AMORE - Mission concept overview for a progressively independent and self-sustainable lunar habitat

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Abstract

Throughout the last decade a renewed interest for lunar space exploration has been expressed through the announcements of many ambitious missions such as Artemis. Annually the Space Station Design Workshop (SSDW) tasks students and young professionals to design a space station concept in a concurrent engineering environment. In line with the elevated interest on the Moon this year's SSDW was centred around a self-sustainable lunar habitat. This paper presents the conceptual design of Team Blue at the SSDW 2021. Advanced Moon Operations and Resource Extraction (AMORE) is conceptualized as a public-private cooperation for the creation of a lunar platform that acts as an outpost for human exploration and robotic In-situ Resources Utilization (ISRU). AMORE's proposed location is near the rim of Shackleton Crater at the Lunar South Pole. This location provides opportunities in science and ISRU and favourable sun coverage and thermal conditions. The terrain offers a natural shield for debris and storage advantages for ISRU. The mission architecture allows for incremental crew size increase through a modular dome structure, an initial prioritization of ISRU and a sustainable resource management strategy. Based on the identified system requirements, the initial configuration envisions one core module and two modular structures that would serve as greenhouses or living spaces. The phasing of the base assembly is designed to allow for adequate conditions of an increasing crew size capacity. The greenhouse modules are designed to provide all required oxygen and most required food supply. The modules are constructed using lightweight inflatable structures, while a regolith shell will provide radiation as well as thermal and micrometeorite protection. For reliable communication, a custom relay network named Lunar Earth Telecommand Telemetry Relay (LETTER) is proposed. The mission architecture analysis includes several methods to financially utilize the mission. These include a range of services on the lunar surface such as training facilities for deep space missions, leasing habitats to other Moon explorers, and performing scientific and technological demonstrations. A variety of rovers will be used throughout the mission that will assist in various aspects. In addition to this, a scalable hybrid power generation system that utilizes the abundant sunlight and nuclear energy assures a sufficient power supply throughout the entire mission lifetime. This research presents a holistic architecture for a Moon base, which provides an approach to initially utilize the Moon. Within this context, the mission concept is primarily based on already existing or currently in-development technologies. Hence, AMORE offers an approach for a financially and technologically feasible as well as a continuous and expandable human presence on the lunar surface.

Keywords
Moon, Lunar-base, space-exploration, ISRU, self-sustainability, SSDW, AMORE

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Acronyms/Abbreviations

SSDW	*Space Station Design Workshop*
AMORE	*Advanced Moon Operations and Resource Extraction*
ECLSS	*Environmental control and life support systems*
LETTER	*Lunar-Earth Telecommand Telemetry Relay*
RTG	*Radioisotope Thermoelectric Generator*

1. Introduction

SSDW is an international and multidisciplinary workshop which is held annually by the Institute of Space Systems at the University of Stuttgart, Germany. SSDW 2021 consisted of two teams of twenty-five individuals each, from diverse educational backgrounds and skillsets. In 2021 the task was to design an increasingly independent and self-sustainable lunar base. This base could eventually function as a gateway for deep space missions. Given this context, team blue designed a crewed space station on the lunar surface, which could establish human presence on the moon as well as improve the robotic capacity for lunar operations. The proposed concept focuses on two main objectives: Human and robotic exploration of the lunar surface and research opportunities beyond Earth. To fulfil these goals in an economical fashion and to become self-sustainable, the proposed architecture relies heavily on In-Situ Resource Utilization (ISRU).

2. Methodology

To sufficiently develop the concept, it was decomposed into several segments: a launch segment in charge of transporting equipment and personnel to the lunar surface, a communications segment to facilitate transporting data between the habitat and earth as well as a lunar segment consisted of the actual habitats. The lunar segment was further composed of a core module, transported in a pre-assembled state for astronauts to live in while the expansion modules are constructed, inflated, and commissioned. As time progresses, different types of expansion modules from greenhouses to Environmental Control and Life Support System (ECLSS) and science modules would further expand the base.

To facilitate in the development process, the systems engineering team distributed relative material to different teams to help avoid “blank-page syndrome”. Besides that, material was made available to individual systems teams, by SSDW’s organizers, in the form of recipes.

Valispace was used with a concurrent engineering approach. This immensely supported a rapid iterative development, as teams could easily access the most up-to-date numbers of other subsystems. To combat inaccuracies, a margin philosophy was also defined, roughly based on ESA’s margin philosophy for science assessment studies. As the SSDW 21 took place fully digitally the use of “Gather town” was crucial to the team’s success. Gath-er town facilitated a sense of “presence” and improved overall team cohesion.

2.1. Assumptions

At the beginning of the project various assumptions were made. AMORE space station utilizes different systems, which is assumed will be operational:

- Lunar Gateway by early 2029
- SLS Block 1B in early 2029
- SpaceX Starship in 2034.

For logistical aspects, it was assumed that the vehicle transporting crew to the lunar base would also carry enough consumables (food, water, oxygen, clothing etc.) to comfortably survive 30 days. Quantities and schedules regarding radioactive material for RTGs and RHUs should be compatible with AMORE to allow for launch of the core module in 2029. To fit into the launch sequence timeline, SLS Block 1B needs to be operating and available for a launch cadence of six months by 2030 and three months by 2034. Lunar Earth Telecommand Telemetry Relay (LETTER) and Gateway would need to make their communication systems available for relay operations. In early 2029, the Earth orbit relay satellite net-work and corresponding ground stations on earth would need to be available to facilitate communication between them.

2.2. Requirements

Several mission-level requirements were established, allowing communication between teams in a concurrent way. Given the harsh nature of the lunar environment, various issues that impact the mission were considered. All systems should be either radiation-tolerant or radiationshielded. Systems must be able to withstand enormous temperature swings between day and night cycles, as well as periods of over six months of continual solar exposure or darkness. Regolith dust must either be tolerated or insulated from systems. The same criteria as on any spacecraft apply to accommodate human life for extended periods of time, with the addition of increased radiation protection and dust mitigation.

The cognitive needs the base needs to cover were studied through the scope of Environmental Psychology. Given the expanding nature of the base, and the different durations of stay for different crews, the expansion of both space and variety in uses was made apparent.

Finally, the role of plants in the environment was considered, as a result, a Closed Loop Environmental Control and Life Support System (ECLSS) was proposed, which included plants as part of the system for the overall well-being of an Astronaut.

3. Discussion

3.1. Mission Design

Several requirements had to be met by the landing site both imposed by other subsystems and by the mission planning. The landing place was narrowed down in several steps. ECLSS and TCS pointed towards the lunar poles because of the unique lighting conditions, the utilization of gateway then led to the lunar south pole. Scientific goals can also be fulfilled as a wide variety of geological features is available there.

The selected landing site at the slopes near Shackleton crater fulfils all critical request given by the other subsystems except for a requirement by Human Factors Engineering demanding a line of sight to the earth for psychological reasons. To mitigate this, an early deployment of a crewed rover is planned that will allow the travel of crew to a viewing spot on top of the hill.

3.2. Mission Architecture

For the implementation of the mission, mainly existing and proposed vehicles were used. These included: i) SLS Block 1B, ii) Falcon Heavy (with recurring launches) and once available, iii) Starship. These vehicles would bring cargo from Earth to Lower Lunar Orbit and from there to the AMORE station.

For Crewed missions, a Standard Transfer from Lower Earth Orbit to the Near-Rectilinear Halo Orbit is selected as this is proposed for the selected flight hardware and therefore professionally researched. While for cargo missions, a Weak Stability Boundary Transfer is chosen to increase efficiency and payload mass. This trajectory takes up to two months to reach the Lower lunar orbit but is more fuel efficient than the crewed transfer.

To bring the crew to the lunar surface, NASA Gateway and HLS programmes will be utilized, which will make use of an ORION vehicle to bring the astronauts from Earth to Near-Rectilinear Halo Orbit using an SLS Block 1B Crew variant, and the HLS Starship, by SpaceX will transport the astronauts from Gateway to the AMORE station. AMORE requires a landing system for transporting a crew of four from the Gateway to the lunar surface before the HLS is available, therefore, two custom-designed human landers will be transported along with the first crewed missions. These vehicles utilize an oxidizer/fuel combination which can be sourced from lunar ISRU operations.

3.3. Mission Outline

The AMORE Operation can be split into three initial phases and one late expansion phase, each with a dedicated purpose and function.

i. Phase 0 (2027-2028): On the first launch planned in 2027 a group of scouting rovers would be deployed to the landing zone to determine the exact landing/building spot, search for ISRU options and provide basic construction. A communications network would be deployed into a stable lunar orbit. On the final launch of this mission the Core module should be ferried and deployed onto the moon to be then buried in regolith by the rovers.

ii. Phase 1 (2028-2031): The first two missions would bring their lander with them and leave it on the gateway station after departure to provide a lander for the following missions. These initial missions continue construction and scouting as well as construction of the first inflatable structures and greenhouses to vali-date ISRU concepts and prepare the base for increasing crew numbers.

iii. Phase 2 (2032-2035): expands the ISRU and scientific capabilities of the station by deploying more mining and processing equipment, additional living. A larger fleet of rovers and support vehicles is also deployed, and the crew is raised gradually to twelve individuals.

iv. Phase 3 (2035-x): continues the expansion with additional core modules, living quarters, greenhouses, processing facilities and gradual increase of the crew as per demand of probable future objectives.

3.4. Human Factors

Human factors were prioritized early in development of concept. Requirements were generated to address three different aspects.

i)Physical factors: Regarding physical factors, requirements were pulled from NASA's Technical Standards and Handbooks. [1,2]

ii)Cognitive factors: For the cognitive factors, a combination of environmental psychology's approach to the interaction between a user and their environment [3] was analysed to identify existing issues in space stations design.

iii)ECLSS solution: Understanding the cognitive requirements of the astronauts, an ECLSS was proposed that utilized plants to produce food, recycling of water, O2, and CO2.

Lastly, the main architectural design drivers that were generated called for: i) segmentation of modules to loud and quiet spaces, ii) interconnected and complex floor plans, avoiding zoning of uses, iii) complexity and variety in privacy levels in different spaces, iv) modularity and reconfigurability and lastly, v) the strong recommendation for windows that made use of exterior vistas towards the Earth.

3.5. Habitat Design

Inflatable solid-framed structures should be coated with a 3D-printed moon regolith to create the HEART modules, which thus protects against all physical threats. To achieve good conditions for the psychological well-being of the crew, all modules have soft zoning into different gradations of privacy, from sleeping to working areas.

The first CORE module differs from the HEART modules, in that it would be launched from the ground in a ready-made form. This unit is cylindrical for transport efficiency. To avoid permanent stress by noisy facilities such as those used in ECLSS or other systems, there are two different HEART modules. One of them contains all the functions that cause negative exposure and the other hosts compatible systems and crew living areas. The design connects all the spaces but makes entry into the private areas unattractive. This ensures easy access, emergency escape, and ease of retreat.

The generic system of 3-axis domes with adjustable functionalities allows the base to be expanded in line with requirements that emerge over time. To create a good working environment for scientists, training and exploration, the mission is expected to install nine HEART modules on top of the CORE module and host four crews of four until 2040. The approaches to scalability, adaptability and ISRU make it a sustainable concept for the development of a lunar base.

3.6. Radiation and Thermal Control System

To protect astronauts from the harmful deterministic and stochastic radiation, a composite of regolith, aluminium, HDPE, Kevlar, and Nomex is used. For emergency situations (such as Solar particle events), the core module is additionally equipped with a reinforced radiation bunker with thicker walls. This allows for reduced absorbed doses during intravehicular activities and gives more opportunities for longer stays in the base or longer duration EVAs

The temperature fluctuations on the lunar surface range from -180 to +120°C, but the internal temperature of these structures must be maintained at an ambient temperature of 22-25°C for optimal performance of equipment and astronauts. The thermal control system of these structures was designed to adapt itself to lunar nights and days where the temperature reaches extreme limits. Regolith along with a composite of insulation is added on the outermost wall which acts as an excellent insulator against external temperature conditions such that regardless of external temperature almost no heat is conducted to the interior of the structure. The heat produced inside the structure by life support missions would be dissipated into space using a radiator.

3.7. Habitat Structure

The habitat structures have been designed by considering environmental conditions such as vacuum environment, radiation shielding, and micro-gravity. The core module is designed to host the astronauts until the completion the HEART modules. Aluminium is used as the construction material for the core module. Hybrid structures are used in the design of the modules, which takes advantage of both inflatable and rigid. An inflatable habitat supported by rigid structural elements has been preferred due to its high strength, low mass, and volume. Titanium is selected for the attachment fittings of composites and fasteners due to its high strength and low mass. The HEART Module is the module to be expanded from the core module. Sandwich structures have been used for the support systems due to the shape of the HEART modules. Aluminium tubes are planned to be transported in smaller pieces and then assembled by the crew using fittings and rings. Both structures that are proposed would, after deployment, be covered with a one-meter-thick layer of regolith.

3.8. Communication

The communication subsystem ensures payload downlink and telemetry and telecommand (TTC) exchange. Furthermore, video and audio communication between AMORE station and mission control and audio only between astronauts is provided. A 99.99% link availability shall be realized for the first permanently inhabited lunar station. For compatibility and availability reasons the dedicated LETTER network including three orbiters is designed. At least three dedicated ground stations form the ground interface. The high-speed link in the Ku-band is assumed to only provide 99.90% availability in downlink, due to rain attenuation. Gateway might reduce these weather dependent gaps as backup station in future. The worst-case LETTER to Earth transmission is considered to demonstrate the feasibility of the high data rate concept: The radio telescope payload generates the most data and is downlinked with the Data Downlink System. Eight virtual channels are available, respectively for video and audio calls in the Crewed Mission Support System. Those systems function as the high-speed line with 159.92 Mbits uplink and 335.5 Mbits downlink. This is achieved with a transmitting antenna diameter of one square meter and a receiving antenna diameter of thirteen square meter with an antenna gain of 63.02 dBi. With a DVB-S2 waveform with 8PSK modulation, 2679 user bits per symbol and a code rate of 9/10 the required Energy per Bit to Noise Density results in 6.70 dB. The provided Energy per Bit to Noise Density characterizes various aspects of the link and comprises with 11.15 dB a system margin of 3.45 dB. While the voice loop can be used during work hours, payload data is downlinked during recreational hours, when the video calls can be used limitedly. For psychological and emotional recreation, a local entertainment server with music, series and movies is planned. The low-speed S-band link is unaffected of rain and fits the human factor requirement for emergencies. TTC utilizes the low-speed line with 0.05 Mbits uplink and 1.39 Mbits downlink.

3.9. Electrical Power Systems

AMORE, being subjected to a cycle of twenty-two lunar days and six lunar nights needs two power sub systems. The primary should be a solar array farm and the second an RTG farm. The solar farm shall have a dimension of five hundred m2. AMORE, despite being located on a peak with a solar radiation factor of 100 cannot cover the energy expenditure during lunar nights. To compensate for this energy, an RTG developed by Lockheed Martin is used to charge Li-ion batteries during the lunar days. AMORE is proposed to run in a minimal safe operating mode during lunar nights to compensate for the limited power production. To distribute energy evenly through the different phases, a power control distribution unit should regulate power during different operating phases of the mission.

3.10. EVA´s and Robotics

Robotics will play an integral role in the success of such a mission. The robotics payload of the system consists of units that should fulfil three objectives: ISRU, exploration and base assembly. For the ISRU objective a three staged set of payloads is foreseen. The ISRU robotics system shall investigate the locations close to the lunar base for volatiles that can be extracted. The actual extraction stage will make use of a rocket mining system under development by Masten Space Systems [4]. Finally, as part of an R&D campaign, a tethered mining drone concept would be put to test to see if mining of permanently shaded regions is a feasible solution for long term missions.

The exploration robotics system would include autonomous drones, which would be able to explore lava tubes nearby. This would create a high scientific exploration output [5].

Finally, robotics will be used to prepare the base prior to astronaut arrival. The ATHLETE rovers designed by National Aeronautical Space Agency are the current foreseen robotic system for this task. As suggested in studies [6] the ATHLETE rovers would use tools adapted to fit their legs and conduct tasks such as excavation and 3D printing. In addition, to serving as a construction operations tool, the ATHLETE can be adapted to fulfil extra vehicular activities with astronauts thanks to its modularity and high mobility over the lunar terrain.

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3.11. Costs and Risks

This cost estimate should be viewed as an early preliminary estimate using various simplifying assumptions. The module development costs have been estimated through the “Advanced Missions Cost Model” pre-purchased modules and operation costs are estimated by analogy with known and available costs in literature. So-called “Wrap factors” are used to quantify different less predictable costs, and “Beta functions” have been used to accurately spread production costs over the mission’s timeline [7]. Lastly costs estimated in older US$ have been transformed into 2021 US$ with the NNSI [8] and then changed into 2021 EUR. As a result, the estimated total cost for the program’s initial duration (2022-2035) is calculated to be 70 billion 2021 EUR. However, this cost estimation shall only be seen as a tool to get a grasp on the order of magnitude for the mission costs.

4. Conclusion and Outlook

The concept that was preliminarily developed and showcased through this paper highlights that a lunar settlement is within reach in the next decade. The technologies that need to be utilized exist or are currently under-development. The aspect we need to overcome is the political and financial capital needed to undertake such a task. The proposed base has the capacity to function as an outpost of permanent human presence on the moon and as a gateway for humanity’s expeditions to other deep space exploration. This workshop also showed the inherent value of interdisciplinary teams in developing such concepts in a concurrent way. The team explored and better understood the intricacies of a crewed exploration mission. Participants were exposed to a variety of scientific and engineering disciplines. From propagation and planetary mechanics to propulsion technologies and inner architecture.

This workshop allowed for both teams to explore the field of space exploration and better develop their passions, while exploring previously unseen aspects of it.

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