemes. All of this closely coupled to the modelling and simulation of a digital twin.

While the planetary landers need to land on large flat surfaces and rovers can traverse only moderate slopes and overcome only relatively small rocks, the currently most interesting areas from scientific point of view are very uneven.

Based on investigation of Nonlinear Oscillatory Modes we will design and demonstrate multi-legged robots which can move at similar speed and mechanical energetic efficiency as animals and humans and with comparable uneven terrain versatility and robustness.

An application task motivating the focus on robots with independently controllable segmented legs (in contrast to specialized machines) is the careful, well-controlled ascending of steep and rocky slopes by exploiting the intrinsic compliance properties of the elastic multi-body robot. This permits precise positioning of instruments and their gentle transportation. If the mission requires it, legged robots furthermore provide the option of a dynamic ascend and descent, including stone hopping.

The primary application scenario is space exploration on Moon or Mars in canyons, caves or steep ridge slopes.

Operational Aspects: From Teleoperation to Autonomy

Perception: Autonomous Navigation, Search and Exploration

In all fields of automation engineering the user interface is a crucial component that needs to be solved for broad acceptance. The usefulness of robotic systems is always strongly combined with the usability. This is why the first approach is to increase the user's immersion. Thinking this way the user interface for tele-manipulating a humanoid robot like Justin HUG was developed and demonstrated for different scenarios. The user can see through the "eyes" of the robot and feel the real torques in the robotic arms. The user gets virtually connected to the robot and becomes strongly involved to the environment of the robot. A similar approach was the development of the MIRO surge robot. The robot is used for minimal invasive surgery by the surgeon who can see a 3D image from the inside of a patient and feel the forces applied to the used instruments. Again, the operator can be separated from the robot and long distances may be bridged with this kind of system.

As the communication delays and disturbances increase with the distance that needs to be bridged, the level of commanding needs to be abstracted. First teleoperation from earth to an orbiting space shuttle with large time delays was conducted within the ROTEX experiment in 1993. A direct teleoperation with closed loop feedback was tested in the space context in the frame of ROKVISS experiment in 2005 (Preusche, 2003). From January 2005 until November 2010 a 2-DoF robotic arm was mounted to the outside of the Zvezda-Module of the International Space Station ISS. By use of a force-feedback joystick at ground control the user could feel the robotic arm's contact forces within a metal contour or could feel the force that is needed to apply to expand a spring. In that experiment it could be observed in practice how seriously the closed feedback loop suffers from signal delays. Even relative short delays of 20 ms cause challenges to the control algorithm. For human operators this delay poses also a big challenge. To investigate on the astronauts' ability to command robotic systems with a force feedback joystick at ISS and a robotic system down at earth with Kontur an additional experiment was conducted. Due to bandwidth limitations and signal quality, the level of connection from astronaut and robotic system needs to be optimized. Force feedback needs to be focused on applications that profit the most from its features. This is typically the case when dexterous manipulation is needed or force feedback is used to assess situations.

To investigate further on that idea a robotic arm was set-up and equipped with a shovel. When taking a soil sample the reflection of the contact force of shovel and ground may be helpful to solve the task. Again, the signal delay is the bottleneck of the quality that can be achieved.

When thinking of a scientific observatory on moon that is setup and maintained by robots, much higher complexity needs to be solved. As shown in the METERON experiment a tablet computer could replace the HUG system and command the same humanoid robot Justin. In that experiment the robot is working at the robotics institute and is commanded by an astronaut from the orbiting international space station ISS. Depending on the perception results of the robot different types of actions are offered to the operator. These actions are then initiated by the astronaut and the robot carrying out the task on its own. Even when communication signal gets lost completely the task can be completed safely. The working speed and also the safety is increased dramatically by that advantage.

In future, all results of these experiments need to be used to develop an ideal way of commanding for every kind of application. The goal is to use as much immersion as possible and still be able to handle signal delay and disturbance in the communication channel. As a result, the immersion needs to be cut back to a level that is comfortable for operating astronauts in orbit and technically feasible in terms of bandwidth and signal delay. The most robust way of operation is a robotic system that is able to perceive its environment and rating different actions that could be taken as a next step. A fully autonomous robot would mean to replace the skills of a scientist by an algorithm. This is not recommended as the decision taking of human operators always involves a lot more parameters than only the factors bound to the task itself. Considering the consequences of each task execution is one of the things a human is in advantage of each robotic system.

Autonomous Task Control

To orchestrate all software components of the LRU in order to create a robust, autonomous behaviour we employed RAFCON. Developed at DLR since three years, RAFCON represents a powerful flow control programming framework. It is based on hierarchical state machines and features an elaborate visual programming environment. All navigation, manipulation, object localization and world model actions are controlled by RAFCON in a centralized manner. Easy collaboration between several developers is enabled via library states, which represent modular components designed for easy reusability and versioning. Fig. 17 schematically shows the layout of a subtask, programmed for the ROBEX mission.

Terramechanics

Terramechanics is the science of locomotion on rough, sandy surfaces. This comprises the study of soil properties and the interaction of objects, often wheels or tracks, with the soil.

DLR has many years of experience in terramechanics. The work can be grouped into several areas, the most important of which are the use of simulation in systems analysis, the use of reduced models for controller synthesis and optimisation and the performance of physical experiments. The model types used are based either on the Discrete Element Method (DEM) or on empirical models with a focus on full system simulation or on single-point models with a special focus on control or optimization.

Partsival is a DLR developed DEM code operating on GPUs. Low computational times, when compared to other DEM implementations, enable the use of this tool in new areas like optimization for rovers. The Discrete Element Method is a particle based method widely used to simulate granular matter. High accuracy is achieved by volumetric discretization of the soil and allows covering the underlying effects of soil failure. Due to its particle based approach gravity acts on each single portion of simulated regolith which makes it especially suitable for high-fidelity regolith simulations in planetary exploration. Partsival is developed to be easily extendable via plugins and versatile via a highly abstracted interface and thus enables easy simulations during design studies.

For full system simulation the DLR Soil Contact Model (SCM) uses a discrete surface representation to model the deformation and the resulting forces. This simplification and focus on the surface enables SCM to have a low computational complexity while still providing a good a representation of the interaction with the soils surface.

The operational environment of a rover is comprised not only by sand but also by rocks. Therefore a Hertzian contact model for the contact between wheel, rocks and other components is available.

Currently this knowledge contributes to the development of the MMX rover for Phobos. So far the focus of the terramechanics models has been on gravity properties in the same order of magnitude as on planet Earth. With the radically lower gravity of the Martian moon Phobos the models need to be adapted because some effects like cohesion and adhesion, that are negligible for dry sand in earth gravity, become important in a milli-g environment. Adhesion affects the wheel when the regolith sticks on the rim. This is an effect that is challenging to model but very important to add because it changes the traction properties of the wheel.

A significant influence on the performance of a rover system on soft sandy ground is its wheels and their traction characteristics. The multitude of variation possibilities and their dependencies complicated wheel design. To tackle this challenge as best as possible the use of optimization in the wheel design is essential. DLR's Institute of System Dynamics and Control has been chosen to design the wheels for the MMX rover. During the design of the MMXs wheel a combined optimization in regards to traction and topology is performed. Due to the extreme difference in conditions between the Martian moon Phobos and earth DEM simulations are especially important to design wheels that provide sufficient traction. The terramechanics work done in the past contributes to this new task and vice versa the experience gained while designing and operating the MMX wheels is going to improve the terramechanics models.

Possible applications for future missions such as Luna 28 are, apart from those already carried out in MMX, the analysis of other ground interactions similar to those for the HP³ mole in the InSight mission. DEM and simplified models were used to optimize the hammer mechanism of the HP³ mole. With the available models and experimental equipment, dynamic ground interactions, e.g. for ISRU, can be analyzed, enabling the development of lighter, more versatile hardware in less time.

The optimization of the MMX wheels and the lessons learned from this task are going to be of great use if DLR once again is selected to design wheels and tools for this mission. Based on this experience the optimization methods previously applied to the wheel could be extend to other parts of the rover, for example an optimized rover topology for agile locomotion.

The Terramechanics Robotics Locomotion Lab (TROLL) is a robot test bed designed to perform experiments for the validation of terramechanical models. Due to its high level of automation, precision and flexibility, the test bed is able to quickly provide repeatable data for a specific situation. An essential feature is the automated soil preparation. Due to the chaotic nature of the soil, it is of utmost importance to prepare the soil repeatable before each experiment.

All terramechanical work can be summarized by the goal of extending the operational range of systems into previously hazardous areas like dusty craters or soft sand pits. This is achieved by simulations, system analysis, optimization and the development of appropriate models for controller synthesis.

System Simulation

The design and testing of advanced robotics can only be efficient and economically viable if virtual prototypes and simulations replace or complement part of actual prototypes and hardware. In space missions simulation also helps to cut down development time to allow fast paced missions with advanced technology.

Simulations should accompany the initial design, development, operations and post-processing of the mission during all its phases. It is therefore important to have continuous simulation model philosophy for full system simulation including the definition of data exchange or other interfaces with more detailed models for specific domains. Starting with feasibility studies and optimization based concept derivation, it allows to study feasibility in greater detail in the beginning of the first design phases, run a high number of critical tests and identify failure points. In later phases design and sub system optimization of chosen concepts increases the maturity of systems even before the first prototypes are built. As the process of development goes on and prototypes exist, simulations are steadily refined and verified using lab tests. In critical mission phases simulation models have to be used further in order to identify possible malfunction and failure points in designs and during testing by simulation based forensic engineering.

For the development of the MMX rover for Phobos exploration there exist some simulators for specific domains on the subsystem level, for example the structural stresses on the rover casing or thermal behaviour of payloads. The simulator on the full system level so long consists of the mechanics of the locomotion. Of course the terramechanics as explained in the preceding section play a major role. Rudimentary energy calculations are also already part of the simulation as well as mechanisms e.g. for the solar panel deployment.

In future it is planned to extend the full system simulation model to other domains such as thermal and structural stresses. For some domains this will require new development steps but the specific subsystem simulators will also be merged to the full system simulation. Eventually the whole rover life cycle is to be jointly developed and analysed with prototypes and digital twins together. This is also going to allow optimization of the complete rover system. Today only optimal locomotion performance can reasonably be done with DLR’s simulation tools and experience because the mechanical subsystem has the most details and highest accuracy in the full system simulation model. With the extension to other domains the optimizations of rovers for future missions like Luna 28 and beyond will be possible.

These concepts especially require faster locomotion in order to survive thermal and power bottle-necks in areas shaded from the sun. Thus faster robotic rovers allow for increased exploration of more interesting areas of the moon. In Lunar environments regolith is mostly present in thin layers, which pose a special demand for locomotion different from those encountered on Mars and other bodies. These demands can be faced using specially optimized wheel for the lunar exploration. Faster locomotion together with optimization-based wheel designs will allow for bigger exploration areas at lower power consumption and mission risks. The wheel design could especially contribute to meeting the traction, mass and energy requirements of upcoming and future missions, to not only enhance science but also enable in ISRU.

Beyond the physical design of the system simulation provides the possibility to test software and algorithms without the need of hardware by using software-in-the-loop simulators. In the same way hardware sub systems can be verified using hardware-in-the-loop simulation by feeding hardware outputs back into simulation. The gathered knowledge on the system is also used in operations, in decision making and planning during in situ phases. Additionally the simulation models used in development may also be used to enhance planetary science by using model inversion in order to identify in situ parameters of the planetary body to be explored.

Finally DLR’s knowledge of simulators is also going to be useful during the operations phase of the exploration mission. In the lunar environment fast locomotion may be used, and actually necessary, to escape places shaded from the sun within thermal and power constraints. Moreover detailed multi-physics simulations assist to ensure the survivability in design phase and to check operation scenarios.

Currently reconstruction of the internal rover state from sensor measurements is easily possible with the tools at hand. For a more comprehensive support of operations some additional capabilities need to be implemented. The reconstruction of the environment from images and radar (or some other scientific payload instrument) must be done and processed in such a way to be included to the simulation tools in order to permit reliable statements on the driveability of the terrain.

Rover Chassis Control

For redundancy reasons rovers are usually over actuated, i.e. a desired movement can be realized with different combinations of actuator motions. In a model-based control approach, rover and wheel-ground interaction models are used to optimize additional goals such as minimizing energy consumption and slippage. Depending on available measurements, an on-board adaption for different ground characteristics and fault recovery could also be developed to allow for fully autonomous optimal locomotion on largely heterogeneous terrain.

Currently DLR’s Robotic and Mechatronic Center does fundamental research on such advanced model-based control schemes for rover locomotion. The test facilities TROLL (see the section on Terramechanics some paragraphs above) and Planetary Exploration Lab (PEL) are used for verification on the component and on full system level, respectively.

For the MMX rover, a kinematic controller is currently under development to control the wheels and active chassis. This allows different driving modes such as skid-steering, inching locomotion and body orientation. Besides these driving tasks, scientific instruments need body orientation and height adjustments which are also performed within the locomotion control software.

Communication, Navigation and Time Synchronization

Reliable communication, navigation, and time synchronization are mandatory components of lunar exploration. Communication is required for autonomous platforms to organise themselves, for all instruments on Moon to report to the lunar base, and for the transmission of data from Moon to Earth and vice versa. Reliable and robust navigation and time synchronization is also indispensable for autonomous robotic platforms and instruments deployed in a distributed fashion. We need accurate navigation both in a relative and an absolute coordinate system.

- Communication on Moon between robotic platforms and a lunar base: Rovers and all types of deployed instruments require appropriate local communication capabilities for exchanging data among each other and towards a lunar base. Requirements are low transmission power, low latency, high reliability, and the ability to set up communication chains for exploring a cave or driving behind the radio horizon of a lunar base. It must also be ensured that communication links are established automatically. DLR has been working on self-organizing communication methods scalable to any number of transmitters.
- Communication between Earth and orbiter or lunar base: The two greatest restrictions are long signal propagation times and strong signal attenuation which demand for a high degree of autonomy and large antennas, respectively. DLR also promotes optical free-space communication as an alternative to RF communications enabling high data rates to locations on Earth which are not covered by clouds.
- Communication between orbiter and robotic platforms: The orbiter will serve as a relay for communication between a robotic platform and Earth. This concept has proven itself. Both omnidirectional and directional antennas must be foreseen.
- Radio-based navigation and time synchronization: DLR is developing a radio frequency based integrated communication and positioning system enabling relative and absolute radio navigation, and time synchronization. This technology under the umbrella of KN's research topic swarm navigation system called Radio-CPT (Communication, Positioning, Time synchronization) can be used by robotic platforms, robotic teams, and deployed sensor networks independent of the day

and night rhythm. The Radio-CPT system allows orientation determination of rovers, and their constellation with sub-meter accuracy and better. In addition, the system provides high-precision time synchronization among all robotic platforms and deployed sensors, which is of great importance for coherent measurements, e.g., a large scale seismic array. For long-range traverses DLR develops the so-called return-to-base navigation which uses a low-frequency radio signal emitted from the lunar base. This beacon signal is observed by all robotic platforms jointly, and is exploited to guide all robots back to the lunar base.

- Navigation with on-board sensors and cameras: Rovers will not only use radio frequency signals for navigation but also on-board sensors like odometers, inertial sensors and cameras. Cameras are very powerful for local navigation, yet require a lot of resources for signal processing. DLR has also been developing a framework for using stereoscopic cameras for accurate navigation in unknown environments.
- Multi-sensor navigation and sensor fusion: A key for accurate, reliable and robust navigation in all phases of a lunar mission will be multi-sensor navigation: the fusion of various sensors on a robotic platform will provide the best performance and profits from the strengths of the individual sensors.

DLR actively contributes to the Valles Mariners Explorer Initiative led by the DLR space agency. Within this framework, DLR further developed the Radio-CPT system and successfully demonstrated it in a field experiment.

Payloads and Instrumentation

Cameras

Cameras as technical copies of the human main senor play a very important role for exploration missions. Due to the high spatial resolution these sensors can capture vast amounts of different states of the object space which has to be observed. Accordingly, the scope for interpretation of the scenery is huge. New developments in computer vision and machine learning enable to perform more complex perception and cognition tasks and allow robots to plan and act.

“Classical” cameras (panchromatic or RGB, VGA resolution, 25Hz) will play an important role for all robotic exploration missions, e.g. for the evaluation and selection of landing sites, the control of mobile robots and tools or as a monitoring system. Such cameras are state of the art for decades, nevertheless standard tasks like calibration, registration or referencing, are needed and challenging in space conditions.

Science Cameras

Robotic lunar landers/rovers will form a key part in the next phase of lunar exploration, and such landers will require high-performance scientific camera systems. The functions of such camera systems include (a) setting the context for all the other measurements, including morphological and geological context, (b) providing complementary data for use with those of other instruments, and (c) pursuing scientific objectives defined by the camera investigators (Coates, Lunar PanCam, 2012).

DLR has substantial experience in designing, developing, building, and operating cameras, both regarding remote sensing cameras on orbiters (e.g. Mars Express HRSC, Dawn FC) and cameras on surface robots (eg. Rosetta Philae-ROLIS, MASCOT MASCam, ExoMars PanCam).

Based on the design concept of the ExoMars PanCam, DLR (together with international partners) is already in a position to provide a modular Surface Camera Package for landers or rovers. Due to its highly modular design (each of the three cameras forms an independent scientific instrument, which can be individually controlled), the Surface Camera

Package can be provided in different configurations, depending on the intended objectives. Imaginable examples are:

- A system of a stereo panoramic camera, complemented by a center high resolution channel, for accommodation on the mast of a lander or rover (baseline, heritage design: ExoMars PanCam)
- The same configuration as in 1), mounted on a tripod, could be used by astronauts as a mobile camera system for all kinds of context documentation, monitoring, investigation planning or resource assessment.
- Each of the three proposed camera heads could be mounted as single camera or combination of cameras (stereo) outside or within e.g. habitats to serve as surveillance cameras for monitoring all kinds of activities. (The CMOS APS detector of the high resolution camera can also be operated in a video mode).
- Any configuration which uses as basis unit a wide angle and/or high resolution camera.

Based on the MASCOT MASCam concept, DLR can provide context, descent and arm imagers. These can be used both for scientific observations as well as serve as engineering/ monitoring cameras (e.g. monitoring the deployment of an instrument by a robotic arm).The MASCam is equipped with active illumination with a panel of LEDs in order to enable colour imaging and multi-spectral science. For lunar missions, illumination of the camera FoV is required anyway, because robotic platforms may be shadowed from direct sunlight by terrain, rocks, and/or the spacecraft itself.

Numerous studies are underway in order to improve the accuracy of the spectra, e.g. by using multi-wavelength LEDs in order to keep the angle of illumination when changing wavelengths (e.g. Núñez et al., 2014)

Science cameras are designed w.r.t. their spatial, radiometric, spectral and temporal parameters depending on concrete scientific goals and requirements. New detector materials and technologies will increase the spectral range (e.g. Terahertz) or sensitivity (e.g. sCMOS). Novel concepts, as light field cameras or single pixel cameras applying compressive sensing can be of interest in future.

UV-, VIS- and IR- Spectrometers

Over several decades, DLR has built up its expertise in developing multi- and hyperspectral systems for different wavelength ranges. Reflectance spectroscopy is an ideal bridge between remote sensing and in-situ surface analysis. Depending on the wavelength range, information about mineralogy, presence of water or ice, or biological activity can be obtained. Imaging systems allow for a fast record of the context that is of high relevance for the navigation of the robotic systems or necessary for follow-up analysis that require localization such as laser spectroscopy.

DLR is also working on miniaturizing spectral systems that could be achieved in particular by new sensor systems. Hyperspectral imaging systems allow for improved situational awareness in particular when combined with advanced on-board data processing.

Laserspectrometers

Laser-induced breakdown spectroscopy (LIBS) and Raman spectroscopy have a high potential for the geochemical and mineralogical analysis in in-situ planetary exploration, in particular when combined. Both techniques provide complementary information about the elemental composition (LIBS) and the molecular structure (Raman).

Laser-induced breakdown spectroscopy (LIBS) permits rapid (<minutes) in-situ multi-elemental analysis at a sub millimeter scale with no sample preparation and optical access only. It can be applied remotely over several meters distance with no need for being put into direct contact with the sample. Dust layers are removed by the LIBS plasma shockwave,

allowing the analysis of covered surfaces and even depth profiling up to ~mm through weathering layers is possible with subsequent laser shots. LIBS is particularly sensitive to all kind of metals but also to oxygen and hydrogen. During in-situ exploration, a LIBS instrument can serve as a primary scientific tool for independent qualitative and quantitative determination of sample composition but also as reconnaissance tool to quickly identify potentially interesting targets for further analysis with more laborious and time-consuming contact instruments or guiding selection for samples to be returned to Earth.

Monitoring Stations and Observatories for Lunar Surface Networks

A geophysical monitoring station for future lunar seismic surveys has been developed within the frame of the Helmholtz alliance Robotic Exploration of Extreme Environments (ROBEX, Witte 2017). The concept for this station is inherited by DLR's Mobile Asteroid Surface Scout (MASCOT), which successfully landed on its target asteroid on-board JAXA's Hayabusa 2 mission.

This geophysical monitoring station is a highly integrated instrument carrier with dimensions of 340mm x 240mm x 200mm and a mass of ~10kg. Its intended lifetime is up to several weeks. The modular design enables the accommodation of different payload types and adaption to various deployment concepts. In the design reference scenario, the carrier is equipped with a seismometer to serve as a geophysical monitoring station.

The lunar reference mission considers two scenarios: (i) seismic profiling: the rover deploys (and picks-up again) the seismic station at several measurement spots along a linear path with increasing distance from an active seismic source. Such an active seismic experiment would help resolve the uppermost subsurface layering of the lunar crust. (ii) Seismic network: Four stations are deployed as a Y-shaped array to passively monitor natural seismic activity such as quakes and meteorite impacts, meaning a robotic build-up of a system infrastructure on the Moon.

In both scenarios a medium sized lunar lander with ~1400kg landed mass, and ~160kg payload is assumed to deliver four seismic stations and the roving unit. The Roving Unit autonomously deploys the monitoring stations with ground segment involvement only at check gates to assure and confirm the correct build-up.

The key elements Monitoring Station, Rover, and Control Center were deployed on the occasion of a Moon analogue field test conducted near the Laghetto cinder cone on Mt. Etna / Sicily in summer 2017. During this field campaign the individual elements were tested in an end-to-end mission demonstration of the active and passive scenario. Figure 2 shows a sample seismogram obtained during the monitoring station operations. Intensive laboratory and field-testing of this geophysical monitoring station has verified and validated the involved mission elements, their key technologies and the overall scientific approach.

Future Mission Concepts and Opportunities

National and International Activities

ESA

ESA also published a "Strategy for Science at the Moon" in 2019, defining among others ESA top science priorities on the Moon for the next ten years:

- Analysis of new and diverse samples from the Moon.
- Detection and characterisation of polar water ice and other lunar volatiles.
- Deployment of geophysical instruments and the build up a global geophysical network.
- Identification and characterisation of potential resources for future exploration.
- Deployment long wavelength radio astronomy receivers on the lunar far side.
- Characterisation of the dynamic dust, charge and plasma environment.
- Characterisation of biological sensitivity to the lunar environment

ESA is working with the Canadian and Japanese space agencies to prepare the Heracles robotic mission to the Moon in the mid-to-late-2020s. Using either the Deep Space Gateway as a halfway point or a direct flight, a robotic rover will scout the terrain in preparation for the future arrival of astronauts, and deliver lunar samples to Earth. The ESA-led international robotic mission shall return samples from the Schrödinger crater, around 600 km from the South Pole.

This mission offers the best and earliest chance to deliver Moon samples to Earth on NASA's Orion spacecraft as early as its fourth or fifth mission.

At the forthcoming ESA Ministerial Council Conference in Seville, a decision will be taken on the content and financial resources of the second period of the European Exploration Envelope Program (E3P2). ESA's current program proposal plans a division into four cornerstones: Humans in LEO (CS#1), Humans Beyond LEO (CS#2), Lunar Robotic (CS#3) und Mars Robotic (CS#4). For this roadmap, of course Lunar Robotic is of high relevance.

ESA is also participating in the Roscosmos LUNA program. For the 25 and 27 missions ESA is designing the landing camera and technology for a safe and precise soft landing. While LUNA-26 will be an orbiter, LUNA-27 shall deploy the European Prospect drill that will search for water ice and other chemicals under the surface. For LUNA-27, ESA is providing the PROSPECT package, in which DLR is involved with a scientific contribution, and support of knowledge for the PROSPECT cameras development (Prospect User Group members, Science Team members). The Russian-led Luna-27 mission to the South Polar region will be the first flight opportunity for PROSPECT, but the system is suitable for additional flights to different locations, so there is potential for future collaboration.

Concerning lunar samples, ESA suggests that a European Sample Analysis Network of Centre shall be established as a virtual cross European institute for sample analysis. Initially the network will use near-term opportunities. DLR could join this initiative with its Sample Analysis Lab (SAL).

The investigations will involve multi-centre research on common samples to deliver new science whilst preparing the organisation structures, management and curation standards and approaches, lessons learned, analytical capabilities, and technical requirements to prepare for future missions. Such a network could be extended beyond Europe through bilateral or multilateral agreements. This is currently under discussion with CNSA.

Further activities of ESA in the astronautical context are looking to invest in the development a of technology that can turn indigenous material into useful resources like oxygen and water (ISRU), critical resources for sustaining future human operations in deep space. The long-term plan on bringing back astronauts to the moon is very much alive and ESA is actively testing technology and equipment for the human exploration of the lunar surface.

German National Program

The German National Program is aligning with ESA's plans when it comes to the robotic exploration of the moon. Therefore, it enjoys a high priority in German planning. However does the German Space Agency await a HERACLES concept maturation into an internationally fully viable scenario. The outcome of the forthcoming ESA Ministerial Council Conference will also shape the spectrum the German National Program can provide in this context.

NASA

Very recently, NASA has reshaped its Moon to Mars program on a request by the Trump administration. Currently a 2024 human landing on the moon is of the highest priority for the agency. The shift is very ambitious given its short time frame and it is unclear how much robotic exploration will be possible in its vicinity.

Before that, NASA was preparing to purchase small lunar payload delivery services, develop lunar landers, and conduct more research on the Moon's surface ahead of a human return. The U.S. commercial space industry was to be encouraged to introduce new technologies to deliver payloads to the Moon. NASA intended to award multiple contracts for these services through the next decade, with contract missions to the lunar surface expected to begin as early as 2019, and with a company's first delivery no later than Dec. 31, 2021.

This activity goes hand in hand with the reestablishment of the US human space flight capabilities, seeking a return to the Moon's orbit and surface as a stepping-stone to Mars. For the latter, it is intended to build two mid-size lander demonstration missions that will help NASA understand the requirements and systems needed for a human class lander. These landers will be capable of sample return, resource prospecting, demonstrating use of in-space resources, and their implementation will reduce the risk when building landers for humans. The ongoing small payload delivery missions mentioned above will provide important data on landing precision, long-term survivability, guidance and navigation for the demonstration landers. Resource prospecting itself will get its efforts boosted since the ongoing Resource Prospector mission concept is too limited for the vast robotic and human exploration plans of NASA. NASA also targets the South Pole for sample return.

Besides NASA's plannings there are several commercial activities in the U.S.. SpaceX's Crew Dragon would be usable as a spaceship to a lunar orbital station. Their Super Heavy Rocket (formerly known as BFR) shall carry a private passenger around the moon in 2023. The long-term company's plans are very ambitious, sounding a bit like science fiction however: SpaceX aims at delivering 100 t of usable payload to the surface of the moon with their Starship and Super Heavy Rocket.

Blue Origin intends to set up capabilities to supply a moon base starting in 2025 with a 4.5 t resupply ship, but the exact plans are unclear at the moment and probably are dependent on the New Glenn rocket, intended to have its maiden flight in 2021.

No matter how we rate their long-term plans, both companies should play a vital part in a dynamic launcher field, decreasing the costs of getting to the moon and NASA will heavily use these companies to fulfil the ambitious Moon to Mars goals. Opportunities to take along payloads or robotic systems from international partners, among them DLR, should be pursued.

JAXA

The Japanese long term lunar activities are centered around a future sustainable lunar base and the lunar gateway before that.

In the near future, JAXA aims at sending the SLIM mission to the moon as a technology demonstrator for safe and precise landing in 2021. Later a water-prospecting mission is set to touch down on the moon in 2023 and a robotic sample return mission in 2025. All these are however mainly technology experiments for their ambitious long-term goal of flying a reusable lander for human exploration and sample return.

Roscosmos

A lunar exploration program is currently being developed by Roscosmos and the Russian Academy of Sciences and it will cover the period until 2040. In the long run, Russian scientists plan to mine water ice to extract hydrogen and oxygen, the two fuel components, and build shelters from regolith found on the moon surface.

A close next step of the Russian exploration of the moon is the reopening of the LUNA program from the 1970s with the aforementioned LUNA 25, 26, 27 and 28. The new missions aim at landing on the moon (LUNA 25), establishing a communication relay satellite around the moon (LUNA 26) and getting to the South Pole/Aitken Basin to explore the possibility of resource extraction there for human exploration (Luna 27). Luna 28 is then a sample return mission to the South Pole/Aitken Basin. DLR is currently exploring the possibility to provide a hardware contribution to the Luna 28 mission

CNSA

The Chinese Lunar Exploration Program (CLEP) is coordinated by the Chinese Space Agency CNSA. Its mostly know for its lunar orbiters and lander called Chang’e 1 to 4. Chang’e 4 is the most famous of them, since it completed a successful landing in the Kármán crater in the South Pole Aitken Basin on the far side of the moon in January 2019 and deployed the Yutu-2 rover. The next mission, Chang’e 5 is scheduled for December 2019 and is a sample return mission, aiming to return at least 2 kilograms of lunar soil and rock samples back to the Earth. As landing site, the Mons Rumker region of Oceanus Procellarum is foreseen. Actually, the CLEP is divided into 4 phases with the soft landing and rover phase of Chang’e 3 and 4 being phase 2 and the upcoming sample return of Chang’e 5 (and 6) being phase 3. The last phase will then be technology demonstration missions for permanent surface stations, currently planned for 2023. Especially ISRU shall be tested, for both fuel generation as well as habitat building.

As we can see, the robotic lunar exploration plans of the CNSA are very ambitious, fast paced and so far very successful.

ISRO

India’s Space agency ISRO has launched the Chandrayaan-2 mission to the moon, which includes a rover that is going to land in the South Pole region. In the event of a successful landing, India would be the fourth country to place a probe on the lunar surface.

Beyond Chandrayaan-2, ISRO is currently looking for international partners for the robotic exploration of the moon, intending to upgrade their arm technology in order to be able to handle samples on the surface and improve the capabilities of their in-situ exploration systems.

Further Players

OHB Germany and Israel Aerospace Industries have signed a treaty to jointly offer a commercial Moon landing mission to ESA with a 150 kg payload capacity.

Road Ahead

Missions

Currently, one exploration mission is in the planning stage – JAXA’s MMX mission to the Martian Moon Phobos. DLR contributes to this mission with robotic elements (e.g. locomotion system) and scientific instruments (e.g. Raman spectrometer).

In collaboration with Russian Roscosmos and ESA, Germany is involved in Luna-27. Scientific and technical knowledge will be provided, but no hardware contribution is foreseen.

Luna 28 is under investigation w.r.t. a German hardware contribution. Robotic and sensor technologies shall be provided.

Other possible robotic exploration missions will be kept under review. All these missions are seen as preparations to approach the final goal - a German robotic exploration mission to Moon.

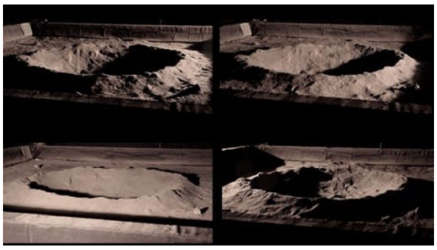
Contributions and Roadmap

After defining scientific goals for a Moon mission, analysing the environment and after identifying technologies needed, possible technical contributions of DLR’s space institutes were identified and listed below. A more detailed description of these contributions including key developments and schedules can be found in the attachment.

Contribution	Lead institute	Missions	TRL in 2019	Flight model	Required key technologies
LRU rover	RM	MMX, Luna28	3-6	2025	Manipulation, Docking Interface
Agile scout rover system	SR	MMX, Luna 28	3	2030	Wheels, module, control
Raman and LIBS spectrometer	OS	MMX, Luna 28	3-5	2021, 2028	Laser, temperature control
Lightfield camera	RM		3	2029	Onboard processing, Micro Lens Array
Testbed LUNA	RB				
Optimal wheels	SR	MMX	3	2021	Traction optimization, mass reduction, design and manufactoring
Radio communication, positioning, and time synchronization	KN		3	2025	Space grade software-defined radio
Rover chassis control system	SR	MMX, Luna 28	2	2027	Nonlinear model-based controller, controller design , terramechanics know-how, rover controls library, algorithms for parameter adaption, observer design
Simulator	SR	MMX, Luna 28	3	2025	Merged simulation, spacecraft state simulation, user interface
Surface stations	RY		4	2025	Core avionics
Swarms	KN		3	2028	Distributed data analysis
Rover Control Center	RB	MMX		2021	

Appendix: Relevant Projects

LUNA


NASA Lunar crater testbed © NASA

DLR and ESA plan to establish a Lunar surface testbed at next to the existing EAC (European Astronaut Center) building on the premises of DLR Cologne-Porz. LUNA will consist of various elements which represent a future human and robotic spaceflight architecture on the lunar surface. The whole LUNA analogue site aims at symbolizing the Earth model for the future "Moon Village" and will in future consist of the following additional elements: the Flexhab, the Flexhab energy container, potential extension options for Flexhab (e. g. ISS Eden greenhouse module, crew quarters module), and additional external lab containers. ESA and DLR intend to join forces by involving human space flight expertise from both sides and by jointly operating the LUNA facility.

Although LUNA is primarily set up to allow simulations involving astronauts it is also a sophisticated facility to test robotic elements or a combination (robotic elements installed by humans, like e.g. the ALSEP stations during the Apollo missions).

LUNA will provide a realistic Moon (and Asteroid) analogue environment for technological tests and assessments in an integrated operational setup, for the training of astronauts for future human-robotic operations as well as for supporting outreach and Public Relations activities. It is planned to construct a new hangar over around 1100m² total area, comprising around 750m² simulated lunar soil complemented by an area of approx. 350m² of additional secondary rooms. Next to this hangar, a habitable lunar station simulator called Flexhab will be built, which shall be expandable in later evolutions through the addition of future modules. A completion of the LUNA hangar structure followed by a start of its technical and operational outfitting and first operations is planned for end of 2020/beginning of 2021.

Rimless Wheel based Agile Scout Rover for Extreme Terrain

Strategic Goal

DLR will develop a small scale (10-30kg) agile scouting rover based on rimless wheels, that is able to carry 3-6kg of payload into extreme terrain (rubble fields, craters, lava tubes, soft regolith areas and planetary caves). The system shall be mission-ready (TRL 8) until 2030.

Current Status

Current planetary rovers are not able to traverse extreme terrains and are not fast enough to travel up steep pitches like crater walls. Furthermore they are not sufficiently robust to survive terrains like planetary caves. DLR has developed a lab model of an agile modular scouting rover (TRL 3) and its rimless wheels (TRL 4). With these lab models several extreme terrain traversals have been demonstrated in 2018 and 2019 alongside robustness tests (dust, snowy/icy terrain, drop test up to 1.5m). After finalizing the lab model a small research group has been formed that pushes the development of the system towards TRL 6, while pursuing several PhD thesis on this topic.

Key Technologies

Several key technologies were identified which need to be developed. Components, units and technologies with a high maturity level and/ or a sufficient heritage (e.g. mechatronic actuation (DLR-RM), multi-physics system simulation (DLR-SR), terramechanics simulation (DLR-SR)) and other strategic goals like optimized rover wheels, which also apply for the agile scouting system are not considered in this section of the roadmap.

The first key technology identified on component level is the rimless wheel of the agile scouting rover. With TRL 4 its applicability has already been shown in the lab. Even though materials have been chosen to be space qualifiable in a basic manner, the material choice and characterization requires further work to reach a TRL 6 compliant design by 2021.

The second key technology is the control and coordination of the individual wheels on rover locomotion level (TRL 2/3). This control will be developed to serve as a terrain adaptive control in order to assist in obstacle crossing as well as for robustness in traversal of planetary caves. The key technology itself is described in the section "terrain-adaptive control system".

The next key technology are the single modules of the system containing the actuation and power electronics for the locomotion with being the overall locomotion system with a baseline of three locomotion modules connected together. DLR will push these three key technologies towards TRL 5/6 (6 for the rimless wheels), but does not have, and does not aim to build the knowhow to develop the hardware itself further. For reaching TRLs beyond 6 it is planned to develop the system in the context of all DLR space exploration institutes, whereas DLR takes the lead for the locomotion system and its control. The whole system is aimed to reach TRL 8 at 2030.

Therefore important key technologies to be contributed from across DLR are:

- Autonomy
- OBC
- Mechatronic actuators & power electronics
- Docking interface to lander or bigger rover
- Camera system
- Payload
- PCDU, Battery and solar cells
- Thermal design
- Communication system

Thereby some key technologies may be used from heritage of previous missions, such as MASCOT, InSight and current missions such as MMX.

Inputs for the Moon Roadmap

DLR has applied to include the optimized wheels in JAXA's MMX mission to Phobos which shall be launched 2026. EQM shall be delivered 2020, FM 2021. Therewith DLR will be able to increase the TRL of the rimless wheel to 6 by 2023 and 8 by 2026.

Rimless wheels for an extreme terrain rover could be supplied to missions on EM level by 2023 and FM-level in 2026. Hence a first possible mission to supply the rimless wheels could be Luna 28. While the overall locomotion system will be suppliable as EM in 2026 and FM 2030, it is encouraged to start the contribution of other institutes as soon as possible to include other key technologies as soon as possible and aid to meet the goal of a mission ready rimless wheel scout for extreme terrain in 2030.

Light Field Hand Lens Imager

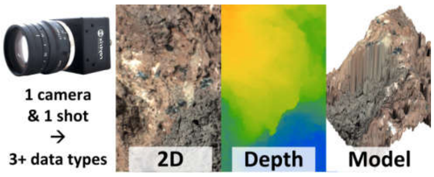
Strategic Goal

DLR will develop a next generation in-situ hand lens imager based on light field cameras until 2030 - 2033 (TBC).

Current Status

DLR systematically investigates the light field camera technology for in-situ hand lens imaging with project LIPA. Light field cameras can provide 2-D and depth data of geological objects with submillimetric accuracy over a relatively wide range if compared to conventional cameras. This can be used for scientific hand lens imaging as well as for robot arm control in terms of collision avoidance and accurate instrument positioning in the range between 0.5m to 20cm, depending on the mission requirements.

The current sensor qualification experiments will result in a TRL3 status by the end of 2019. The experiment will show the camera performance for representative in-situ application scenarios and for different illumination conditions. Currently, the experiment setup consists of high quality components off the shelf including a European image sensor that is space ready (CMV CMOS sensor series by ams, also used on the Mars2020 rover).



Light Field Hand Lens Imager (LFHLI)

Key Technologies

The key technology is the on-board processing of light field data. This is required to create 2-D images and depth data and in order to reduce the amount of data for transmission to earth. It is the main development task as most current light field algorithms are not designed or implemented for resource limited systems. Therefore, they need to be adjusted to the requirements and constraints of a space mission, which is ongoing research at DLR.

A light field camera is achieved by mounting a matrix of small lenses, the Micro Lens Array (MLA), inside a conventional camera. Hence, current space grade cameras and lenses can be reused but a space grade MLA needs to be developed and the modification procedure needs to be verified and validated. As an advantage, the standard workflow of optical design as known for conventional cameras can be applied.

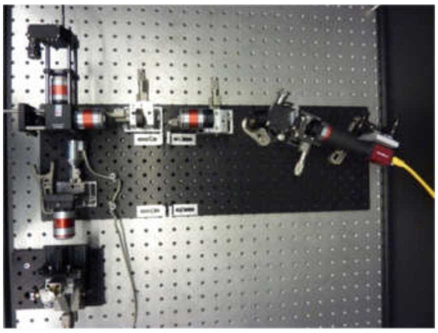
Inputs for the Moon Roadmap (all dates TBD)

DLR will finish the TRL3 review and a development roadmap for in-situ light field hand lens imaging by the end of 2019 and focus on the development of more efficient light field processing from 2020 (TBC) on. Starting in 2023, the technology maturation, with TRL4 as the first step, of a light field hand lens imaging system can begin. Depending on available resources, the overall maturation duration can vary between 7 to 10 years (TBC).

LIBS/ Raman Spectrometer

Strategic Goal

DLR will develop a combined imaging LIBS/ Raman Spectrometer until 2030.



Breadboard of the Raman spectrometer for MMX

Current Status

DLR has built a lab model for a combined LIBS-Raman instrument (TRL 3) in 2017 and has investigated multiple concepts for the integration of the two measurement techniques into a single instrument suite. Individual setups for miniaturized LIBS and Raman with TRL 3 were also built in 2018. A Raman spectrometer breadboard model for the MMX mission will be ready by the end of 2019.

With these lab models, several scientific research questions on samples of specific interest (e.g. samples from the Hayabusa sample return mission, analog samples for Mars, the Moon, Phobos and icy moons, meteorites) and in extreme environments (like Martian atmospheric conditions or vacuum) were investigated. Spectrometer concepts regarding hardware components as well as methodology were developed and evaluated. Several PhD theses were completed on LIBS and Raman in the context of planetary exploration. DLR has close connections to the teams of the ChemCam instrument on NASA’s Mars Science Laboratory (MSL) mission and of the SuperCam instrument on NASA’s upcoming Mars 2020 mission and has know-how on in-situ operations of these instruments. DLR is involved with a Raman spectrometer in the Japanese MMX Sample Return Mission, with French and German rover and payload contributions.

Furthermore, DLR has developed concepts and algorithms for single-pixel cameras which can provide spatially resolved images based in compressive sensing approaches. The techniques were demonstrated in a lab with a THz system.

Key Technologies

Several key technologies were identified which need to be developed. Components, units and technologies with a high maturity level and/ or a sufficient heritage are not considered in this roadmap (e.g. spectrometer unit, power supply, on-board software).

The most demanding technology for LIBS/ Raman spectrometers is the laser. It needs to be stabilized and aging/ degrading processes need to be handled. DLR does not have the knowhow and degree of vertical integration to solve the issues by its own and cooperates with INTA (Spain), LZH and FBH (both Germany). In this context, an additional challenge is the interface between the laser and the spectrometer unit, which emerges as an optical design driving task, and which needs to be fully understand.

Thermal control can turn out to be a major design driver, since requirements for small/ compact measurement devices and the existing environment conditions counteract.

Inputs for the Moon Roadmap (all dates TBD)

DLR has applied for a Raman spectrometer on JAXA's MMX mission to Phobos which shall be launched 2024 and will last till 2026. EM/DM shall be delivered Q2/2020, EQM Q4/2020, PFM delivery Dec. 2021.
DLR will apply for Roscosmos' Luna-28 mission to Moon with a LIBS spectrometer. EM shall be delivered 2024, QM 2026, FM 2028.
DLR is willing to provide Raman/ LIBS to CAS/ CAST and ISRO missions, first consultations took place in 2018 and 2019.
Considering these missions and mission proposals core technologies shall be available before end of 2019 (EM), 2021 (QM) and 2023 (FM).

Modelling and Simulation of In Situ Exploration Systems

Strategic Goal

DLR will develop a comprehensive robotic exploration system simulator, ready for use throughout all mission phases. It shall facilitate phase 0 feasibility studies, design definitions in phase A/B, integration and testing in phase C/D/E and operations and science activities in phase F using one consistent simulator product line. The simulator covers all relevant physical domains of the robotic system and is intended to simulate all mission events on the planetary surface.

Current status

DLR has implemented simulators for planetary missions and mission studies since almost two decades, e.g. for ExoMars by ESA. Latest experience is gained through the asteroid exploration mission MASCOT on Hayabusa 2 in cooperation with JAXA and CNES. DLR also provided the HP3 payload instrument to NASA JPL's InSight mission that landed on Mars in November 2018. Today's activities are focused on the simulation of the rover for the Martian Moons Exploration (MMX) mission to Phobos, also in cooperation with JAXA and CNES.

For the development of the MMX rover, a number of simulators and simulation tools exist that cover specific domains on subsystem level, e.g. for structural analysis of the rover casing or for thermal analysis of payload and electronic board accommodation spaces. The simulator on vehicle system level so long consists of the mechanics of the locomotion subsystem. Here, multi-body dynamics and terramechanics play a major role. To a minor extent, energy aspects are also already subject of the simulation as well as mechanisms e.g. for the solar panel deployment.

Small body missions like MASCOT on the asteroid Ryugu and MMX on Phobos operate in very low gravity environments. This results in several constraints regarding the robotic locomotion strategy and requires very careful and slow operations in general. So far, it is not fully verified how well simulation models, especially terramechanics models, validated under earth gravity conditions scale down through five or six orders of magnitude. However, the scaling issue is much easier to tackle in the context of missions to Moon where the gravity is about 16% compared to Earth. Here, the results of ground test with prototypes are supposed to be applicable for simulation model validation.

In fact some work packages of the DLR project MOREX (Modulares Robotisches Explorationssytem) were about rover simulations with a focus on Moon and Mars operations, the most likely celestial bodies to be explored at the time of the project inception. Thus, DLR's system simulators for Phases 0 to D of lunar and Martian missions are well advanced and have already undergone some validation for Earth-like gravity.

When it comes to the operations phase there is some heritage from the ROBEX project (Robotic Exploration of Extreme Environments). A tool for software in the loop simulation of a single mobile robot (the Lightweight Rover Unit LRU) was developed and successfully operated in a demo mission on the Etna volcano on Sicily island.

Every simulation activities begin with generating models of the system that is to be simulated. Tools like Dymola already come with many basic and some advanced parts for the multi-body dynamics, electrical and thermal subsystems. But a thorough understanding of the interaction between the wheels and the regolith is crucial. For analysis of the full system a smart combination of the multi-body system, regolith as well as other domains such as thermal and power considerations are essential. Beyond locomotion aspects, the combination of these areas has great potential for the development of in situ resource utilization (ISRU) systems. The in-depth modelling and simulation of both the mechanical systems and the regolith handling is a key factor in the development of ISRU systems.

Key Technologies

In view of future DLR-lead in situ solar system exploration missions, the system simulator of the surface spacecraft has to be extended to other domains in order to have a good matching between the simulation model and the actual system. There are two ways to achieve this: co-simulation of existing domain-specific simulators or integration of methods and models from other domains into the full system simulator. The preferred option depends on the effort to integrate existing simulation models and to implement a performant runtime data exchange.

The mechanical part of the locomotion subsystem for rovers is already well developed (TRL4) including contact dynamics simulations with soft soil (i.e. terramechanics) and obstacles. Validation of the models, at least for environments in Earth-like gravity, is good on its way and is expected to advance to higher TRL fast because of the availability of very good test facilities like TROLL and the ExoMars Breadboard. Validation for milli-g environments are more difficult to perform. In this context, a prototype for the MMX rover is scheduled for the second half of 2019. Correlation of test results with this system and corresponding simulations results will improve the required fidelity level by 2020.

Still to be developed, specifically for terramechanics in a broader sense (i.e. not just for rovers but to get the knowledge needed for regolith processing) is a technology that focuses on the modelling and simulation of the material flow, e.g. needed for scenarios like 3D printing of regolith. This includes extraction of material, transportation, compaction and final handling of the printing process. The control engineering for robotic regolith manipulation needs more development as well. It comprises precise manipulator positioning as well as stable mobility of the platform and can be built upon DLR's large knowledge of advanced control.

When it comes to structural loads on the bodies of the spacecraft, e.g. for the landing, the current full system simulator is not yet sufficiently advanced. It can calculate the overall impact forces based on the contact dynamics of the bodies involved. However, it is currently not possible to get the reactions of the body structures because this simulator operates only with rigid bodies and occasionally flexible joints (this level of detail is enough for a large majority of simulation tasks). Nevertheless, models for the structural behaviour of certain spacecraft components such as wheels, legs and casing exist but must still be linked with the full system simulator on force level. Both simulation models together can thus demonstrate or disprove whether the spacecraft survives the landing. The first proofs of concept (TRL3) have been shown in early 2019 for the impact on the wheels to be expected when the MMX rover is going to land on Phobos. However, this activity is not the best to raise TRL because of the much unknown nature of the Phobos surface. Applying the same methods, i.e. data exchange between different simulators, with lunar exploration in mind would make laboratory validation possible. A time frame of two years, until 2021, is reasonable.

A similar time frame is scheduled for extending the full system simulator to include electrical energy storage. Here again, DLR already has existing simulation models. Due to the fact that these models are also implemented using Modelica technology, the integration into the full system simulator is a relatively easy task. The same DLR team did also implement models for solar power generation in Dymola. The timeline to include these to the simulator for surface spacecraft is somewhat longer because this requires more external knowledge about the actual environmental conditions of the celestial body at hand.

There are currently no experts of thermal engineering working on simulators as understood in this document. Luckily, the Modelica library has very good basic building blocks (TRL2) for thermal simulations. But it’s not just drag and drop some of them into the existing system model to extend it to the thermal domain. The aim is currently to provide simple thermal support on system level for the MMX rover in the coming years up to 2021 and to use this occasion to develop the required expertise in house. However, it seems unrealistic that even a successful MMX mission will be enough to reach TRL8 for this simulation component. But the lessons learned should be of great value for ongoing exploration missions.

Once these modelling and simulation technologies are available, it remains to merge them together and make them available for the operations team since the simulator is intended to be used during every mission phase. In order to link the simulator and the actual spacecraft in the field, a reconstruction of the spacecraft state and the environment from sensor data needs to be implemented. Reconstruction of the internal rover state, for example the positions and velocities of mechanical parts and actuators, from data external to the simulator is already possible at the time of this writing (2019), albeit not in a very user-friendly way. However the reconstruction of the entire rover pose, that is the position and orientation with respect to the surface, is a more demanding task and not yet feasible with the current simulator. And even more challenging will be to identify the surface conditions, although mapping capabilities are good under development along DLR’s navigation and autonomy software.

Inputs for the Moon Roadmap (all dates TBC)

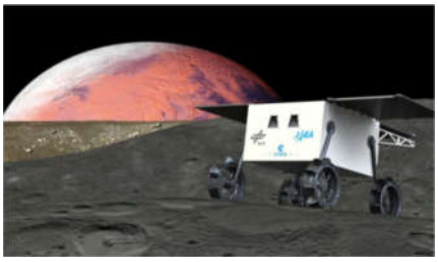
DLR has applied to do the full system simulator on JAXA’s MMX mission to Phobos which shall be launched 2026. EM shall be delivered 2021, QM 2023, FM 2025.

DLR will apply for Roscosmos’ Luna-28 mission to Moon with surface spacecraft simulator. EM shall be delivered 2024, QM 2026, FM 2028.

Rover Control System

Strategic Goal

DLR wants to develop terrain-adaptive control systems for all kind of wheeled mobile robots, including rovers with rimless wheels.



Rover chassis control system, MMX as an example
©JAXA, CNES, DLR

Current Status

DLR is working on locomotion controller for different rovers and terrains. This work covers the development of the control algorithm, Software-in-the-loop as well as Hardware-in-the-loop implementation and testing.

In particular, the following locomotion controllers are studied:

- Kinematic controller for ExoMars (TRL 3)
- Model-based torque controller (TRL 2)
- Locomotion controller for a scout rover with rimless wheels (TRL 2).

High fidelity terramechanics models were developed and validated. A real-time capable empirical model was developed to be used on-board (TRL 3).

Key Technologies

The key technologies are:

- Nonlinear model-based controller design for complex mobile robot systems, specifically including planetary exploration rovers, and other over-actuated mobile robots
- Controller design for mobile robots with flexible components and rimless wheels
- Terramechanics know-how: High fidelity developed and validated, reduced for on-board usage
- Rover controls library with algorithms for different terrains
- Algorithms for parameter adaption and controller switching
- Observer design and machine learning algorithms for terrain characterization

Inputs for the Moon Roadmap (all dates TBD)

DLR is designing and implementing a kinematic chassis control algorithm and a locomotion controller for soft ground for the MMX mission. Thereby, the TRL of the controller design will be raised and experience about space software development will be gained.

DLR will apply for Roscosmos’ Luna-28 mission to Moon with a controller for high velocities on different terrains adapted to the rover design is developed. With these contributions and the developments in the key technologies, DLR will be able to supply a terrain-adaptive control system for a lunar rover in 2030.

MASCOT as heritage system for future surface stations as geophysical/astronomical observatories

Surface Stations as Geophysical/Astronomical Observatories

Strategic Goal

The strategic goal is to develop and qualify a stationary and self-sustained instrument carrier for geophysical and/or astronomical observations from the lunar surface. These surface stations can be deployed stand-alone as precursor mission elements or as an ensemble in a monitoring network.

Current Status

The core concept is based on the MASCOT architecture which has successfully flown in 2019. The mobile asteroid surface scout feature a shoe-box sized structure which is divided into a payload compartment and a common electronics compartment containing the system’s core avionics and the instrument’s back-end electronics. In the ROBEX project this concept has been adapted into robotically deployable surface station. The interaction between surface station and rover/manipulator system has been field tested and demonstrated in an Earth analogue environment. The surface station features several improvements with regard to the original MASCOT bus. These are: (i) extended lifetime in terms of week or month through solar array based power supply, (ii) thermal isolation to achieve lunar night survival without use of radio isotope heating units, (iii) a modular, stackable structure to enable combination of several units into a single system. Further details are outlined in the section.

Core Technologies

Core technology is the highly integrated common core avionics inside the modular architecture. Such surface station is thus capable to accommodate a large variety of payloads and instruments and provide shelter to them. All involved technologies are a different TRL stemming from flight heritage or at least laboratory and/or analogue tests (TRL 4-5). The overall system readiness level can be regarded as SRL 3 as the robotically deployable surface station concept proofed viable through field test demonstration.

Next steps (preliminary schedule)

A further raise in TRL and SRL requires a specific instrument or payload definition to allow reverting from a generic concept towards a specific application. Such a “mission pull” will allow to define the system’s budgets and interfaces to the specific mission scenario. It is estimated that SRL 5 can be reached within two years after mission and (strawman) payload definition. Flight readiness can be achieved within four years.

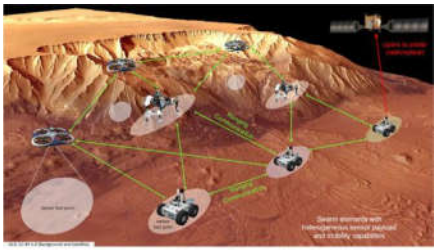
Swarm Exploration

Strategic goal

Develop and test a swarm-based exploration system for distributed data processing with application to fast territory scouting and subsurface seismic imaging by 2028

Current Status

In 2015 DLR has established a new research group whose goal is to investigate into the use of exploration strategies for robotic swarms – platforms consisting of multiple identical robotic platforms working cooperatively towards a common objective. The focus of the studies is placed on two complementary problems in swarm exploration: development of distributed data processing algorithms for (i) cooperative computations of a model of a sensed phenomenon, and for (ii) computations of new sampling locations for the swarm.



Conceptual view of swarm explorations

DLR has succeeded in solving both tasks (at TRL3) for swarms of up to 5 robots for exploration of spatial time-invariant processes, such as mapping of a magnetic field variations, as well as for exploration of spatiotemporal processes, specifically, exploration of gas sources under the influence of diffusion and convection. In both cases the techniques were demonstrated in laboratory and outdoor environments with real hardware. In 2018 in the context of final experiment of Vales Marineris Explorer Project we successfully performed and experiment with 5 mobile robots demonstrating fast real-time processing of data and distributed computing.

Core technologies

Distributed exploration schemes are in the focus of swarm exploration activities in the Lunar Exploration roadmap. Two specific applications scenarios are identified as particularly relevant for possible future Lunar missions: fast territory mapping/scouting and seismic subsurface exploration. In both cases, the underlying processes can be considered as static; swarm is used in these applications as a distributed adaptive sensing array. For the first application the key challenge is increasing the TRL level of distributed data analysis algorithms beyond TRL3, as well tight integration with swarm communication and localization system. In case of seismic exploration the adaptive aperture of the swarm can be used adjust the system parameters to needs of a specific scientific mission. Through cooperation between several scientific and engineering DLR institutes an optimal exploration strategy for seismic data can be derived that permits a swarm to automatically reconfigure itself.

Next steps (preliminary schedule)

Development of the considered applications for scientific missions defined within this road map, such as fast mapping of a spatially-distributed field using distributed data processing over a swarm network, and swarm seismic subsurface exploration.

- Development of the EM for swarm-based mapping by 2024 and demonstration of the technology in experiments by 2027.

- Development of the EM for seismic exploration by 2025 and demonstration of the technology in experiments by 2028.

Wheel Optimization, Design and Testing

Strategic Goal

DLR will develop a methodology to deliver optimized rover wheels as components to exploration missions till 2022 with TRL 8. DLR aims to contribute optimal wheels to as many exploration missions as possible until 2030.

Current Status

Current wheels of planetary rovers usually feature experience and terrestrial test based design. Several missions (MER, MSL) showed that this design is not sufficient for more demanding terrain and soft soils. Hence DLR has developed and validated a set of terramechanics models and simulation techniques in various accuracy levels over the last decade. Furthermore DLR has developed a traction optimization strategy in Project MOREX, which is currently used for MMX (2019 TRL 4). For MMX this will be developed to TRL 8 till 2022 and will reach TRL 9 after operation of the MMX rover in 2026.

DLR is also designing, building the wheels as a product for the MMX rover. Therefore mass optimization, light-weight technologies, topology optimization and manufacturing processes are investigates and are currently at TRL 3. Finally thorough physical testing and characterization of wheel prototypes is critical. To achieve the necessary testing capabilities the Terramechanics Robotics Locomotion Lab, or short TROLL has been developed within the MOREX project. It is a continued development of conventional single wheel testbeds. Due to its heritage from industrial robotics the TROLL feature a high level of automation and is thus capable of automated testing and soil preparation. Within the MMX Project the TROLL is used for wheel design support, model validation and physical testing. In the MMX Mission all key technologies will reach TRL 8 till 2023 and TRL 9 in 2026.

Key Technologies

Several key technologies were identified which need to be developed. Components, units and technologies with a high maturity level and/ or a sufficient heritage are not considered in this roadmap (e.g. particle based terramechanics modelling and simulation (DEM), initial testbed design and construction), but will partially be considered in the timeline.

The most demanding technology for optimized wheels is the traction optimization which requires high-fidelity particle simulations, which are computationally demanding. Thus the simulation framework *partsival* needs to further apply the used GPU technology to speed up simulations in order to lower the overall optimization duration.

The second important key technology is the mass reduction, application of light-weight technologies and sustainability of high loads, which includes the topology optimization of the wheel design using FEM simulations.

The third key technology required is spanning the design and manufacturing of the complicated, light-weight and traction optimal wheels, which are usually thin walled and of complex shapes.

With regards to the physical wheel testing a second set of technologies were identified which need to be developed in parallel. The core feature, the traction characterization of a wheel is divided into the testing procedure, the necessary hardware as well as the regolith simulant selection and preparation. These technologies need to be adapted to the specific use case of each application, e.g. extremely low gravity on Phobos, or the characteristics of a Luna-28 mission.

Inputs for the Moon Roadmap (all dates TBD)

DLR has applied to include the optimized wheels in JAXA’s MMX mission to Phobos which shall be launched 2026. EQM shall be delivered 2020, FM 2021.

DLR will apply for Roscosmos' Luna-28 mission to Moon with optimized wheels for a lunar mission. EQM shall be delivered 2024, FM 2026.

DLR is willing to provide further optimized wheels for different planetary bodies throughout upcoming years and proposed to deliver a wheel design for the Part Time Scientist team lunar mission. Considering these missions and mission proposals core technologies traction optimization, mass reduction as well as TROLL shall be available in 2020 (EM), 2021 (FM) and 2026 (TRL 9). An adaption of the TROLL in the Luna-28 context will be necessary.

Appendix: Abbreviations

ALSEPs	- Apollo Lunar Surface Experiment Packages
APS	- Active pixel sensor
ARCHES	- Autonomous Robotic Networks to Help Modern Societies
BB	- Breadboard
BFR	- Super heavy rocket
CAESAR	- Compliant Assistance and Exploration SpAce Robot
CAS	- Chinese Academy of Sciences
CAST	- China Academy of Space Technology
Chandrayaan	- Indian spacecraft
Chang’e-1-5	- Chinese spacecraft
ChemCam	- Chemical Camera onboard Curiosity
CLEP	- Chinese Lunar Exploration Program
CMOS	- Complementary metal-oxide-semiconductor
CNES	- Centre national d'études spatiales
CNSA	- China National Space Administration
COTS	- Commercial off-the-shelf
CPT	- Communication, Positioning, Time synchronization
CS	- Corner stone mission
DEXHAND	- DLR’s multi-finger robotic hand
DEM	- DLR’s particle based terramechanics modelling and simulation
DLR	- Deutsches Zentrum für Luft- und Raumfahrt e.V.
DM	- Development model
DoF	- Degrees of freedom
DSG	- Deep Space Gateway
E3P2	- European Exploration Envelope Program
ECSS	- European Cooperation for Space Standardization
EM	- Engineering model
EMI	- Electromagnetic interference
EQM	- Electrical and qualification model
ESA	- European Space Agency
ExoMars	- ESA’s and ROSCOSMOS’ mission to Mars
FBH	- Ferdinand-Braun-Institute
FEM	- Finite Element Model
FM	- Flight model
FoV	- Field of view
GPU	- Graphics processing unit
GPR	- ground-penetrating radar
GRAIL	- gravity data record
H2020	- Framework Programme for Research and Innovation of the EU
HAYABUSA	- Japanese spacecraft
HERACLES	- ESA’s Moon mission
HP3	- DLR’s Heat Flow and Physical Properties Package on InSight mission
HRC	- high resolution channel
HRSC	- High Resolution Stereo Camera
InSight	- Interior Exploration using Seismic Investigations, Geodesy and Heat Transport
INTA	- Instituto Nacional de Técnica Aeroespacial
IR	- Infrared
ISRO	- Indian Space Research Organisation
ISRU	- in situ resource utilization
ISS	- International Space Station
JAXA	- Japan Aerospace Exploration Agency
JPL	- Jet Propulsion Laboratory

LAN - Local Area Network
LCROSS - Lunar CRater Observation and Sensing Satellite
LED - Light-emitting diode
LEO - Low Earth orbit
LIBS - Laser induced breakdown spectroscopy
LIPA - Lichtfeldkameras für In-situ Planetologie und Astrobiologie
LRO - Lunar Reconnaissance Orbiter
LRU - Lightweight Rover Unit
Luna - Russian robotic spacecraft missions
LZH - Laser Zentrum Hannover e.V.
Mangalayaan - Indian spacecraft for Mars mission
MARA - MASCOT Radiometer
MASCam - DLR Camera on MASCOT
MASCOT - Mobile Asteroid Surface Scout
Mastcam - Mast Camera
MCI - MoonRise Context Camera
METERON - Multi-Purpose End-To-End Robotic Operation Network
MEV - Mission Extension Vehicle
MLA - Micro Lens Array
MMX - Martian Moons eXploration, JAXA mission to Phobos
MoonRise - NASA's robotic mission concept to Moon
MOREX - MOdulares Robotisches EXplorationssystem
MPE - mobile payload element
MSL - Mars Science Laboratory
MUPUS - Multi-purpose Sensors for Surface and Subsurface Science
NASA - National Aeronautics and Space Administration
OBC - On-Board Computer
NIR - Near infrared
PanCam - Panoramic Camera
PFM - Proto-flight model
PP - Permittivity probe
ProSEED - Context and drill camera
QM - Qualification model
RAFCON - RMC advanced flow control, software tool box
RF - Radio frequency
RGB - Red green blue
ROBEX - Robotische Exploration unter Extrembedingungen, Helmholtz project
ROKVISS - RObotic Components Verification on the ISS
ROLIS - Rosetta Lander Imaging System
Roscosmos - Russian space agency
ROTEX - Robot Technology Experiment on Spacelab D2-Mission
SAL - Sample Analysis Lab
SamCam - sample camera
SCM - Soil Contact Model
sCMOS - scientific CMOS
SELENE - JAXA Moon mission
SMART-1 - ESA Moon mission
SPA - South Polar Aitken Basin
STATIL - Tiltmeter for HP^3 mole
SuperCam - Instrument on NASA's Mars2020 mission
TBC - to be confirmed
TCP - Tool center point
TINA - Small Arm for Planetary or Indoor Manipulation
THz - Terahertz
TRL - Technology readiness level
TROLL - Terramechanics Robotics Locomotion Lab
UKSA - United Kingdom Space Agency
VGA - Video Graphics Array

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DLR at a glance

The German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt; DLR) is a research institution in the Federal Republic of Germany. Operating on an international scale, it conducts research and development activities in the fields of aeronautics, space, energy and transport, as well as in the cross-sectoral areas of security and digitalization. DLR's headquarters are located in Cologne. DLR uses the expertise of its 47 research institutes to develop solutions to global societal and economic challenges related to climate, mobility and technology.

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The 8500 members of staff at DLR share a mission – to develop technologies for a sustainable future. In doing so, DLR contributes to strengthening Germany's position as a prime location for research and industry.

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