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Defining Mars-Forward Capabilities of the Lunar Gateway Space Station

Aaron Thornton[a,b], Abhijeet Kibe[a], Alessandro Battegazzore[a,c], Ali Llewellyn[a], Amanda Ales[a,d], Amit Kumar Singh[a,e], Amy Smith[a], Anamarija Pejic[a], Ben Nathaniel[a], Bianca Diana Turneanu[a,f], Damian Pietrusiak[a,g], Dilani Selvanathan[a,h], Elisabetta Marrucci[a], Emi Maruyama[a,i], Etienne Leteurtre[a,j], Fabiola Luna La Fazia[a,k], Francesc Domene[a], Francesco Morgese[a,l], Frederik Voldbirk[a,m], Hakim Abid[a], Ian Luca Benecken[a,n], Ibrahim Alkathery[a,o], Ignacio Krasovitzky[a,p], Ilaria Pia Fiore[a,q], Iqbal Grewal[a], James Fettes[a,r], Jeff Kerrie[a,s], Laura González Llamazares[a], Laurence Hou[a,t], Leena Shirolkar[a], Lilach Gurman[a], Lucrezia Romagnolo[a,u], Maëlle Mathieu[a], Malica Schmidt[a,v], Marc Casanovas Ventura[a], Mehmet Sevket Uludag[a,w]*, Mohsin Alfarsi[a], Nadine Duursma[a,x], Najla Alahmadi[a,y], Ola Mirzoeva[a], Remya Raj[a], Ricardo Gomes[a], Robert William Sterling[a], Shay Gurevitch[a,z], Waleed Amur Alhakmani[a,aa], Zuzanna Filipecka[a]

[a] *Space Studies Program, International Space University, France*.
[b] *Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia*, aaron.thornton@csiro.au
[c] *Delft University of Technology, Netherlands*, battegazzore.alessandro@gmail.com
[d] *3 Canadian Space Division, Canada*, Amanda.Ales@forces.gc.ca
[e] *Indian Space Research Organisation, India*, amit@istrac.gov.in
[f] *Copenhagen Suborbitals, Denmark*, bd.turneanu@community.isunet.edu
[g] *Wroclaw University of Science and Technology, Poland*, damian.pietrusiak@pwr.edu.pl
[h] *EngTech, United Kingdom*, *dilaniselvanathan@outlook.com*
[i] *Japan Manned Space Systems Corporation (JAMSS), Japan*, maruyama.emi@jamss.co.jp
[j] *Conservatoire national des arts et métiers, France*, leteurtre.e@gmail.com
[k] *University of Naples, Italy*, luna2001@live.it
[l] *Politecnico di Milano, Italy*, francesco.morgese@mail.polimi.it
[m] *Saga Space Architects, Denmark*, Frederikvoldbirk@outlook.dk
[n] *University of Stuttgart, Germany*, ian.benecken@ksat-stuttgart.de
[o] *Saudi Space Agency, Kingdom of Saudi Arabia*, Katheryi@ssa.gov.sa
[p] *Humans2Venus Foundation, United States*, ignacio@humans2venus.org
[q] *Politecnico di Milano, Italy*, ilariapia.fiore@mail.polimi.it
[r] *Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia*, james.fettes@csiro.au
[s] *University of British Columbia, Canada*, Jeff.kerrie@islandhealth.ca
[t] *Hackensack University Medical Center, United States*, laurenceww@gmail.com
[u] *UK Space Agency, United Kingdom*, lucrezia.romagnolo@ukspaceagency.gov.uk
[v] *University College London (UCL), United Kingdom*, m.schmidt.17@ucl.ac.uk
[w] *Delft University of Technology (TU Delft), Netherlands*, M.s.uludag@tudelft.nl
[x] *Delft University of Technology (TU Delft), Netherlands*, n.a.duursma@outlook.com
[y] *Saudi Space Agency, Kingdom of Saudi Arabia*, Ahmadin@ssa.gov.sa
[z] *Israel Aerospace Industries - MBT space, Israel*, shaygu@gmail.com
[aa] *Ministry of Defence, Oman*, Service95179532@gmail.com
* Corresponding Author

Abstract

The Lunar Gateway is an essential element of deep space infrastructure that provides a multi-purpose long-duration cislunar platform. As such, it also provides an opportunity for Mars-forward use and technology development. Building on an analysis of NASA's Moon to Mars (M2M) Program objectives, architecture documentation, and Gateway's existing capabilities and requirements, this paper will recommend ways to utilize the Gateway as a testbed for future missions and operational concepts, and hardware to fill gaps in enabling future human Mars exploration. Areas of assessment include extending human life, enhancing quality of life on deep space missions, establishing a sustainable cislunar ecosystem, international partnership and commercial opportunities around the Moon. This paper is a condensed version of the final report produced by the Lunar Gateway Team Project for the International Space University's Space Studies Program 2024. It aims to define the Gateway's role in advancing capabilities for sustainable lunar exploration while serving as a springboard for future missions to Mars. The results of this study will advise recommendations to NASA's Gateway Program on leveraging the lunar outpost for Mars and beyond.

Keywords: Artemis, Lunar Gateway, Space Exploration, Mars, Moon, Deep Space.

1. Introduction

The Lunar Gateway will be essential in enabling and facilitating unprecedented long-term duration crewed exploration missions in deep space. Gateway provides an unmatched platform in the deep-space environment for testing of critical technologies, life support systems, and autonomous operations. This unique position will facilitate the development of a cislunar ecosystem, provide a stable environment for long-duration missions, and act as a conduit for deeper space exploration.

This paper is a summary of a full study done by participants in the International Space University's Space Studies Program 2024 [1] which provides comprehensive recommendations to leverage the Gateway as a testbed for Mars-forward capabilities and close the technical and operational gaps required for future missions to the Moon, Mars and beyond.

There are several key focus areas of this paper. Section 4.1 discusses extending human life on the Gateway using closed loop systems, an extension module, and in-space manufacturing. Section 4.2 focuses on enhancing human quality of life onboard the Gateway via operational autonomy, robotics and AI, improving medical performance and addressing space psychology. Section 4.3 explores the development of a self-sustaining cislunar ecosystem by suggesting lunar surface and in orbit infrastructures for communications, navigation, energy and power systems. Finally, section 4.4 focuses on international partnerships and commercialization.

2. Methods

In order to formulate recommendations that will optimize and elevate the Gateway's currently planned capabilities, a systematic approach was followed. It aimed to identify discrepancies between the Lunar Gateway's current state and its desired future state to support long duration Mars missions and the development of the cislunar ecosystem.

First, an assessment of the Gateway's current functionalities and the specific requirements needed for future deep space exploration and a robust cislunar ecosystem was conducted. Multiple resources were consulted to determine the current capabilities of the Lunar Gateway and the needed capabilities to achieve future Mars missions and activate the cislunar ecosystem, such as the NASA Moon to Mars (M2M) Architecture [2], NASA white papers that focus on M2M and the Artemis program, and a plethora of research papers and publications. Second, the identified current capabilities and future needed capabilities were analysed and prioritised based on their development level and criticality to achieve long term space exploration objectives. Third, recommendation development was conducted by identifying suitable solutions to the identified gaps.

3. Results

Investigating the current plans for the Lunar Gateway functions and modules resulted in identifying multiple technological and operational gaps that will need to be addressed in order to support Mars-forward capabilities and the cislunar ecosystem. Two overarching areas were chosen due to their crucial role in achieving humanity's goal of Mars habitation. The first area focuses on the Lunar Gateway's essential role in the testing and verification of technologies required for human exploration of Mars. The second area focuses on identifying the requirements and strategies needed to incorporate the Gateway in lunar surface operations and infrastructure to create a sustainable human presence on the Moon. In addition to the expansion of international governmental and commercial partnerships.

The recommendations proposed in this paper are divided into three phases: from 2025 to 2035, short-term recommendations focus on developing foundational infrastructure and technologies. From 2035 to 2045, medium-term recommendations focus on integrating and enhancing these technologies. From 2045 and onward, long-term recommendations focus on envisioning the complete implementation and expansion of sustainable habitats on the Moon and deep space.

4. Recommendations

The first area of the recommendations focuses on the extension of human life support systems and improvement of the human experience in space which are key in preparing for future Mars missions and beyond.

4.1 Extending Human Life

4.1.1 Closing the Loop

The current systems for air, water and food are inadequate for supporting long duration human missions to Mars. Using the Lunar Gateway as a testing platform offers a valuable opportunity to improve and refine these systems for Mars forward capabilities. Developing closed-loop systems for the production and recycling of air, water, food and solid waste that addresses NASA's requirement HBS-02-LM [2] is essential.

For short-term recommendations (2025-2035), to solve the gaps in air systems, research should focus on investigating options for the electrolysis of water to produce oxygen. For water systems, efforts should be made to enhance the efficiency and speed of the current water recycling and filtration system and should aim to approach 100% water recovery target. This process shall be conducted in addition to the development of filters that can be cleaned and reused, omitting the need for Earth re-supply and additional generation of waste. For waste management, having a system that ensures the separation of organic and inorganic waste is essential. Organic waste should be recycled into organic waste bags. Inorganic waste should have designated landfill sites on the Moon and Mars with the establishment of international guidelines and regulations for waste management on planetary surfaces.

In the medium-term (2035-2045), for air systems it is recommended to focus on the testing of advanced carbon dioxide removal technologies to achieve air quality similar to Earth while using minimal volume [3]. Additionally, a Sabatier reactor should be developed to convert carbon dioxide into water and methane. Also, it is recommended to focus research on generating oxygen through photosynthesis. For water systems, water cleaning and filtration should utilise bioremediation for both black and grey water. For instance, bacteria, algae, and fungi are key groups of microorganisms identified in bioremediation processes, which can be utilised to break down organic matter in contaminated environments [4]. For organic waste, recycling should be advanced to produce fertiliser to be used in growing plants and food, which will require the development of space agriculture technologies [5]. Inorganic waste management should involve standardisation of packaging that can be cleaned and reused. Furthermore, a laundry machine directly connected to the Water Processor Assembly should be developed [6].

Looking beyond 2045 for the long-term recommendations, air system efforts should be directed towards extracting oxygen from lunar regolith. Research should also explore oxygen generation from carbon dioxide using plasma reactors on Mars. For water systems, it is recommended to use water storage and filtration systems as radiation shields to protect astronauts from harmful space radiation. In addition, organic waste should be utilised as a radiation shield for future Mars trips. Finally, breeding Argentine ants to process organic waste into a nutritional source for the crew should be considered [7].

4.1.2 Extension Module on the Lunar Gateway

16 research payloads are currently targeted to be in the Habitation and Logistics Outpost (HALO) module on the Lunar Gateway [8]. For short-term (2025-2035), it is recommended to include modular payload slots with a focus on human performance and biological research, specifically focusing on ionizing radiation impacts on the human body, as well as musculoskeletal, biomechanical, and neuromuscular human physiology. For the medium-term (2035-2045), there should be a progressive restructuring of payload slots to fit future research purposes. Looking beyond 2045 (long-term), the integration of a Lunar Gateway deep space research module is advised. This module should include research capabilities on physiology, biology, food production, critical medical care, surgery, and robotics. This additional module is essential to enhance research capabilities in physiological and biological sciences, as well as addressing unresolved questions concerning deep space exploration.

4.1.3 In-Space Manufacturing

The International Space Station (ISS) relies on frequent Earth-based resupply missions for essential parts and consumables, but this approach will not be viable for deep space missions due to longer flight durations, which creates significant logistical challenges in acquiring, storing, and transporting resources. In order to address this challenge and achieve earth-independence, in-space manufacturing should be used. For the short-term (2025-2035), it is recommended to use the Lunar Gateway to test 3D printing capabilities using real lunar regolith to generate parts and tools for use on-board. In the medium-term (2035-2045), it is recommended that waste materials from consumables or inventory consisting of thermoplastic should be utilised to be reused as new spare parts or tools. Looking beyond 2045 (long-term), more complex materials for in-space manufacturing should be used, such as alloys extracted from regolith and decommissioned hardware on board.

4.2 Enhancing Human Quality of Life

4.2.1 Operational Autonomy, Robotics and AI

The Lunar Gateway incorporates an extensive network of autonomous systems managed by the Vehicle Systems Manager (VSM) and the Autonomous Spacecraft Management Architecture (ASMA) [9].

For the short term (2025-2035), it is recommended to initiate emergency drills using a VSM simulator that incorporates ground control and analog astronauts to simulate the Martian time delay. Additionally, it is advised to explore robotic and 3D scanning opportunities with Artemis Accords partners (e.g. Australian mining companies), and to investigate continuum cable and tether arm technologies for Intravehicular Robotics (IVR) movement in restricted spaces. Enhancements to systems that support crew activities should also be pursued [10, 11].

For the medium term (2035-2045), it is suggested to commence a program of work aimed at extending Extravehicular Robotics (EVR) towards achieving optimal autonomy for Mars missions. Concurrently, preliminary testing and training of artificial intelligence (AI) models on Earth should be conducted for operational support in deep space missions, serving as an alternative to ground support. These AI models should be stress-tested on Earth to ensure reliability [12].

Looking beyond 2045, it is recommended to conduct robotic testing on board future deep space research modules or Mars transit vehicles in preparation for missions into deeper space. Furthermore, AI models should be run in parallel with traditional autonomous and supervised activities to verify their performance. Gateway data should be downlinked continuously for AI model training on Earth, with the objective of delivering updates to Gateway along with cargo and/or crew [13].

4.2.2 Medical Performance

Deep Space human spaceflight missions pose severe medical risks to both human health and performance. Therefore, the recent developments in artificial intelligence and automated technologies are increasingly important to overcome these challenges and improve human capabilities under deep space conditions.

In the short term (2025-2035), it is recommended to develop an integrated Clinical Decision Support (CDS) system that uses AI and Machine Learning (ML). The CDS will incorporate both static and dynamic data sources to aid medical decisions. Space agencies would need to collaborate in creating a global physiological database of astronaut health data [14]. Additionally, continued testing and improvement of commercial surgical platforms on the Lunar Gateway is advised.

For the medium term (2035-2045), it is suggested to integrate new laser communication technologies with telemedicine and telesurgical platforms to enhance remote medical care [15]. Deployment of humanoid robots to assist with clinical and surgical tasks should also be pursued, alongside the development of AI software for predictive movements to counteract communication delays during surgery [16].

Looking beyond 2045, it is recommended to establish specialised medical facilities, such as a module on the Lunar Gateway equipped with an intensive care unit (ICU) and medical operation room capabilities. These facilities should support comprehensive healthcare and research.

4.2.3 Psychology in Space

Content astronauts are essential for productivity, which is critical to mission success, but the challenge lies in keeping them content over the years during long-duration space travel.

For the short term (2025-2035), it is recommended to use dimmable, colour-controllable LEDs to mimic Earth’s Day-Night cycle and encourage a more natural circadian rhythm [17].

For the medium term (2035-2045), it is suggested to use naturalistic approaches such as artificial viewports with displays simulating the outside environment or pre-recorded scenes from Earth to reduce stress from the enclosed space. As payloads become less expensive, astronauts on longer missions should be allowed to bring more personal items to facilitate a connection with home [18].

Looking beyond 2045, it is recommended to customise spaces to meet astronauts' needs, incorporating a greenhouse module and personal custom design elements to improve mental health and reduce isolation [19].

4.2.4 Space Sexology

The emerging field of space sexology addresses intimate relationships and sexual reproduction in space, highlighting a current gap in research on sexual health, intimacy, and reproduction [20].

For the short-term (2025-2035), it is recommended to increase funding for research on the psychological and physiological effects of intimate relationships in space, and their impact on astronauts' reproductive and mental health. Space agencies should promote an open attitude towards discussing intimate ties and sex, ensuring a balance with privacy. Additionally, resources should be allocated specifically for the study of space sexology.

For the medium-term (2035-2045), a framework should be implemented to integrate space sexology into mission planning. This includes astronaut training and conducting analog missions to address the subject. In addition, privacy in crew quarters should be maximised, including the ability to close doors for personal space [21].

Looking beyond 2045, larger capacity sleeping spaces should be designed and incorporated into space habitats to better accommodate intimate relationships.

The second area of recommendations focuses on key primary infrastructures such as communications and navigation, energy and power systems, autonomy and robotics, along with international partnerships and commercialization strategies as crucial enablers of these systems.

4.3 Infrastructure for Space Exploration

4.3.1 Communication and Navigation

One of the main requirements for deep space missions is having a reliable communication infrastructure for data transfer. This goal can be achieved using multiple options such as Direct to Earth Communication Networks (DTE) or satellite relay networks. Deep Space Networks (DSN) are an example of DTE and it can command, monitor and track spacecrafts. Satellite relay networks support in navigating satellites and spacecrafts visibility issues and guarantee communication from deep space to Earth that is interruption free. NASA and other international space agencies are developing satellite relay networks under the Lunar Communications Relay and Navigation Services project.

An additional main requirement is the ability to navigate on and around the moon and in transit and on Mars. An essential requirement for navigation is a

Global Navigation Satellite System (GNSS) like GLONASS or GPS.

For the short-term (2025-2035), it is advised for the Lunar Gateway to be utilized as a relay to the lunar surface which can be achieved using optical links [22,23].

For the medium-term (2035-2045), there shall be communications satellites around Sun-Earth-Moon (SEM) Lagrange points and the Lunar Gateway shall be a testbed for delay simulations to demonstrate Mars mission communications [24,25].

Looking beyond 2045 (long-term), there should be an advanced navigation system such as Delta Differential One-way Ranging, using Earth & Lunar Gateway Infrastructure [26].

4.3.2 Energy and Power

Deep space logistics is central for deep space exploration, requiring consumables and the use of permanent structures. The Lunar Gateway will be a crucial hub, connecting the Earth, the Moon, and eventually Mars, facilitating power transmission, storage, and supply. The Gateway Logistics Element will support cislunar operations and cargo activities which will require power, fuel production, in-situ resource utilisation and in-space manufacturing.

For the short-term (2025-2035), the focus should be on deploying and testing crucial technologies like solar panels [27], batteries [28], and small portable fission reactors [29] to ensure a reliable power supply. Additionally, integrating power management systems for autonomous telemetry reading and optimising energy usage is essential. Pioneering In-Situ Resource Utilisation (ISRU) methods, particularly for extracting oxygen from lunar regolith, will aid life support systems and propulsion needs. Standardisation efforts need to be made on the moon’s surface, similar to Automotive and IEEE standards, to streamline interfaces and voltage levels.

For the medium-term (2035-2045), local power transmission technologies should be developed and implemented, utilising laser and microwave power beaming. Energy storage solutions need to be enhanced with high-density batteries and regenerative fuel cells to support increased surface activities. ISRU technologies has to progress to include water extraction from lunar regolith and local additive manufacturing for infrastructure construction. Stress-testing models on Earth shall be conducted to ensure reliability and efficiency.

Looking beyond 2045 (long-term), a multi-source, redundant power transmission system needs to be implemented, incorporating laser and microwave power beam technology for longer distances. Advanced energy storage systems, such as solid hydrogen storage through ISRU, should be developed to meet long-term energy needs. ISRU activities shall advance to extract volatiles and metals from lunar regolith, facilitating various uses and further supporting sustainable lunar exploration and habitation.

4.3.3 Autonomy and Robotics

While technological & operational autonomy in orbital space stations is still in the development phase, robotics with supervised autonomy is proven for extreme environments on Earth, the Moon, and Mars. Autonomous and robotic capabilities’ gaps are addressed, with possible solutions for handling the operations and maintenance of the Lunar Gateway during crewed, and especially uncrewed periods.

For the short-term (2025-2035), there is a demand to collect data for planned maintenance from current component sheets and ISS experience, additionally, data collection is needed on unplanned duties that are in need of reactive maintenance.

For the medium-term (2035-2045), it is critical to validate consistent maintenance trends and advance towards proactive maintenance.

Looking beyond 2045 (long-term), the Lunar Gateway shall comprise ML and AI system capabilities that achieve an intelligent autonomous system capable of making maintenance decisions.

4.4 International Partnerships and Commercialization

4.4.1 International Partnerships

The international partnerships strategy for the Lunar Gateway highlights the Gateway’s opportunity in strengthening the current partnership model and lessons learned from the International Space Station (ISS), and former NASA-partnered programs, while establishing a pipeline for new partners.

For the short-term (2025-2035), it is recommended to decrease legal barriers and diversify partnership opportunities. In addition, it is recommended to utilize the Artemis Accords’ signatories as future contributing partners.

For the medium-term (2035-2045), it is recommended to assist partners to pull in international private sector actors through incentive programs.

Looking beyond 2045, it is recommended to adapt the developed model to be mission needs specific.

4.4.2 Commercialization Strategy

Building upon the alignment of international partnerships, an additional strategy for commercialization is recommended that focuses on utilizing the Lunar Gateway as a hub for initiating and sustaining commercial activities in cislunar space. While collaborating with companies necessitates the development of clear policies regarding liability, appropriation and insurance, it also creates an environment that allows all ecosystem participants to prosper together.

For the short-term (2025-2035), the focus shall be on fostering stakeholder contributions and feedback while establishing a legal framework and contractual instruments. This shall be conducted in addition to defining commercial incentives to lay the groundwork for the Lunar Gateway's future operations.

For the medium-term (2035-2045), it is recommended to prioritise strategic partnerships to develop and operate essential infrastructure at the Gateway, as well as to facilitate technology demonstrations to showcase the capabilities and potential of the Gateway's infrastructure.

Looking beyond 2045 (long-term), it is recommended to scale up infrastructure to support a broader range of commercial ventures, develop new facilities, and upgrade existing ones. Also, it is suggested to establish manufacturing capabilities and streamline logistics operations to support enduring and complex commercial operations with efficient and reliable supply chains.

6. Conclusions

In essence, the development of the Lunar Gateway represents a fundamental step in advancing human space exploration by offering a platform for development and testing of technologies needed for deep space missions on the Moon, Mars and beyond, with the goal of reducing associated risks and enhancing mission readiness.

By capitalizing on the Gateway's potential capabilities, we can achieve significant technological milestones, such as creating a closed-loop life support systems and autonomous operations, which are both critical for the success of deep space missions. The Gateway will also enable an integrated lunar infrastructure capable of supporting continuous and sustainable space exploration. Furthermore, by fostering international collaboration and the implementation of advanced technologies, the Gateway can facilitate building a thriving cislunar economy, driving innovations that will create positive impact on Earth.

In summary, the Lunar Gateway is a key component in advancing human space exploration, acting as essential infrastructure for developing and testing technologies needed for future Mars missions. The success of these initiatives will rely on standardized technologies and strong international cooperation, paving the way toward a multi-planetary future and ensuring sustained human presence in space.

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