53rd International Conference on Environmental Systems
21-25 July 2024, Louisville, Kentucky
ICES-2024-281

System Design of the EDEN LUNA Greenhouse: Upgrading EDEN ISS for future Moon mission simulations

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The joint DLR-ESA project LUNA aims to develop a facility to simulate future lunar surface exploration missions. As part of this project, the EDEN LUNA project will modify the EDEN ISS semi-closed space analogue greenhouse, which has previously been operated at the German Neumayer Station III in Antarctica from 2018 until 2022, for operation at the LUNA facility in Cologne, Germany. The EDEN ISS Mobile Test Facility will be refurbished and outfitted with updated Controlled Environment Agriculture technologies based on lessons learned from operations in the Antarctic. Additionally, EDEN LUNA will integrate and test two new main payloads. The first payload, the EDEN Versatile End-Effector, will test the use of a robotic arm and hand on a linear rail system for automated plant health monitoring and plant handling. The second payload, the C.R.O.P.® biofilter, will demonstrate conversion of urine into nutrient solution for plant cultivation. This paper introduces the EDEN LUNA project and describes the preliminary system design of the EDEN LUNA greenhouse.

Nomenclature

P/L	Payload
AMS	Atmosphere Management System
BLSS	Bio-regenerative Life Support System
CDR	Critical Design Review
CEA	Controlled Environment Agriculture
CEF	Concurrent Engineering Facility
CO2	Carbon Dioxide
CROP	Combined Regenerative Organic food Production
DHCS	Data Handling and Control System
DLR	German Aerospace Center
EAC	European Astronaut Center (by ESA)
EDEN	Evolution & Design of Environmentally-closed Nutrition-Sources
EOL	End of Life
EOM	End of Mission
ESA	European Space Agency
EVE	EDEN Versatile End-effector
FEG	Future Exploration Greenhouse
FDIR	Failure Detection, Isolation and Recovery
ISRU	In-situ Resource Utilization
LCS	Lighting Control System
ISS	International Space Station
MCC	Mission Control Center
MTF	Mobile Test Facility
NDS	Nutrient Delivery System
OBJ	Objective
PCDS	Power Conditioning and Distribution System
PHM	Plant Health Monitoring
SES	Service Section
TCS	Thermal Control System
TRL	Technology Readiness Levels
VOC	Volatile Organic Compound

I. Introduction

The EDEN LUNA Mobile Test Facility (MTF), a almost closed-loop greenhouse, is based on the EDEN ISS project which was successfully deployed in Antarctica for almost five years. The MTF was located 400 meters south of the German Neumayer Station III (70°40´S, 008°16´W) on the Ekström ice shelf in the vicinity of the Atka Bay. The station was operated year-round with a summer (November to February) crew of 50-60 people and a winter (February to November) crew of 9 people. During the winter period, no supply missions are able to reach the station, which means that all supplies (e.g. food, spare parts, tools) need to be delivered during the few summer months. This remoteness makes the Neumayer Station III an excellent test area for human space exploration test missions.

Long-term human exploration missions as planned as part of the e.g. ARTEMIS program[1] to the lunar surface or terrestrial habitated areas suffering from envrionmenal changes require food supply and reliable life support systems. Sustainable long-term human exploration missions are in preparation and require new concepts and throough tests. One element for such an undertaking is a greenhouse system, which is able to produce fresh food for the crew and at the same time provide a bio-regenerative life-support system. EDEN LUNA will be outfitted with updated Controlled Environment Agriculture (CEA) technologies based on lessons learned from operations in the Antarctic. The goal is to develop and test technologies which might be necessary for the exploration and possible economic use of the moon. Within the project LUNA, the German Aerospace Center (DLR) and the European Space Agency (ESA) will build a Moon-Analogue Simulation facility at DLR Cologne. EDEN LUNA will extend the simulation environment and add a greenhouse for space to the facility. New ideas and technologies shall be tested with exploration and space experts, validated and applied. Together with different partners the entire LUNA environment shall push innovation and excell prototypes until becoming spaceworthy equipment. LUNA is a complex project contributing to various aspects human lunar surface missions by feasibility tests in an analogue environment.

This paper will show first findings regarding the redesign including the upgrade by the EDEN Versatile End-Effector (EVE) and C.R.O.P.® biofilter. Furthermore, the paper explains how EDEN LUNA will be embedded into a analogue lunar mission scenario embedding other LUNA simulation facilities as well as be a stepping stone for the follow on space element EDEN Next Gen.

The paper is organized as follows: Sec. II provides an overview of the EDEN LUNA project. In Sec. III, we describe the new design of the Greenhouse and its supporting CEA systems. Details of the Payload concepts and the control levels to carry out the tasks are provided in Sec. IV. Finally, Sec. V concludes and gives an outlook to the upcoming steps.

II. THE EDEN LUNA PROJECT

The LUNA facility

A lunar analogue facility named LUNA[2,14] is currently in joint development by ESA and DLR in Cologne, Germany. The main hall has an area of aprox. 700 m^2 and will be filled with lunar regolith simulant (EAC-1). It is planned that astronaut training, robotic operations and scientific activities are carried out in this analogue testbed. Besides several features such as a solar simulator (for lunar light conditions), In-situ Resource Utilization (ISRU) experiments, and reduced gravity operations with an offloading system, external modules are expected to be installed as part of the LUNA facility. Amongst them, a Habitat for astronaut multi-day isolation simulation and the EDEN LUNA Greenhouse as a breadboard for plant cultivation for extreme environments.

EDEN LUNA

The EDEN LUNA project, as part of the LUNA project, focuses on developing a (semi-) closed-loop Controlled Environment Agriculture greenhouse. EDEN LUNA is based on the successful heritage of EDEN ISS[15,16], an European Union funded project with a consortium of 15 international partners, which operated a Mobile Test Facility greenhouse in a space-analogue environment near the German Neumayer Station III in the Antarctic until 2022. After this period, the MTF was disassembled and transported back to Germany, where it is being refurbished and outfitted with new CEA elements, payloads and the autonomy will be enhanced by developing and implementing AI monitoring and control. Among the payloads is the EVE robotic payload. Data gathered from operations in the Antarctic indicated that a significant amount of crew time was required to carry out nominal and off-nominal tasks, such as cleaning and plant handling [3]. The EVE system is intended to demonstrate the capability to carry out such tasks and thereby reduce the required crew time demand. At the same time the C.R.O.P.® biofilter will be introduced to the CEA system to transform urine into a usable nutrient solution base for the Greenhouse. It will be connected to the Nutrient Delivery System (NDS) and the transfer of the new nutrient solution element will be automated.

Figure 1: Former EDEN ISS returned to DLR in Bremen, Germany, for full refurbishment and upgrade

Research and development carried out by a variety of international organizations and agencies has focused on specific aspects of a bio-regenerative life support system.

The Lunar P.A.L.A.C.E. (Permanent Astrobase Life-Support Artificial Closed Ecosystem)[17] of the University of Beihang in China is among the more advanced closed-loop systems, consisting of a habitation module along with two cultivation modules. Although available technical information is limited, it is known that it does both waste processing and food production and can operate with humans in the loop.

The Lunar Greenhouse of the University of Arizona[18] has a deployable structure, which would be more suited to a space mission. The facility has been used to test plant cultivation with artificial and hybrid lighting strategies and to develop multi-crop plant cultivation system models[24].

NASA's research into bioregenerative life support systems and habitats include analogue test campaigns as part of their Lunar Surface System Habitation Demonstration Unit (HDU) Programmes[19]. During these missions, small plant cultivation systems within the habitats are used to produce salads for crew consumption.

The Japanese Closed Ecology Experiment Facility (CEEF)[20], operational since 2005, investigates biochemical resource loops with the aim of better understanding the Earth's resource loops. Although the facility operates and cultivates plants in a closed-loop system, the facility is not aimed towards space use.

Additionally, development activities are ongoing with respect to plant production systems suited to microgravity, such as VEGGIE[21,22] or the Advanced Plant Habitat (APH)[23]. These systems have some overlap with planetary systems with respect to the CEA technologies which are utilized, but are limited regarding a larger scale closed-loop production system and, furthermore, do not incorporate waste treatment technologies yet.

However, no integrated space-rated system exists of sufficient scale which can provide both food production and waste recycling capability, and significant research gaps remain which need to be addressed before a future system can be implemented on Moon or Mars

The EDEN LUNA greenhouse, similar to the EDEN ISS MTF previously, will aim to address some of these research gaps and be one of the most advanced space analogue planetary greenhouse systems in operation by implementing the aforementioned EVE robotic payload, the C.R.O.P. ® payload, improved CEA systems and novel monitoring and control systems

EDEN LUNA CEA Subsystems

Apart from EVE and C.R.O.P.®, EDEN LUNA Mobile Test Facility comprises of several subsystems required to supply, monitor and control the greenhouse. Figure 2 shows an overview of the EDEN LUNA sections:

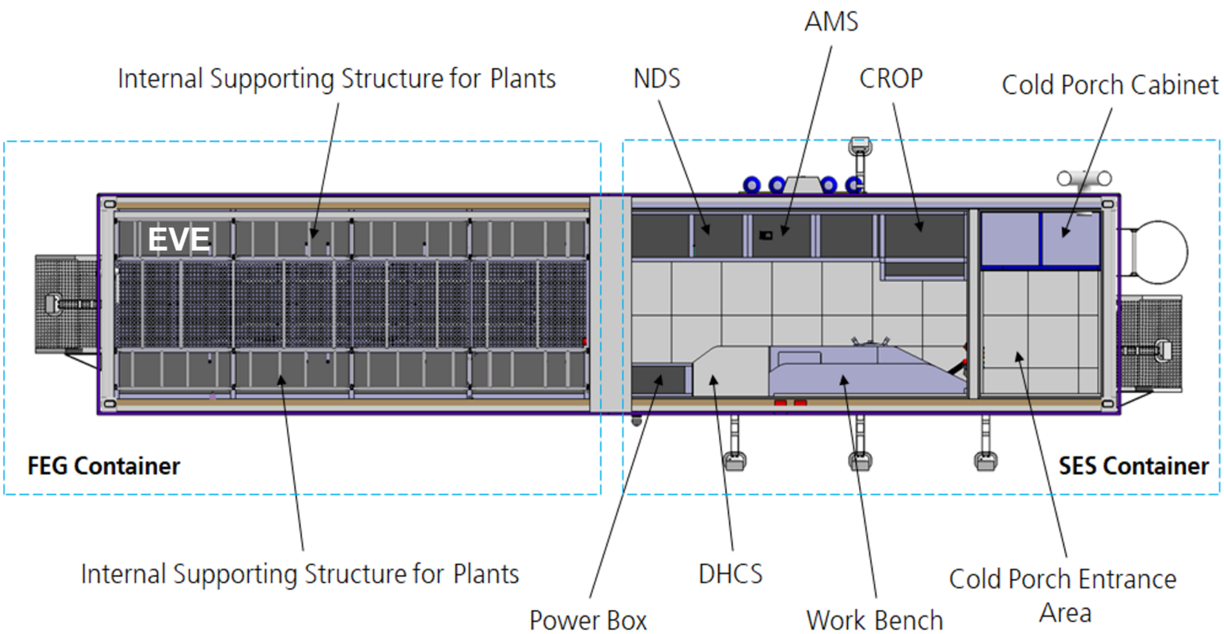

Figure 2 EDEN LUNA MTF Sections and Subsystems

The Nutrient Delivery System (NDS) has two bulk nutrient solutions for leafy greens and fruiting crops. It is connected directly to the different plant cultivation trays through a system of pumps, pipes and automated valves to supply nutrient solution to the crops.

The Atmosphere Management System (AMS) is responsible for controlling the internal atmospheric conditions, maintaining temperature and relative humidity at desired levels, removing contaminants and ensuring a safe atmospheric composition. The Atmosphere Management System consists of two distinct systems, the FEG AMS and the Service Section AMS, although the majority of components for both parts is located in the Service Section.

The FEG AMS is a closed air circulation loop which allows temperature and relative humidity control through the use of a condensing heat exchanger (CHX) and subsequent heating elements. The recovered water is processed and reused for crop irrigation via the NDS. The FEG AMS loop also provides air filtration and decontamination through the use of pre-, HEPA- and VOC filters along with UV-C lamps installed in the air ducting. To improve overall yield of the greenhouse, the FEG AMS has the option to inject CO2 from gas bottles stored externally into the atmosphere. To ensure crew safety, a CO2 scrubber will be added as a new addition to the system, to handle any build-up as a result of crew emissions.

The SES AMS provides air circulation within the Service Section and Cold Porch and enables air filtration, temperature and relative humidity control. An interface to the external atmosphere is foreseen as a safety feature, to enable air exchange in case of (potentially) hazardous atmospheric conditions in the Service Section (e.g. high CO2, dust or trace gas contamination)

The C.R.O.P. ® biofilter developed by DLR will be integrated into the greenhouse to demonstrate the capability of recycling urine into nutrient solution for plant cultivation. The nitrogen-rich solution from the C.R.O.P.® system is then transferred to the NDS, where it can be used in the composition control of the two bulk solutions. The transfer can be commanded via the DHCS and monitored accordingly.

The Power Control and Distribution system (PCDS), redesigned with reduced complexity and size, has the function to distribute power to the different subsystems and components, monitor power consumption, and provide backup power in case of a power supply issue.

The Data Handling Control System (DHCS) has dedicated subsystem and payload controllers which will interface with a redundant DHCS on-board computer. The DHCS will receive and transfer telemetry and telecommands from/to the subsystems inside the greenhouse. It will also provide Fault Detection, Isolation and Recovery (FDIR) functionality. The new DHCS will incorporate a DLR development for avionic systems: OUTPOST, which is a modular library that provides a set of common low-level space system functionalities and the abstraction layer to different operating systems and hardware platforms.[12]

The Lighting Control System (LCS) has liquid-cooled LED panels to provide four different individually controllable wavelengths. Light intensity, spectrum and duration can be changed according to the needs of the selected crops and cultivars.

Finally, the Thermal Control System (TCS), which corresponds to the fluid loop system, collects the heat from the EDEN LUNA subsystems/payloads and transfers the collected heat to the external environment. Specifically, two internal coolant loops circulate coolant fluid through the LED panels and the AMS CHX, to transfer heat away from the subsystems. Plate heat exchangers enable heat transfer from the internal coolant loops to an external coolant loop which then circulates the coolant to an external heat rejection unit.

III. Redesign to become EDEN LUNA

EDEN LUNA Design Model

DLR uses a Concurrent Engineering Facility (CEF) for designing of complex systems by applying the collaborative CE-process. This means relying on an iterative work scheme, where design team members work on a common model of the respective system, the whole design team is assembled and guided by a moderator/project manager through the design process. Work switches from "off-line" work, where team members work individually or in small groups and "on-line" work, where the whole team is engaged in moderated discussions, design trade-offs and presentations[9].

In preparation of the CE study to define the preliminary design, the objectives for EDEN LUNA were derived from the lessons learnt of EDEN ISS operation and new objectives were added to include the new elements and improvements. The following objectives have been defined by the team for EDEN LUNA:

Table 1: EDEN LUNA mission objectives

ID	Objective
OBJ-001	EDEN LUNA shall adapt the EDEN ISS (semi-)closed loop bio-regenerative life support system (BLSS) for higher plant cultivation for operation at the LUNA facility and improve the system by incorporating (at least) the following upgrades: 1. Automated fresh and waste water exchange 2. CO2 removal capability 3. A cold climate chamber for seed storage and cold vernalization 4. Increased atmosphere monitoring capability (Particulate Matter, VOCs) 5. Improved NDS reliability by reducing the number of pumps 6. Implementation of a space-system-analogue Data Handling and Control System
OBJ-002	EDEN LUNA will test and validate the use of a robotic platform payload for plant handling and plant health monitoring (to determine the potential for crew time reduction in future systems)
OBJ-003	EDEN LUNA will test and validate the use of the C.R.O.P. ® biological filter payload for waste (urine) recyling and nutrient recovery
OBJ-004	The mission concept shall include a contribution on a global scale embedded into the international exploration strategy. Therefore, international partners and industry must be involved from the very beginning (e.g. ESA).
OBJ-005	The EDEN LUNA greenhouse shall enable astronaut-in-the-loop testing and training of lunar greenhouse operations and procedures as part of simulated Moon exploration missions.

Based on these objectives, a functional analysis was conducted, defining functions needed to fulfil these objectives . Premise for the work has been that the EDEN LUNA greenhouse module would be part of the LUNA infrastructure, i.e. allowing astronauts to train real mission scenarios, communication, power supply. This functional analysis was then used to complement the requirements formulation.

Requirements were formulated. There were programmatic aspects, e.g. concerning the schedule and cost. Furthermore, lessons learned from operating the MTF in Antarctica during the EDEN ISS project[4,5] led to requirements, e.g. improved accessibility for maintenance, repair and cleaning, CO_2 removal capability to handle crew emissions. Other requirements are added based on safety aspects and regulations, e.g. maximum noise levels, or concern the plant growth, e.g. maximum amount of trace gases, light spectrum and intensity.

With these objectives and requirements defined, the preliminary design adjustment was started. As part of a CE Study, subsystem and domain experts matured their respective designs. Trade-off workshops, e.g. concerning crops selection, robotic arm location and autonomy were conducted to discuss advantages, disadvantages, while observing the requirements and constraints for the design. Additionally, the (potential) scientific investigations and technological demonstrations to be conducted have been detailed and interfaces have been defined and discussed with the partners.

Following the CE Study to define the mission goals and major design changes, the Preliminary Design Review (PDR) has been passed successfully in 2023. A preliminary design is presented in this paper.

Preliminary results of the EDEN LUNA Redesign

The overall system, including technologies for subsystems, cover various functionalities, e.g. nutrient delivery or water sanitation, have to be developed, matured and tested if they are to be used on a space greenhouse with sufficient reliability. This testing has to occur as close as possible to the actual circumstances of operation on Moon. Besides testing, their implementation and usage have to be optimized concerning resource efficiency (e.g. the amount of water and energy needed), crew time or for increase in crop yield and its nutrient content.

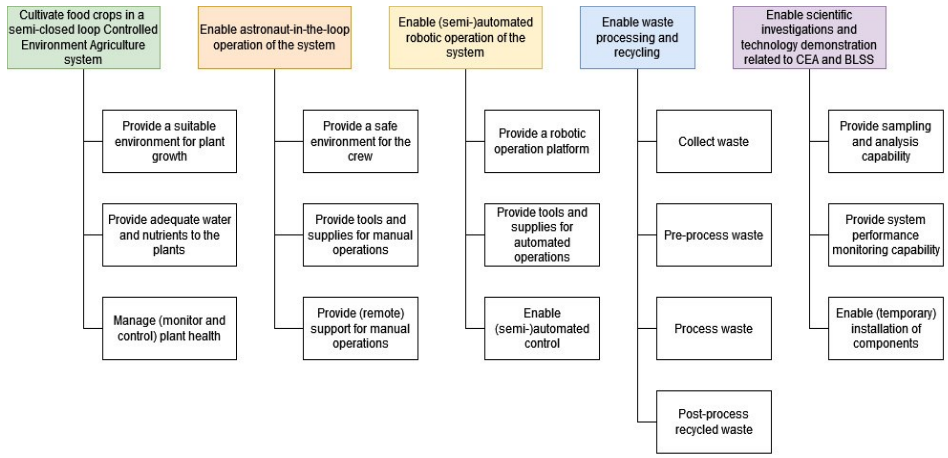

Figure 3 EDEN LUNA preliminary Functional Overview

A. Future Exploration Greenhouse

The Future Exploration Greenhouse contains the plant cultivation racks which provide the main plant cultivation area. A detailed overview of the FEG for the EDEN ISS greenhouse can be found in Zabel et al.[10]

Compared with the current as-built situation in the Mobile Test Facility, the main change involves the installation of the robotic arm payload with the supporting rail system. The rail system and robot arm will be installed at the ceiling of the FEG, which necessitates moving several components, such as the Ethernet switches, to new positions. Furthermore, for safety reasons, the robotic arm requires a space inside the plant cultivation rack where it can be stowed when not in operation. As a result, there will be a small reduction in plant cultivation area as two plant trays (and LED panels) will be removed to accommodate the robotic arm.

The subfloor structure and floor panels will be adjusted to improve handling. Furthermore, the NDS supply and return piping will be replaced and, in particular for the return piping, improved. For the return piping, the aim will be to reduce microbial growth inside the pipes as a result of nutrient solution remaining in the pipes by improving the drainage. The interface between the plant cultivation trays and the drain pipes has been adjusted to allow for a better routing of the piping, thereby reducing areas where nutrient solution flow is impeded. Additionally, the complex valve system of EDEN ISS, which allowed switch-over from one nutrient solution to the other on an individual rack level has been removed. Instead, the system is divided into left- and right-side, which reduces the amount of piping and valves in the FEG subfloor. This will allow the sump tank positioning to be adjusted and, as a result, the slope of the drainage piping can be increased for improved drainage. The sump tanks and pumps which collect the runoff nutrient solution and transfer it back to the bulk solution tanks will be re-designed for improved maintainability and redundancy. The sump tanks will be modified to accommodate two sump pumps per tank as opposed to EDEN ISS which had a single pump per sump tank. Additionally, the integration of the level sensors in the sump tanks, monitored by the DHCS, will be modified to prevent accidental triggering of level sensor alarms, and corresponding safety measures, during maintenance activities. Redundancy is a crucial element in space engineering due to its limited accessibility for repair.

The Illumination System for the EDEN LUNA greenhouse is expected to remain nearly unchanged from the EDEN ISS Mobile Test Facility, aside from the total number of lamps which will be installed in the Future Exploration Greenhouse. Each lamp used by EDEN ISS will be tested in the Planetary Infrastructure Laboratory at DLR Bremen to ensure its re-usability for the next mission. These tests will also aim to determine the level of optical degradation after multiple years of operation, and adjust the operating setpoints accordingly to get the desired spectrum and intensity for the plants.

Additionally, a larger Nursery area is foreseen opposite the EVE infrastructure. The Plant Health monitoring will be improved by different cameras either mounted on the EVE arm or permanently installed within the ITEM racks.

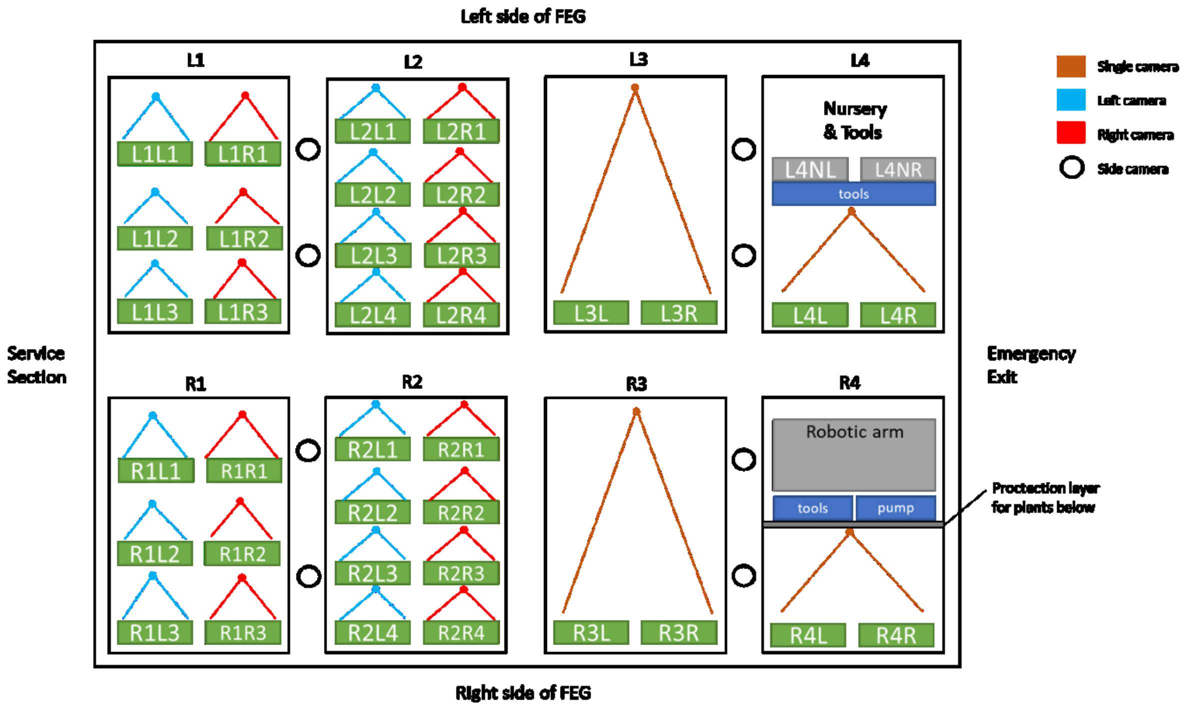

Figure 4 EDEN LUNA FEG Layout

The cameras previously used in EDEN ISS proved suitable for plant health monitoring purposes, so will be reused for EDEN LUNA. A few additional cameras will be installed in the short plant cultivation levels (L2 and R2) to improve coverage of the crop canopy[11]. The cameras on the EVE robotic payload will allow close-up inspection of areas of interest. Different multi-spectral cameras are being investigated as further improvement to the overall plant health monitoring.

B. Service Section incl. Cold Porch

The Service Section houses the Controlled Environment Agriculture subsystems, the DCHS and Power, the C.R.O.P.® system payload and a working area with a sink for the crew to carry out various nominal and off-nominal tasks. For EDEN LUNA it is foreseen to update the ITEM structure design to improve maintainability by implementing drawer systems which can be pulled out to allow easier access to the different components. NDS, AMS and TCS are incorporated into the ITEM profiles.

Previously, the Service Section had three GK-Packsystem openings for piping and cabling to the outside. For EDEN LUNA these openings will be replaced by sealed, weather-protected, interfaces to ensure an air- and water-tight seal and to facilitate the installation and disconnection of the interfaces.

Aside from the previous connections for the main power and data lines, the power and data connections for externally mounted equipment, the thermal lines to the free cooler and the CO2 injection line, the Service Section container will be adapted to have interfaces for fresh and waste water.

Aside from the external interfaces, the Service Section has connections to the Cold Porch and the Future Exploration Greenhouse. Data and power cables run from the DCHS and Power to components in the FEG and fluid lines run from the TCS to the LED lamps and between the plant cultivation trays and the NDS. The harness and the piping will be updated throughout the Mobile Test Facility and the interfaces. In particular between the two containers, interfaces will be altered to facilitate installation and disassembly in the future. The decision has been taken to semipermanently connect the two containers and therefore increase the length marginly. The additional space allows for better interfacing hardware. Between the Service Section and the Cold Porch, modifications to the separation wall will improve air circulation between the two sections and the overall effectiveness of the upgraded AMS.

EDEN LUNA Operations

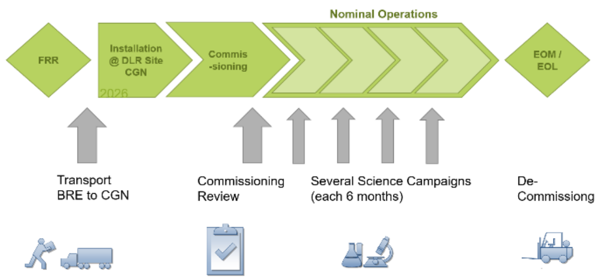

Figure 6 EDEN LUNA prelim. Mission phases

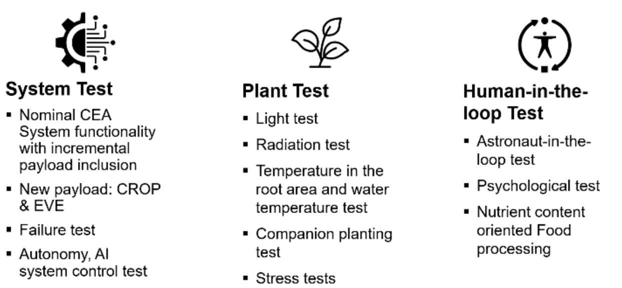

Figure 5 EDEN LUNA Preliminary Operations Elements

Mission planning for the Mobile Test Facility in Cologne is being performed at the Mission Control Center (MCC) Bremen. Certified users can now access their experiments remotely. The EDEN LUNA overall system elements are:

- EDEN LUNA Mobile Test Facility (Cologne)
- EDEN LUNA Mission Control Center (Bremen)
- LUNA and Site interfaces (Cologne)
- EDEN LUNA user (Remote)

There are two level of operation: the complete LUNA mission simulation as well as the EDEN LUNA system maturation scenarios regarding the Technology Readiness Levels (TRL) - qualification and proof of concepts for the integration in upcoming space missions. The nominal operations phase is divided into mission test campaigns as shown Figure 6. Once the MTF assembly is completed, the project will undergo a thorough review before the MTF is being certified for shippment to Cologne: Flight Readiness Review FRR. When the site integration test is completed, System and Payload commissioning and check out will start. Then Nominal operation can begin.

At the end of its mission operation (EOM) or lifetime (EOL), a Decommissioning procedure will be executed.

Nominal operation includes scientific campaigns each lasting approx. up to 6 months. The campaigns will be detailed after CDR and include the mission objectives as well as commercial partner tests. An overview of test topics to be carried out is shown in Figure 5. The campaigns will balance between max. crop output, type, power consumption and nutrient tests as well as system stress and tests regarding human psychology during a luna mission simulation.

IV. EDEN LUNA Payloads and additional opportunities

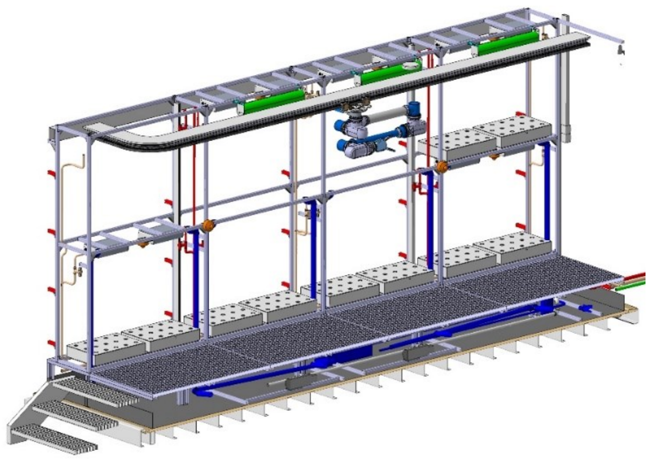

Figure 7 EVE design within the EDEN Greengouse, in motion position

EDEN LUNA EVE Payload

The EVE system (Figure 7) is a robotic system to automatize the plant cultivation tasks of the EDEN LUNA greenhouse. The execution of the tasks happens in a shared-autonomous manner.[6] The Robotic arm is based on the TINA technology[7] developed by DLR. For the EDEN LUNA project seven joints are used. This guarantees a high degree of manipulability in a very constrained space and a good reachability taking advantage of the full length of the arm.

To grip the crop elements, the CLASH hand[8], a sensorized robotic hand, can handle soft objects such as strawberries. The rail system is a modularsystem. For the application in EDEN LUNA, the 24 motor modules and guidance rails will be configured in an L-shape. This will allow the robotic arm to drive along the entire 5 m longitudinal extension of the FEG greenhouse and to be stowed in a parking position when not in use. A selection of capabilities is shown in Table 2.

Table 2 EDEN LUNA Robotic Arm Capabilities

EVE Capabilities objectives	Description
Plant cultivation task execution	Handle rock wool plugs, manipulate trays, monitor crops, harvest vegetables
Shared autonomy	An initial commando from the operator triggers the autonomous operation of the robotic system
High manipulability	Ability to operate in a higly restricted space
Modularity	Rail system and robotic arm can have different configuration by design
Versatility	Perform different tasks, be installed in different structures besides the greenhouse, exchange the end-effector to benefit from different tools
Safety	SW based restricted operation, collaborative, Emergency Stop

EDEN LUNA CROP® Payload

Biological life support modules are designed to be combined with other biological or physical - chemical modules in order to increasingly close material cycles. The C.R.O.P.®-system uses a trickling filter to produce N-fertilizer from urine. The process relies on biological nitrification of the urea contained in urine and leads to a nitrate-rich fertilizer solution that also contains small amounts of P, Mg, SO4 etc. The microorganisms responsible for nitrate production are immobilized in a biofilm grown on expanded clay particles. Therefore, the system does not produce sludge which would have to be removed from the solution. The produced fertilizer reduces the amount of waste in a Moon base and decreases the fertilizer supplies needed for greenhouse operation.[13]

The C.R.O.P.®-system is added to the EDEN greenhouse in order to produce enough nitrate to satisfy the N-requirements of the FEG. As the greenhouse does not have a toilet, the urine will come from external sources and during campaigns will be brought into the filter system in canisters daily. A quick-disconnect interface will prevent the need for manual transfer from the canister into the filter tanks. Before reaching the filter tank, the urine passes through a UV treatment, which reduces the microbial load, and a particulate filter, which removes precipitations. Pumps ensure continuous recirculation of the C.R.O.P.®-solution through the trickling filters. After a defined processing time, fertilizer solution can be captured by the NDS. When the fertilizer solution is transferred to the NDS, it undergoes post-processing to ensure that no pathogens or xenobiotics enter the NDS storage container. The post-processing unit is currently under development. It is envisioned to be an electro-chemical one-step treatment, which removes microorganisms and xenobiotics at the same time. In case of issues with the C.R.O.P.®-solution composition, or if there is excessive C.R.O.P.®-solution, the solution can be automatically discarded via a waste water interface. The process flow diagram and a CAD design of the C.R.O.P.®-system are shown in Figure 8.

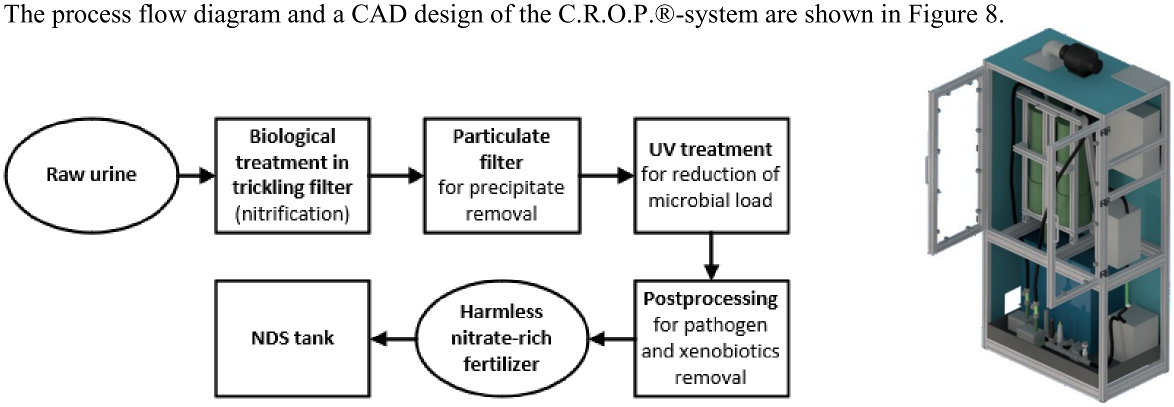

Figure 8 Functional overview C.R.O.P.® in EDEN LUNA (left), CAD Design of the C.R.O.P.®-filter rack (right)

V. Conclusion

The EDEN LUNA project aims to build on the successful heritage of the EDEN ISS project by adapting and upgrading the Mobile Test Facility which previously operated near Neumayer Station III in the Antarctic, for future analogue lunar exploration missions at the DLR-ESA LUNA facility in Cologne, Germany.

An intensive Concurrent Engineering study enabled the team to define the mission objectives, system and subsystem requirements as well as prepare the overall design of the EDEN LUNA greenhouse for a successful PDR in September 2023.

Based on lessons learned from the Antarctic operations phases, subsystems were modified to improve reliability and performance, and reduce crew time demands. Furthermore, improvements were implemented to improve scientific investigations (e.g additional sensors) and the space-readiness (e.g. the renewed DHCS) of the system.

Those subsystems and components which were functioning well in EDEN ISS, such as the LED plant cultivation lamps, will be kept to improve the overall sustainability and cost-effectiveness of the project.

The inclusion of the EVE robotic payload and the C.R.O.P.®-biofilter system will enable testing of critical new technologies for future Bio-regenerative Life Support Systems on the Moon and Mars. The EVE robotic payload will demonstrate the ability to carry out various plant handling tasks, to reduce crew time demand in future greenhouse systems. The C.R.O.P.®-system meanwhile will enable processing of urine into a nutrient solution contributor, which would allow closure of one waste recycling loop in future space exploration missions. In EDEN LUNA, the functionality, safety and impact on crop yield for space missions and quality will be investigated.

Detailed the design work, component and subsystem qualification and testing, as well as definition of the operations procedures following the PDR will lead into a Critical Design Review (CDR) later on in 2024. An extensive testing campaign at the DLR Institute of Space Systems in Bremen in 2025 will ensure a fully-functional EDEN LUNA greenhouse can begin operations at the LUNA facility in 2026.

The lessons learned from the EDEN LUNA project will flow into the development of the next generation Lunar Agriculture Module design which will be a follow-up of EDEN LUNA.

Acknowledgments

The authors, the entire LUNA and EDEN LUNA project team, want to acknowledge and thank the government of North Rhein Westphalia for the funds received to finance the outfitting of the LUNA facility. We also thank all the colleagues not mentioned in the author list and partners who have contributed to this project.

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