LUNA ANALOG FACILITY: MOON SIMULATIONS IN COLOGNE

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Summary
With LUNA, a globally unique facility is being created in Cologne that will make a replica of the lunar surface combined with various technical possibilities and extensions accessible to a large circle of users. The project, jointly conducted by the European Space Agency (ESA) and the German Aerospace Center (DLR), benefits from the expertise of both organizations in the field of human and robotic spaceflight missions. The present paper describes the elements of LUNA, the project status, and operational structures.

1. INTRODUCTION

With the Artemis 1 mission in December 2022, humanity has once again set out for the Moon, which means that in a short time we will once again see surface activity by astronauts on the lunar surface.
After several U.S. and Soviet missions landed on the lunar surface in the 1960s and 1970s, there was no further surface activities for decades until with China (2013, Chang'e-3 [1]) and, more recently, India (2023, Chandrayaan-3 [2]), two more countries demonstrated their ability to perform a lunar landing.
Thus, the surface of the Earth's companion is once again moving strongly into the focus of scientific and technological, but also economic interest:
The mission plans and visions go far beyond the goals of the Apollo program: Infrastructure is to be built on the Moon, the operational scenarios are much longer and more complex [3], and the moon's natural resources are to be exploited and processed, with robots and astronauts playing an equally important and integrated role.
In preparation for these ambitious plans, test capabilities that allow validation of mission components and elements and provide training possibilities are essential.

2. LUNA - A JOINED PROJECT

The European Space Agency (ESA) and the German Aerospace Center (DLR) have recognized the need for Moon surface test capabilities and have joined forces to establish a globally unique facility for this purpose in Cologne: In the immediate vicinity of the European Astronaut Center (EAC) and various space-related institutes and facilities, a research and technology complex named LUNA is being built on the DLR premises.
The hall has been in conception since 2016. Efforts have been made from the outset to capture simulation requirements from the broadest possible user community and to integrate them into the project. The usage scenarios here include the training and validation of astronautical surface activities, as they will be expected in the context of the Artemis missions, as well as the testing of rovers, the possibility of seismic validations, up to psychosocial studies or the exploration of practical aspects of sintering processes.
It was an important decision to design the facility as an open research facility: Not only DLR and ESA should have access to it, but it is planned to open the hall to universities, other agencies and research institutions, industry, start-ups or institutions with an educational character. Users would then profit from an operations team with a high level of space expertise, which also have access to further experts from their respective organizations.

3. THE LUNA FACILITY

3.1. The LUNA main hall

The centerpiece is a 700 m^2 regolith-filled area, as depicted in figure 1. After balancing out the occupational health and safety implications and the requirement for the most realistic possible simulation possibility with regard to dust, simulant EAC-1A [4] was selected as the regolith replacement, which can be obtained in appropriate quantities from a local quarry.
The simulant is to be brought in over the largest part of the hall with a depth of 60 cm, but a 60 m^2 area of the facility is also planned as a "deep floor area". In this area, the regolith coverage is to be 3 m deep, to enable for example drilling or the formation of underground structures or deep craters.
The design of the surface is not fixed here, but can be changed and adapted as required. In order to move around the regolith accordingly, various technical concepts are under discussion. Furthermore, several rock-like elements will be available, partly with corresponding real geological properties, partly simple dummies, which are e.g. only used to create a light-dark contrast.
A mock-up of the future European Large Logistic Lander (EL3) [5] will also available for investigations of the interaction between the lander and its cargo on the one hand and the astronauts on the other. A rover is also planned, which can serve as a carrier for experiments or simulate the human-machine interface accordingly.

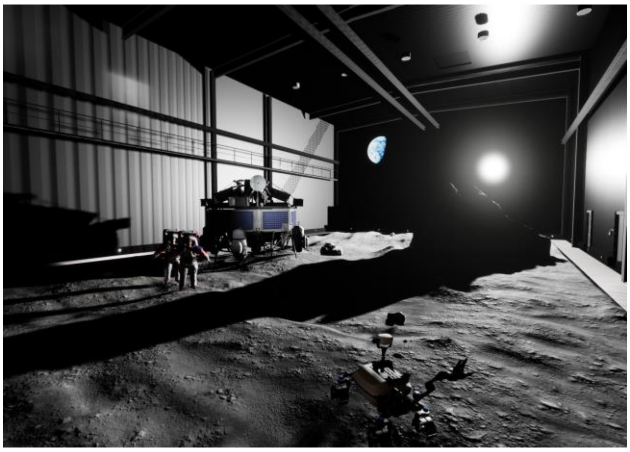

Figure 1: *The main hall of the LUNA facility (virtual reality rendering)*

The hall is darkened and reflective surfaces were largely avoided so that lighting scenarios [6] corresponding to the Moon can be simulated by means of a sun simulation system. Here it is possible to represent both an equatorial and a polar [7] landing site.
A unique feature of the facility will be the Gravity suspension system, whereby two astronauts can be unloaded by a vertical force in such a way that they only feel 1/6 of their body weight. This system will be realized by two ceiling-mounted trolleys that can be moved independently of each other and thus follow the movement of the astronauts in the hall. Attached to the trolleys are mechanical constant force mechanisms from which the astronaut is suspended in a dedicated suit similar in its basic characteristics to the Extravehicular Mobility Units that will also be used for Artemis.
In order to simulate different slopes for rovers or to practice operating on slopes with astronauts, an adjustable ramp will be integrated that can provide an inclined regolith surface.
Furthermore, a seismic measuring system is permanently installed in the regolith hall. Together with the series of measurements taken at various stages of hall construction, this will enable the hall to be used for seismic experiments as well [8].
Another feature is the possibility to explore and test different sintering technologies [9,10] for regolith processing. For this purpose, a microwave-based facility will be available as well as a 15kW CO_2 laser and a facility that will simulate sintering with sunlight [11]. In addition, other laboratory facilities will be available to allow research with and on regolith simulants.
In terms of both size and equipment, the LUNA facility allows work with astronaut teams, integrated robotic systems and representative infrastructure elements for the lunar surface. This closes an important gap between field experiments and laboratory development.

3.2. The LUNA Technology Center

Attached to the main hall is a technology center that provides further research facilities. The dust laboratory and the XR studio are particularly noteworthy here.
While dust is to be avoided as far as possible in the main hall, it is possible to conduct experiments in the encapsulated dust laboratory that stir up dust. Furthermore, other regolith types are also available in the dust lab, covering other geological areas of the lunar surface.
The eXtended reality (XR) studio allows the development of methods that enhance the analog lunar surface simulations in the hall via virtual elements, so that the trainees' immersion in the lunar environment can be pushed even further. In addition, professional equipment for video recording and editing is available in the studio, which is of particular interest for the public relation activities of the neighboring astronaut center.
A visitors' room rounds off the technology center.

3.3. LUNA attachments

The outdoor area around the hall is also reserved for research facilities on the subject of the Moon.
First, a research greenhouse that has already provided important research results and technology demonstrations as EDEN-ISS in Antarctica [12] is currently being converted to be connected to LUNA in an expanded and upgraded successor configuration [13]. Also here, a focus will be on robot-human interaction.
Furthermore, it is planned to connect a habitat to the LUNA main hall that can be used for integrated simulations of lunar excursions as well as for testing techniques for dust mitigation, in-situ sampling, rescue scenarios or similar. An initial study of habitat characteristics has already been run [14], however an extension and improvement of the concept is planned.
The size and equipment of the planned habitat is not sufficient for the simulation of a longer mission, but with :envihab [15] in the immediate vicinity, a facility is available that would also make long-term mission simulations possible with little additional effort. :envihab will therefore be connected to LUNA as part of the LUNA project.
Further research is to be conducted into how an autonomous energy supply can be represented on the Moon and integrated into the operational processes. To this end, a simulator for a radio thermal generator (RTG) is currently being planned, as well as a system that stores solar energy in electrolytically generated hydrogen and converts it back into energy via a fuel cell. The corresponding infrastructure will also be housed in a container next to the hall.

4. CONCEPT OF OPERATIONS

An important unique selling point of the LUNA facility is its integration into the existing research infrastructure at the DLR site in Cologne as well as its integration into the operational ISS ground segment which connects the German Space Operations Center (GSOC) in Oberpfaffenhofen, the European Astronaut Centre (EAC) and the ISS Microgravity User Support Center (MUSC). This allows realistic operational concepts to be developed and validated.
Accordingly, with GSOC, MUSC and EAC, there are three centers from which the hall can be operated. All three centers have different areas of competence - and so the operating concept of LUNA foresees that after a review of an incoming experiment or campaign proposal by a board established for this purpose, the center that has the best professional overlap with the content of the experiment takes over the lead of the experiment execution in LUNA.
The operations team, which then supports the experiment preparation and execution, consists of a LUNA campaign lead, who assumes overall coordination and responsibility.

He is assisted by a LUNA campaign planner who plans the experiment campaign and, if necessary, also develops a dedicated simulation timeline mimicking the on-board timeline of a "real space mission".
Depending on the amount of LUNA elements to be used in the planned experiment, one or more LUNA Ops Engineers will be designated to operate and monitor the LUNA elements.
And finally, the team will be completed by a LUNA Ground Segment Engineer who will configure, operate, and monitor the LUNA ground segment.
If needed, astronauts are also available through the EAC, and GSOC can provide a flight control team if necessary.

5. PROJECT SETUP

The size of the project (see figure 2 for all LUNA elements) and the many parties involved make its management a challenge.
A steering board, staffed by senior leaders from ESA and DLR, is the final decision-making authority in the project.
The project is led by a project management team, on which ESA and DLR are represented, and which consists of the authors of this article. One member of this team acts as the prime project manager in order to prevent a diffusion of responsibilities.

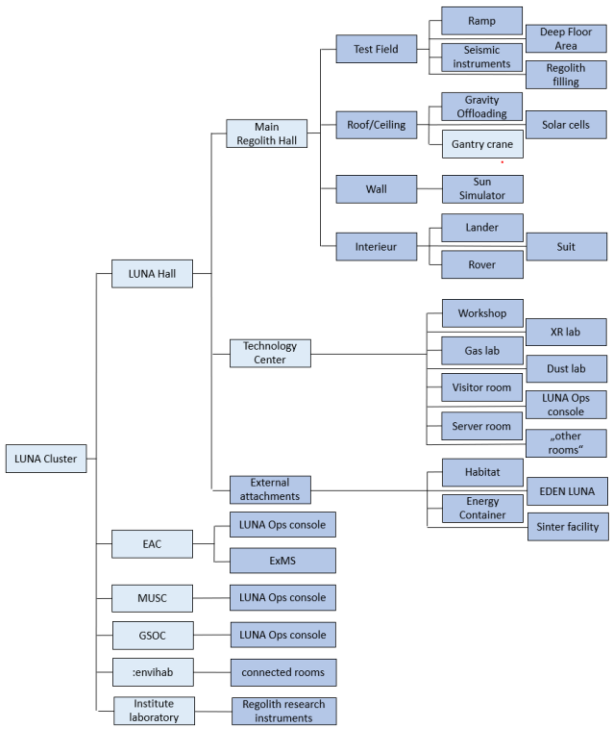

Figure 2: *Elements structure of the LUNA outfitting project*

The project management team acts within a core team that also includes the LUNA Systems Engineer, four advisors (science, ground segment, operations, astronaut) and the administrative functions such as controlling, Product Assurance and Safety, contract administration, risk manager or configuration manager.
This is followed by the work package manager level, which essentially reflects the above-mentioned elements of LUNA. They each lead their team of project members in the individual work packages.
On work package level, eight DLR institutes and ESA are involved, all of them working according to their own processes, with own reporting lines and within their own IT infrastructure. The definition of a common set of tools, processes and responsibilities is complex, time consuming and sometimes impossible - then exceptions or deviations from important project management principles need to be accepted by the project.
The Core team internally coordinates closely in weekly meetings and maintains regular communication with all project staff via a LUNA newsletter, which reports all achievements, but also practical advises or actions for the entire project team.
A commercial ticket system was introduced and configured to track action items across the project and to collect and manage requirements.
All work package managers are supposed to fill out a reporting form every quarter of the year, where they list their major successes, problems, travels, publications, or purchases. This ensures that the project managers are informed about the progress within the individual work packages while leaving a maximum of flexibility and responsibility with the work package managers.
The reports are also used by the project managers to compile the agenda and inputs for a quarterly project status meeting, which is usually conducted as a teleconference open to all project members.
A key role has also the Work package Integration Meeting (WIM): It has turned out, that communication between the work package managers is a key success criterion, hence the biweekly WIM was introduced as platform for all work package manager to briefly address problems or requirements to other work package managers. This meeting is on purpose without agenda and without minutes, however the ticket system is displayed and any actions can immediately be captured there.
A file-sharing system as common information data base has been introduced. A key element of that data are two Microsoft OneNote based notebooks, one for the core team, one for the entire project, where minutes, lists, essential information or “work areas” are maintained.

6. PROJECT STATUS

After the initial conceptual work and studies, which started as early as 2016, an important step towards realizing the project was taken in September 2022 with a funding commitment from the state of North Rhine-Westphalia.
At about the same time as the project kick-off for the scientific/technical outfitting, the invitation to tender for the actual construction of the hall was initiated.
Due to the difficult economic situation, particularly in the construction industry, the search for a general contractor proved more difficult than initially anticipated, but was ultimately successful.
Construction work for the hall has now been underway at the DLR site in Cologne since July 2023.
In parallel, the requirements and concept definition are being driven forward in the individual work packages. Studies are being conducted to find ideal solutions for the planned goals of the various work packages.
It is currently planned that the outer shell of the building will be completed in 2023, and in March 2024 the interior will be ready for the scientific and technical equipment to begin.
The goal is to be able to use the partially equipped hall for operational tests or training at a very early stage, already

mid of 2024, so that LUNA will also become an important building block on the way to the Moon as part of the Artemis missions.

7. SUMMARY

The LUNA facility in Cologne is to become a crystallization core for European, but also international activities dedicated to the lunar surface. The project, which is conducted commonly by both ESA and DLR, is a unique facility worldwide by combining the advantages of other lunar analogue setups. In particular, its embedding in the operational ecosystem is a unique selling point. While the hall is currently still under construction, the first user campaigns are already planned for 2024.

8. ACKNOWLEDGEMENT

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