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Crew training and concept of operations testing for future lunar mission at the ESA-DLR LUNA facility

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Abstract

The space sector is nowadays experiencing profound changes with the advent of a new commercial era expected to be extended to the forthcoming lunar surface missions. In this context, European institutions will eagerly play a fundamental role in this new lunar renaissance in cooperation with other institutional partners such as the National Aeronautics and Space Administration (NASA) for the Artemis program.

The German Aerospace Center (DLR) and the European Space Agency (ESA) are currently working together towards the construction of LUNA, a lunar analogue facility in Cologne, Germany. This facility will bring together experts from the DLR Cologne campus, the European Astronaut Centre (EAC), the German Space Operations Center (GSOC) and from the surrounding European institutions ranging from industries, research institutions, start-ups and universities. The ultimate ambition of LUNA is to offer a platform where to train all future Moon astronauts by providing the capabilities for a full mission simulation on ground under realistic conditions, also enabling the validation of robotic systems and operations. In fact, cooperation between human and robots will be paramount to roll out a new era of lunar surface exploration missions. In this sense, the LUNA facility will be the first and most advanced of its kind for allowing different engineering and operational teams to work together within the same common platform. The worldwide unique selling point for LUNA will be its scale since it will incorporate a regolith testbed area of 700 m^2 that will allow for end-to-end testing of lunar Extravehicular Activities (EVAs) and rover traverses, including prospecting activities for In-Situ Resource Utilization (ISRU). Being able to close the gaps between analogue field activities and lab testing is what characterizes the new facility.

The main features of LUNA include a gravity offload system, a solar illumination simulator, a dust and gas laboratories, a regenerative energy system, a future crew habitat and the possibility to integrate Virtual (VR) and Mixed Reality (MR) tools. All these features are paramount for utilizing LUNA in a campaign mode set up in support of full Artemis mission simulations, also enabling the possibility for infrastructure deployment and operational concept testing for training. As a technology centre, LUNA will also be utilized as a technology platform for the technical maturation of specific hardware to be flown onto the lunar surface.
Keywords: Moon, Lunar exploration, Human spaceflight, Lunar science, Lunar operations

Acronyms/Abbreviations
European Astronaut Centre (EAC)
European Service Module (ESM)
European Space Agency (ESA)
Extravehicular Activity (EVA)
Future Lunar EXploration Habitat (FLEXHab)
German Aerospace Center (DLR)
In-Situ Resource Utilization (ISRU)
International Space Station (ISS)
Mixed Reality (MR)
National Aeronautics and Space Administration (NASA)
Virtual Reality (VR)
eXtended Reality (XR)

1. Introduction

The world and specifically the space sector are currently experiencing a new era of coordinated human and robotic exploration missions. Started in the early 2000s, a renovated interest in the Moon is nowadays reaching a critical point: ambitious programs have been launched by different countries and national space agencies, with global scientific objectives as documented by [1]. New actors are also starting to create and populate the market that is flourishing during these novel lunar renaissance times: private companies and investors are starting to recognise the lunar economy as a potential investment to generate future revenues.

In this globally crowded framework, also Europe is preparing to play an active role in this collective lunar endeavour with the ambitious Terrae Novae 2030+ program [2] developed by the European Space Agency (ESA). Collaborations with international partners such as the National Aeronautics and Space Administration (NASA), are also included. In this sense, ESA and its member states are playing a very important role within the NASA led Artemis program [3]. In particular, ESA is contributing by building the European Service Module (ESM) of the Orion capsule that recently completed the Artemis I mission in a successful way. Moreover, ESA will significantly contribute to the Gateway station, a multi-purpose outpost orbiting the Moon as part of the Artemis program, by building the habitation and refuelling modules [4]. Starting from Artemis III [5], the objective of this ambitious program is to land again on the lunar surface with humans after the last time dated back in 1972 during the Apollo 17 mission. Cargo and logistic systems will be needed for surface operations and ESA is actively working towards developing the Argonaut spacecraft, also known as European Large Logistic Lander (EL3) [6], to satisfy such need and contribute to the global effort of returning to the Moon to establish a permanent human presence.

To prepare, test and validate technologies for enabling surface activities, to train astronauts, and to develop concept of operations, new facilities are required such as closed analogue locales. Contrary to natural analogues, these artificial facilities allow to control and standardise the test conditions (thus not subject to weather forecast), also easing the logistic to run simulations and campaigns. The German Aerospace Center (DLR) has partnered with ESA to create LUNA, a worldwide unique facility where it is possible to simulate end-to-end lunar missions with a focus on high-fidelity Moon surface representation.

The present paper describes the current status of the LUNA project, focusing on the ongoing activities to establish standard processes for running the facility on a day-to-day basis. Particular emphasis is given to the creation of a general concept of operations to conduct tests and multi-day campaigns.

2. The LUNA project

Conceptually started in 2015, the LUNA facility was always envisaged to address the main aspects of human spaceflight missions to the Moon. Several years has passed since then and the concept evolved from an internal installation of a dedicated closed space in the European Astronaut Centre (EAC) training hall [7], to a temporary inflatable dome to be installed in Cologne between EAC and the DLR :envihab [8], to finally assume its current aspect of a large industrial hall connected with external elements (see Fig. 1), still located within the DLR Cologne-Porz campus.

Fig. 1. Artistic impression of the ESA-DLR LUNA facility (credit: ESA/DLR- F. Saling)

The leading design motto of LUNA has been always addressing the gaps of lunar analogue facilities [7], thus aiming to create a novel, cutting edge and unprecedented facility that can bridge between field and lab work: in fact, several natural and artificial analogues exist on Earth, ranging from deserts to small and hyperspecialized laboratories but none of them is fully complete to simulate all the relevant lunar conditions with full operational capabilities in an easily accessible environment like LUNA will do. However due to its size, its location, its on-site connections with other DLR facilities and the pool of various lunar experts (addressing almost all the domain of lunar science) working for LUNA, the portfolio of activities for mission simulations is broader than any other existing place. The LUNA ecosystem resulting from such features is targeting the creation of a network of scientists, trainers, investors, managers, students, researchers and startuppers who are gravitating around the ESA-DLR facilities and are contributing to enlarge and share knowledge on Moon activities.

This indoor facility will enable new investigations concerning human and robotic missions, also understanding how human and robots can cooperate to achieve mission success when flying on the lunar surface. As symbolized by its key visual depicted in Fig. 2, LUNA will open the door to reach the Moon directly here on Earth.

Fig. 2 LUNA key visual (credit: ESA/DLR)

2.1 LUNA main features

The LUNA training and technology centre is composed by the main hall, a standard industrial building outfitted with special systems, to which several external elements are attached. With respect to the 2019 plans [9], the current version of the ESA-DLR LUNA facility foresees the installation of the main hall in front of EAC [10] as shown in Fig. 3.

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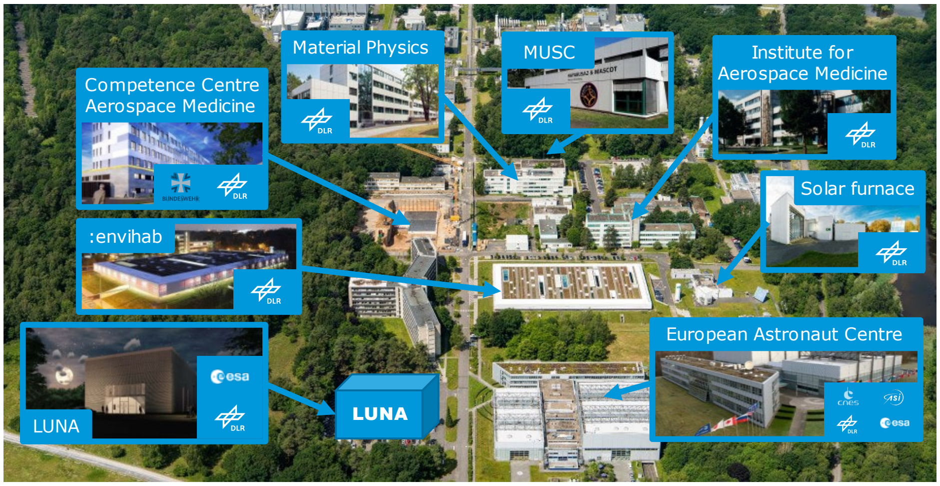


Fig. 3 DLR Cologne-Porz campus competence centre aerial view [10]

Among all the aspects of the harsh lunar environment, there are three main ones that are absolutely paramount to replicate in analogue facilities: dusty terrain, lunar gravity and illumination conditions.

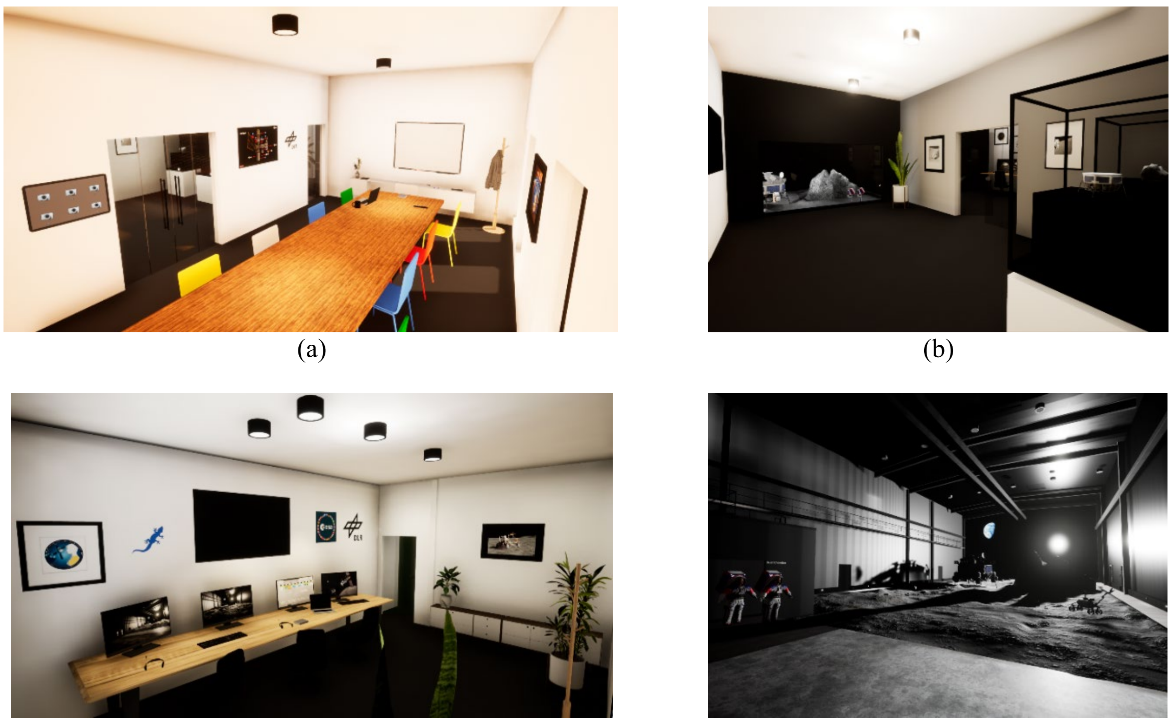
The main feature of LUNA is a 700 m^2 regolith testbed area: it will be completely covered and filled by 900 tons of a specific regolith simulant named EAC-1 [11]. Beside loose regolith also rocks and boulders will be placed on the simulated surface to enhance the lunar environment and to allow the exact replica of specific spots of the Moon surface. A deep floor area with a depth of 3 m and an adjustable ramp are also envisaged and located in a specific spot of the LUNA testbed area. Depending on the type of test to carry out, the terrain can be shaped to resemble different topographic features present on the Moon. Rovers and astronauts should in fact perform activities in or near to craters and in non-flat terrains. A dedicated dust chamber will also be built in LUNA to perform experiments in the area of space resources. Extraction, beneficiation, processing and storage of lunar regolith material for In Situ Resource Utilization (ISRU) techniques will play a key role to enable self-sustainability of future lunar colonies. To complement and study the full lifecycle of the lunar resources extracted in-situ, a fully equipped gas laboratory will also be built in LUNA.

The lunar reduced gravity field poses major challenges for human physiology to effectively live and work on the Moon. Novel countermeasures need to be found to reduce the negative impacts on the human body. In order to study such effects and to design effective protocols for surface Extravehicular Activities (EVAs), LUNA will be equipped with a gravity offload system. This suspension system is currently under study by different entities in response to a DLR invitation to tender. The results of this study will lead to the construction of a first prototype before the fully fledged implementation across the vast testbed area. Such a system will be able to offload astronauts and objects to 1/6 of the terrestrial gravity, also allowing free operations in simulated crater and on a ramp for 2 crewmembers at a time. Moreover, testing in low gravity environments can also be achieved underwater: in this sense, the EAC NBF [12] will be the perfect place where to perform comparison tests with LUNA. Special geological but also medical tools are being developed to provide guidance and help astronauts supported by experts on Earth in exploring the lunar surface or in case of any medical emergencies.Contrary to what has been done during the Apollo era, the current trend is to explore lunar poles as documented by the NASA Artemis plans [5]. The combination of the local topography with low Sun angles above the local horizon creates peculiar conditions such as highly illuminated areas in close proximity to permanently shadowed regions [13]–[15]. To properly replicate these difficult conditions, where bright lit spots are placed next to extremely dark shadowed areas, it is envisioned to build a Sun simulator. This movable system will be adjustable to match specific lunar latitudes and Sun positions. Sensors, cameras, robotic systems, and EVA protocols can therefore be tested and validate against photorealistic light conditions.

To enhance even more the immersion of the users into a realistic Moon landscape, new technologies such as Virtual (VR) and Mixed Reality (MR) will also be used in LUNA. Thanks to the proximity to EAC and the experts of the EAC XR Lab [16], LUNA will integrate VR and MR googles into simulations' protocols. By doing so, LUNA will become one of the largest eXtended Reality (XR) playground area currently available worldwide. With the help of tracking and haptic devices (e.g. force feedback, etc.), real and virtual objects can appear simultaneously in a realistic manner, thus expanding the simulations of analogue activities.

To connect all the different systems and to create a proper lunar framework, a LUNA Ground segment [17] will be established. Its activities will range from monitoring and controlling of experiments up to enabling communication with astronauts during the execution of EVAs. Starting from the existing International Space Station (ISS) ground segment infrastructure, new paradigms and standard are nowadays developed by DLR and ESA experts. The remote connection with other ISS control centres and the establishment of new control rooms from other distant location to operate the LUNA facility and its different elements, will help in the creation of novel standards required for Gateway and surface operations with the international partners [18]. Modern and flexible control room set ups will be tested in LUNA. Analysis and processing of different data (e.g. video/voice signal, telecommand, telemetry values, etc.) will require new solutions both on hardware and software level: by establishing LUNA as a testbed for new technologies, operators and engineers will be free to test disruptive solutions, also including contribution coming from non-space actors dealing with innovative terrestrial technologies

A summary view of the main different rooms of the LUNA hall as described in section 2.1 is represented in Fig. 4.



(a) (b) (c) (d)

Fig. 4 Overview of the virtual renderings of LUNA rooms: meeting room (a), visitors' room (b), control centre room (c), regolith testbed area (d) (credit: ESA/DLR- F. Saling)

2.2 External connections

To complement to spectrum of activities and allow for end-to-end multi-days mission simulations, the main LUNA hall will be connected to external modules.

A key element for enabling long-duration missions on the lunar surface is a pressurised habitat where humans can safely live and conduct scientific experiments. To address this need and to investigate how such habitat can function, LUNA will incorporate the Future Lunar EXploration Habitat (FLEXHab) module [19]. Thanks to its direct connection with the regolith testbed area via a dedicated hatch, astronauts can practice egress and ingress protocols for surface EVAs. Due to its internal flexibility, the habitat can be repurposed according to the needs of the different analogue campaigns. Surface experiments can be controlled from FLEXHab and different payload can be hosted inside to study different aspect of lunar science (e.g. geology, material science, etc.).

To further enhance the capability to investigate aspects related to human physiology and psychology within the LUNA framework, some investigation will be carried out at the DLR :envihab [20]. Living in complete isolation by taking advantage of this DLR facility will in fact help scientist and medical doctors to understand how to adapt mission protocols to regulate the life during future lunar missions.

Directly derived from the EDEN ISS module [21] that was installed at the Concordia station in Antarctica, the EDEN LUNA facility will be placed next to the LUNA hall and connected with the relevant ground segment infrastructure. This will allow the investigation of innovative bio-regenerative life support systems for enabling self-sustainability in view of long-duration missions to the Moon surface.

Another paramount aspect for future Moon expeditions is how to produce and store energy. The LUNA Energy facility [9] will help to cast some light on this topic. Based on solar-hydrogen technologies, also including pilot investigations on thermos-nuclear solutions and thermoelectric materials, this facility will allow to study how such system can work in a closed-loop configuration, also helping to showcase how such technologies can be applied to terrestrial facilities.

Lastly, the LUNA facility will also benefit from the surrounding facilities of the different DLR institutes located at the Cologne-Porz campus. Ranging from material physic to aerospace medicine, these on-site connection of building and experts will foster joint investigations for Moon research.

3. Concept of operations

Due to its intrinsic complexity, the day-to-day operations of the LUNA facility are currently under definition by the entire LUNA project team. At first, to generate requirements and to understand how to use at best the LUNA facility, ESA and DLR experts have firstly started to generate user stories, also including market surveys and interviews with external experts from different industries, space agencies and research institutions.

By addressing the needs from the international community, a science and operations review board will be established, named LUNA utilization control panel. This entity made by ESA and DLR experts, will decide among the different activities to carry out in LUNA, assigning priorities to the relevant and most pressing test campaigns. Once a use case is provided to the LUNA Team, either internally or from external entities, a campaign lead will be nominated including a deputy: he/she will be responsible to provide use cases for the execution of a certain campaign, including resources' planning and schedule. After presenting an integrated plan to the LUNA utilization control panel, the campaign lead will have the green light to execute the agreed activities in LUNA: it will be his/her responsibility to allocate resources and contact the individual experts to support the execution of the campaign and the related debriefing tasks. To ensure a successful execution, team leaders and operations engineers are also nominated as ultimate responsible for every LUNA element used in a specific campaign, including ground segment acting as coordinator among the different control centres involved.

3.1 Crew training

Starting from the ISS experience and EAC heritage of more than 20 years of experience in astronaut training [22], LUNA is aiming to be utilized as training facility for all the astronauts who will travel to the Moon. Developing procedures and operational concepts is in fact essential to ensure mission success and LUNA will establish the perfect platform for preparing lunar exploration missions. In this sense LUNA will complement and help to prepare existing activities such as the ESA analogue outdoor training programmes [23], [24]. Testing and preparing the activities in a closed and controlled environment will de-risk their execution in natural spaces.

The major challenge for crew operations is to conduct planetary EVAs: communication protocols, timelines, sequence of events and terrain hazard identifications are few of the major aspects to be addressed. LUNA will enable the investigation of such aspects via enabling full end-to-end mission simulations. Multi-day campaign as foreseen by the NASA Artemis program can be fully replayed in LUNA. The inclusion of maintenance and repair routines of elements to be deployed on the lunar surface, will enhance the immersion and provide a realistic testbed. Due to its scale, LUNA can also be used to mount and assemble large infrastructure. Novel protocols for new human-robotic interactions such as described by [25], will also be investigated in LUNA.

3.2 Technology testing

LUNA will be a unique worldwide facility that addresses the testing and simulation needs of the forthcoming lunar exploration missions. The high-fidelity analogue environment of the ESA-DLR facility will become the perfect platform where to test and validate technologies in a meaningful operational scenario with the required surrounding infrastructure.

Ranging from complex rover operations (e.g. traverse planning, sensors' calibration, driving, dexterity and robotic arm manipulations, etc.) to single hardware tests, the different facilities within LUNA or directly and indirectly connected to it, will offer a wide portfolio of possibilities for all the international experts interested to conduct experimental tests. An area where the combination of LUNA features and EAC underwater activities will synergically work is the prototyping of geological sampling tools [12]. Additionally, such studies can be augmented by innovative technologies such as XR tools to further investigate how experts can best design the next generation of lunar hardware [26].

By utilizing LUNA as test platform, key technologies currently developed by ESA to assist geological crew activities such as the Electronic FieldBook [27], will benefit from the integration within future ground segment infrastructure, also accounting for satellite connectivity as foreseen by the ESA Moonlight initiative [28]. Integrated test with ground and flight segments could therefore be carried out by using a modern mission control centre. Complex and large robotic initiatives such as the ARCHES project [29] and the ESA Analog-1 investigation [30] will in the near future run in LUNA and showcase how the facility is able to host different actors and third-parties' elements.

4. Current and future schedule

After struggling with many obstacles, including the Covid-19 pandemic, LUNA is finally taking shape. Thanks to the financial support received from the federal state of North Rhein Westphalia (NRW), Germany, for the outfitting phase of LUNA [31], which has been available since the beginning of 2022, ESA and DLR are currently eagerly working towards the construction of the main hall while also preparing its outfitting and first operations. By late spring 2023, ground-breaking will happen and it is estimated to have the main hall built by the end of 2023, thus having the first initial commissioning operations by early 2024. It is in fact envisioned to incrementally ramp up the activities in LUNA by installing all its systems and elements throughout 5 years from the confirmation of the NRW funds received in 2022. Therefore, by the end of 2026, LUNA will reach its full capabilities of world-class lunar analogue facility and will be open to interested partners.

5. Conclusions

Humankind is very close to step back onto the lunar surface ever since the end of the Apollo era: the end goal would be to establish a permanent human presence on the Moon and thanks to the new technologies nowadays available and to the experience gained by such endeavour, humanity will be able to prepare the next giant leap, i.e. landing on Mars. To achieve this ambitious objective, new facilities are needed to develop and test new technologies as well as to train the next generation of astronauts.

This paper describes the forthcoming ESA-DLR LUNA analogue facility and particularly focuses on the creation of its concept of operations. After several years of study and preparation, this unique facility has been designed and will be soon built in Cologne to fulfil a vast list of requirements derived from in depth analysis and interaction with the international partners and the scientific community. This training and technology centre, accessible to as many people as possible, will help to perform tests and validations while using the functionalities available in LUNA, and will provide the capability to perform end-to-end simulations of lunar surface missions. Located on the premises of the DLR Cologne-Porz campus and in the direct vicinity of EAC, LUNA will be capable of replicate most the most relevant environmental conditions of the harsh lunar environment. Human spaceflight operations and scientific experiments will be conducted in a 700 m^2 regolith testbed area, where communication delays, hypogravity and the peculiar lunar illumination conditions can be simulated in a high-fidelity manner. Apart from spaceflight experts, LUNA will be open to research centres, academia, private companies and start-ups: it is in fact essential to spin-in novel terrestrial technologies and help the transitions of space-rated technologies as spinouts. Sharing knowledge and lessons learned to the community of interested Moon actors is one of the major goals of LUNA. By fostering international cooperation with LUNA, Europe will become a central hub of Moon-related research and initiatives.

Given the current project outlook and the ongoing preparatory activities, the ESA-DLR LUNA facility will start to be built around late spring 2023 and finished before the end of this year. Commissioning and first operations are planned in early 2024 with a projection to incrementally achieve full simulation capabilities by the end of 2026.

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