Out of this World Design: Bridging the Gap between Space Systems Engineering and Participatory Design Practices

TOMMY NILSSON, European Space Agency (ESA), Germany
LEONIE BENSCH, German Aerospace Center (DLR), Germany
FLORIAN DUFRESNE, Arts et Métiers Institute of Technology, France
FLAVIE ROMETSCH, European Space Agency (ESA), Netherlands
PAUL DE MEDEIROS, European Space Agency (ESA), Germany
ENRICO GUERRA, European Space Agency (ESA), Germany
FLORIAN SALING, European Space Agency (ESA), Germany
ANDREA E. M. CASINI, German Aerospace Center (DLR), Germany
AIDAN COWLEY, European Space Agency (ESA), Germany

Ongoing democratization of access to space in combination with the prospect of long-duration missions off-planet are setting the stage for a new era in human spaceflight. An era characterized by a growing spectrum of people with diverse professional and demographic backgrounds living and working in space. The development of human spaceflight systems has historically been intertwined with prototype studies in analogue environments that approximate some of the extreme conditions associated with space operations. Examples include hypogravity reenacted during parabolic flight campaigns or challenging lighting conditions assessed during experimental deployments in underground caves. The high cost and logistical complexity of such approaches pose a significant barrier to relevant design activities, typically leading to a low frequency of studies, a relatively small number of participants and slow feedback loops, all antithetical to modern participatory design practices. Whilst successful in underpinning the highly specialized and engineering-driven space programs of the past century, it is increasingly apparent that these traditional approaches to space systems engineering are poorly equipped to accommodate the forthcoming end-user diversification and normalization of space travel. To explore an alternative approach, our team is in the process of developing a testbed facility enhanced through the use of mixed reality technologies. By leveraging physical mockups, gravity-offload systems and digital set extensions, we demonstrate a comparatively cost-effective and accessible way of interactively simulating key challenges associated with space operations. With that, we seek to lower the threshold for participation of relevant stakeholders in design and evaluations of pertinent space solutions. We conclude by reflecting on the viability and potential importance of participatory design and rapid prototyping methods in shaping the future of humanity's endeavours in space.

CCS Concepts: • **Human-centered computing → HCI design and evaluation methods**; **Mixed / augmented reality**.

Additional Key Words and Phrases: Mixed Reality, participatory design, space systems engineering, user studies

ACM Reference Format:
Tommy Nilsson, Leonie Bensch, Florian Dufresne, Flavie Rometsch, Paul de Medeiros, Enrico Guerra, Florian Saling, Andrea E. M. Casini, and Aidan Cowley. 2023. Out of this World Design: Bridging the Gap between Space Systems Engineering and Participatory Design Practices. In . ACM, New York, NY, USA, 9 pages. https://doi.org/10.1145/nnnnnnn.nnnnnnn

1 INTRODUCTION

Our prospects of living off-planet have undergone a substantial evolution since the days of Apollo. We now know, for example, that polar regions on the Moon and Mars hold significant quantities of water [16], offering conditions favorable for power production and other forms of in-situ resource utilization (ISRU) necessary to sustain future human presence. In combination with the ongoing commercialization of Low Earth Orbit (LEO) and proliferation of private spaceflight, the stage appears set for a future where space travel and habitation will become accessible to a growing number and range of people [1, 10].

The fruition of this vision will hinge on supportive technologies being designed in service of our prospective expansion off-planet. A wide spectrum of such solutions, ranging from simple supply containers to extravehicular activity suits, will need to be carefully developed and assessed for operational viability in the extreme conditions of the Low Earth orbit (LEO), Moon, Mars and beyond.

Yet, the approaches used for design and evaluation of these systems have remained surprisingly static over the past decades. Traditionally, the development of novel space solutions has been informed by cumbersome and expensive experimental deployments carried out by engineering teams in analogue environments, such as aboard reduced gravity flights [18] or during field studies conducted in remote geographical sites [4]. The resource-intensive nature of this approach has limited its widespread adoption, with only a select few actors in the aerospace industry possessing the means to engage in these design activities regularly. This, in turn, has contributed to a situation with only a narrow range of prospective users and other stakeholders being adequately represented.

In line with the ongoing democratization of access to space, it stands to reason that space systems design ought to be made more accessible and open to participation of diverse stakeholders whose interests extend beyond the traditional engineering realm. Considerations such as usability, ergonomics, and holistic user experience will likewise have to be incorporated in order to accommodate the evolving needs and expectations of a wider user base.

This paper posits that extended reality (XR) technologies are well-positioned to help catalyze this transition. By combining physical testbeds with digital elements, the simulation of space environments and design solutions can be achieved at a fraction of the cost of traditional analogue studies, thus helping to close the gap between large space agencies and the rest of the industry. In doing so, we argue this approach has the potential to incorporate participatory design elements into a field historically dominated by engineering perspectives and thereby help foster more inclusive evaluations and accessible rapid prototyping activities.

In the remainder of this paper, we provide a brief review of representative traditional approaches to development of space technologies before detailing our alternative approach and reflecting on its potential role in shaping the future of space systems engineering.

2 CONTEMPORARY SPACE SYSTEMS DEVELOPMENT

Space systems design activities have traditionally revolved around experimental deployments and studies of prototypes in analogue environments that exhibit operationally relevant characteristics, such as specific gravity levels, lighting situation, terrain features or geological compositions of interest. Aside from naturally occurring analogues, some of these characteristics have also been replicated through artificial means, such as using neutral buoyancy water tanks or vacuum chambers [5].

While not without merits, the inherent complexities and resource-intensive nature of analogue studies have contributed to a notoriously low frequency of experimental deployments that typically only feature limited numbers of participants. The slow feedback loops and rigid project structures resulting from such constraints have rendered the space systems engineering field largely incompatible with established participatory design approaches successfully utilized in HCI and other disciplines [22]. Furthermore, since no single analogue environment can encompass all the relevant aspects of a space mission, multiple analogue studies are typically necessary, resulting in additional costs.

Reduced gravity and challenging lighting conditions represent two of the most prominent characteristics that influence the design of relevant space solutions. Below, we elaborate the manner in which these conditions are re-enacted during traditional analogue studies and reflect on the main drawbacks of such approaches in design processes.

2.1 Designing for altered gravity

Altered gravity levels constitute one of the primary challenges associated with off-planet operations. The impact of hypogravity, for instance, has been linked to impaired locomotion and sensory-motor performance, making it a major consideration during design projects [9, 31].

A common approach to replicating reduced gravity conditions on Earth utilizes neutral buoyancy water tanks or ocean floor testbeds [26]. The effects of desired gravity levels are emulated by immersing astronauts in water with appropriately weighted-out spacesuits and test equipment [14]. Using this approach, researchers from the European Space Agency (ESA) have, for instance, conducted extensive design assessments of tools for lunar geological sampling [12].

Underwater studies of this nature typically require large teams, including safety divers and physicians in case of an emergency. Moreover, while gravitational conditions can be accurately simulated during low-speed movements, the water-induced drag renders fast movements inaccurate [5].

Another popular approach to recreating the effects of reduced gravity is centered around parabolic flight campaigns. These flights involve a maneuver during which an aircraft rapidly climbs to high altitude, followed by a steep descent, resulting in temporary altered gravity states onboard. Such parabolic flights are routinely used to recreate weightlessness, as well as gravitational conditions of the Moon or Mars [24].

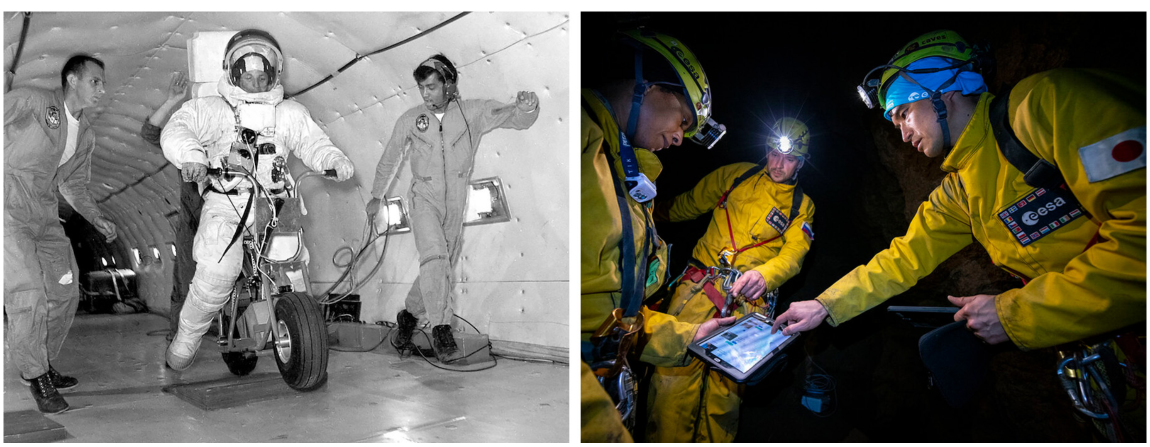

Fig. 1. Left: NASA engineers testing a lunar motorcycle during reduced gravity maneuvers aboard an airplane. Right: ESA organizes regular exercises with international teams of astronauts in the challenging lighting conditions found in underground cave systems.

Parabolic flights were, for instance, utilized during the Apollo program to evaluate and train astronauts to use the Modular Equipment Transporter (MET) Lunar cart for tool transportation, as well as a prototypical lunar motorbike (see left side of figure 1) [18].

However, the cost for parabolic flights is generally high, access to flights is restricted, and reduced gravity can only be experienced in short bursts, typically for 20-30 seconds at a time. As a result, parabolic flight campaigns are mostly utilized for biological or medical experiments that only require brief exposure to reduced gravity [29].

2.2 Designing for Challenging Lighting Conditions

Lighting conditions have emerged as another prominent consideration during design and preparatory activities surrounding human spaceflight. Notably, environments lacking atmosphere, such as the Moon, are characterized by pitch-black shadows and blinding highlights [11, 20]. Apart from affecting extravehicular activities (EVAs) of astronauts, such extreme lighting conditions have likewise implications for the design of ISRU solutions, with key resources, such as water ice, being typically located in permanently shadowed areas [30].

Lighting has thus become a frequent subject of enquiry during various analog campaigns. ESA, for instance, is regularly conducting excursions in natural cave systems to assess astronaut workflows in environments devoid of natural lighting (see right side of figure 1) [27]. Similarly, NASA’s JETT3 campaign simulates Lunar EVAs in the Arizonian desert using an artificial sun at night to approximate the lighting conditions found in the Moon’s south polar region [17].

Apart from requiring considerable time and resource investment, such approaches are likewise constrained by the presence of Earth’s atmospheric light scattering, which precludes a fully authentic simulation of, for instance, lunar lighting scenarios.

In summary, while exploration of reduced gravity and challenging lighting conditions constitute two common objectives of analogue studies, similar approaches have likewise been utilized to replicate other relevant conditions in an attempt to evaluate design solutions in an operationally valid context. The Concordia research station on Antarctica, for instance, has seen frequent use by space agencies due to its unique capacity to facilitate studies of prolonged isolation in inhospitable environments [8].

Nevertheless, as illustrated throughout this section, apart from facing challenges in accurately replicating relevant environmental conditions, analogue campaigns may likewise be prohibitively expensive and logistically demanding. As a result, a gap exists between current space systems engineering practices and the aspiration of achieving more inclusive access to space. In the following section, we will propose a novel approach to analogue studies combining physical infrastructure with XR technologies, thereby offering a comparatively more accessible testing ground for future design exploration.

3 BRIDGING THE GAP

To meet the increasing need for design evaluations in realistic settings, our team is in the process of developing the so called "LUNA" analog facility [28]. Incorporating several XR technologies, LUNA will encompass a large testbed of around 700 m^2 designed to replicate the layout of relevant geological environments and enable the assessment of various mission scenarios and technologies critical for future human exploration [6]. Given its size, the testbed will allow for simulated EVAs and extensive testing of, for instance, ISRU technologies (see figure 2). The testbed will also support rover navigation exercises and teleoperations, allowing a comprehensive range of activities to be conducted within its premises.

A dedicated mission control center will be established to enable end-to-end testing of mission operations in a high-fidelity simulation environment involving the interplay of a large number of relevant systems, including robotic solutions, lunar lander mockups and astronauts.

In addition, LUNA will be attached to a habitation module that can accommodate up to four astronauts and be accessed via an airlock. The habitation module is expected to serve as a starting point for simulated EVAs and will be used to test techniques surrounding Environmental Control Life Support Systems (ECLSS), dust protection, equipment cleaning and maintenance. In addition, the habitation module will be powered by a separate energy module that utilizes hydrogen technology.

The facility will likewise provide access to other relevant amenities on the same campus. For example, medical infrastructure close to the facility can be utilized to host astronauts and simulate isolated conditions, presenting an additional opportunity to further enhance the research potential of the facility. By consolidating such capabilities in a single location, LUNA will offer an easily accessible, cost-effective, and flexible testbed for future design evaluations.

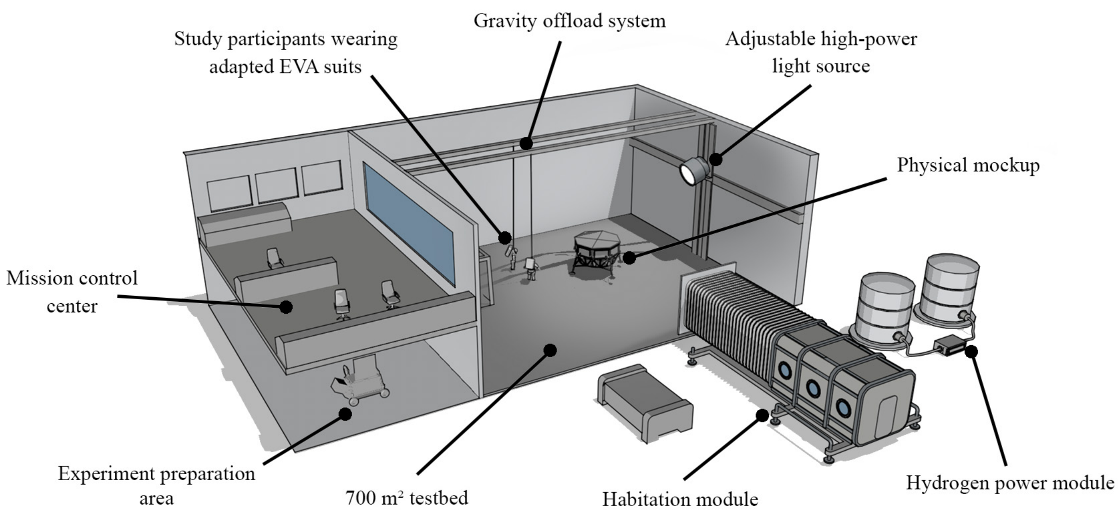

Fig. 2. Illustration of the LUNA analogue testbed facility

The use of XR technologies will play a pivotal role in our ability to facilitate relevant design assessments. By providing users with modified EVA suits featuring integrated XR headsets, we aim to enhance the perceived authenticity of the simulated environments while also elevating the fidelity of the solutions being evaluated. Digital set extensions, such as dust or rocks, for instance, will be used to rapidly adapt the testbed area to match any preferred scenario. Similarly, augmenting physical mockups with digital elements will help reduce the need for fully developed real-world prototypes during early design stages.

Below we illustrate this concept in greater detail by elaborating our approach to simulating scenarios that involve reduced gravity and challenging lighting conditions.

3.1 Approximating Altered Gravity

Reduced gravity will be induced via so-called gravity-offload systems. These dynamic robotic platforms are characterized by anchor points onto which physical mockups can be attached in order to reduce their weight by a desirable factor. Inspired by NASA's Active Gravity Response Offload System (ARGOS) [32], our solution will be integrated directly into the planned testbed area and utilized to provide sensations of low gravity by offloading not just the the equipment the users are manipulating, but also the user's own bodies.

One limitation associated with the reliance on such offloading systems is their capacity to only lift a relatively small number of objects at a time. To overcome this constraint, objects that are not directly interacted with by the user will be simulated virtually. Leveraging the capabilities of state-of-the-art game engines, such as Unreal Engine or Unity 3D, along with their associated physics engines, allows for accurate visual simulation of various gravity scenarios. Computer-generated assets, such as supply containers or Moon rocks, will thus be rendered on top of the user's view of the real world using XR technology to achieve realistic physical behavior with respect to the targeted gravity level. Similar techniques will likewise be employed to simulate environmental effects, such as dust plumes or debris resulting from the user dropping physical mockups on the ground.

This approach has the potential to substantially enhance the validity of design evaluations, achieving a higher level of realism than what could be done, for instance, through studies conducted in neutral buoyancy water tanks, whilst also saving time and resources in the process. In addition, the projection of visual cues into the real world has been proven to alleviate perceived physical space limitations, thereby further increasing the user's sense of presence in the simulated environment [15].

3.2 Approximating Challenging Lighting Conditions

In order to achieve an accurate simulation of lighting conditions on the testbed surface, our facility will incorporate an adjustable high-power light source capable of replicating a wide range of different sunlight angles. This feature will help facilitate comprehensive testing of human exploration procedures and pertinent technologies under lighting conditions that match those of relevant sites, such as the Lunar South Pole.

Much like in other analogue field studies, the lighting will still be subjected to earthly atmospheric light scattering. To compensate for this and accurately recreate the distinct characteristics of no-atmosphere environments like the Moon (e.g. deep shadows and intense highlights [11]), we will utilize extended reality to virtually simulate additional shadows and light blooms overlapping both real and virtually generated objects (see e.g. [21, 23]) thus obscuring the users' view of the environment in a manner that more closely aligns with reality. Leveraging the precise control over light behavior provided by modern game engines, we can achieve an accurate representation of the desired lighting conditions while maintaining flexibility for easy adjustments as required.

4 CONCLUSIONS

Surging interest in human spaceflight necessitates exploration and development of innovative space systems designed to withstand the challenging environments of LEO, the Moon, Mars, and beyond, all while catering to the needs of a user base that is growing in number and diversity.

Yet, the design and development of such space systems has been notoriously inaccessible, as current methods rely on costly and inflexible analog campaigns to test novel solutions.

For instance, a recent ESA study sought to design and evaluate a lunar transportation cart for evacuation of incapacitated crew-members [7]. The production of the initial design and manufacturing drawing for mock-up construction required an investment of approximately 15000 Euro. This was then followed up by construction of a high-fidelity functional prototype, its integration and initial tests, incurring an additional cost of 25000 Euro and requiring significant engineering efforts spanning hundreds of hours. Finally, the prototype underwent comprehensive trials in reduced gravity conditions at the ocean seabed [25]. Although the exact costs of these trials were not disclosed, it can be inferred that they were substantial.

In an attempt to address such limitations, we are currently in the process of developing an innovative analogue facility that will provide a unique and comparatively affordable setting for testing of new design ideas pertinent to future human spaceflight. Combining physical infrastructure with digital set extensions, the LUNA facility will be centered around a large testbed that leverages consumer grade XR technology to enhance the visual aspects of simulated environments and design elements.

Similar applications of XR technology have already seen success in other domains, such as during test flights to simulate aerial refueling, landings, and flying in formation, which would otherwise be too costly or pose a significant safety risk to pilots [2]. Our work seeks to go a step further by utilizing XR to accurately recreate environmental conditions that could otherwise not be adequately emulated through conventional means on Earth.

Beyond simply bringing down the costs and thereby making design assessments of space systems more accessible, we propose our work has the potential to yield meaningful contributions in three overarching areas:

- **Stimulating creativity through rapid prototyping:** The reliance on digital set extensions will not merely help improve the visual fidelity of simulated experiences, but likewise enable their rapid and dynamic customization. By conveying novel ideas visually before they have been turned into real-world prototypes, XR will enable exploration of greater numbers of distinct ideas and facilitate a more iterative design process (see e.g. [3]). Ultimately, we hope this will stimulate out-of-the-box creative thinking and encourage the exploration of unconventional ideas that may otherwise have been considered too risky or costly for assessment during traditional analog studies.

- **Exploring interaction modalities:** Making both real and virtual elements available for exploration under controlled conditions will enable comparative assessments of different interaction modalities and the role they play in evaluation of relevant space systems. By analyzing potential points of equilibrium on the Reality-Virtuality continuum [19], we will develop a better understanding of the extent to which physical infrastructure is needed to achieve a sufficient degree of research validity, and conversely we shall learn where virtual elements might be sufficient. In doing so, we aspire to establish a methodological foundation for the use of extended reality technologies in space systems design. Whilst the facility described in this paper might still be prohibitively expensive for many prospective stakeholders, the know-how gained from its use may thus theoretically help pave the way for more specialized testbeds, such as those fully simulated using the comparatively affordable virtual reality.

- **Fostering interdisciplinary collaboration:** Our work strives to create an inclusive environment where professionals from diverse fields, including scientists, engineers, researchers, and artists, can come together and collaborate on the design of future systems beyond the scope of traditional space systems engineering. By fostering interdisciplinary exchanges and embracing different perspectives, our aim is to facilitate more dynamic discussions and generate fresh insights that may not have been attainable through conventional approaches. In doing so, our work has the potential to inform and expand existing frameworks, such as concurrent engineering [13], while contributing to the advancement of design practices in the field.

Our position, then, is that established space systems engineering approaches run counter to the vision of a democratized access to space and that extended reality technology is well positioned to help tackle this situation. Whilst our design approach will do little to lift the financial constraints associated with space travel itself, we believe it will lower the entry barrier and help facilitate wider participation in ongoing design activities surrounding humanity's push for space. By reducing the associated costs and by establishing design methods centered around more readily available tools, our objective is to involve professionals that might have previously been excluded from this process, thereby enabling a larger spectrum of companies and individuals to engage in ideation, design and development of solutions that might one day prove instrumental in shaping our prospects beyond Earth. Ultimately, then, we aspire to foster innovation by virtue of enabling collaboration and mutual inspiration, thus cultivating a more inclusive and dynamic space industry.

REFERENCES

[1] Harald Köpping Athanasopoulos. 2019. The Moon Village and Space 4.0: The 'Open Concept'as a New Way of Doing Space? *Space Policy* 49 (2019), 101323.

[2] Edward Bachelder, David H Klyde, Noah Brickman, Sofia Apreleva, and Bruce Cogan. 2013. Fused Reality for Enhanced Flight Test Capabilities. In *AIAA Atmospheric Flight Mechanics (AFM) Conference*. 5162.

[3] Leonie Becker, Tommy Nilsson, Paul Demedeiros, and Flavie Rometsch. 2023. Augmented Reality in Service of Human Operations on the Moon: Insights from a Virtual Testbed. In *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems*. 1–8.

[4] Loredana Bessone, Francesco Sauro, Matthias Maurer, and Matthias Piens. 2018. Testing technologies and operational concepts for field geology exploration of the Moon and beyond: the ESA PANGAEA-X campaign. In *EGU General Assembly Conference Abstracts*. 4013.

[5] D Budzyń, H Stevenin, Matthias Maurer, F Sauro, and L Bessone. 2018. Prototyping of Lunar surface geological sampling tools for Moon spacewalk simulations by ESA. In *69th International Astronautical Congress (IAC), Bremen, Germany.*

[6] Andrea EM Casini, Petra Mittler, Aidan Cowley, Lukas Schlüter, Marthe Faber, Beate Fischer, Melanie von der Wiesche, and Matthias Maurer. 2020. Lunar analogue facilities development at EAC: the LUNA project. *Journal of Space Safety Engineering* 7, 4 (2020), 510–518.

[7] David Coan. 2022. *NEEMO 22 EVA Overview & Debrief.* Technical Report.

[8] Brian E Crucian, M Feuerecker, AP Salam, A Rybka, RP Stowe, M Morrels, SK Mehta, H Quiriarte, Roel Quintens, U Thieme, et al. 2011. The ESA-NASA'CHOICE'Study: Winterover at Concordia Station, Interior Antarctica, as an Analog for Spaceflight-Associated Immune Dysregu1ation. In *18th IAA Humans in Space Symposium.*

[9] Enrico De Martino, David A Green, Daniel Ciampi de Andrade, Tobias Weber, and Nolan Herssens. 2023. Human movement in simulated hypogravity—Bridging the gap between space research and terrestrial rehabilitation. *Frontiers in Neurology* 14 (2023), 1062349.

[10] Gil Denis, Didier Alary, Xavier Pasco, Nathalie Pisot, Delphine Texier, and Sandrine Toulza. 2020. From new space to big space: How commercial space dream is becoming a reality. *Acta Astronautica* 166 (2020), 431–443.

[11] Dean B Eppler. 1991. Lighting constraints on lunar surface operations. *NASA STI/Recon Technical Report N* 91 (1991), 23014.

[12] Barbara Imhof, Waltraut Hoheneder, Stephen Ransom, René Waclavicek, Bob Davenport, Peter Weiss, Bernard Gardette, Virginie Taillebot, Thibaud Gobert, Diego Urbina, et al. 2015. Moonwalk-human robot collaboration mission scenarios and simulations. In *AIAA SPACE 2015 Conference and Exposition*. 4531.

[13] Curtis Iwata, Samantha Infeld, Jennifer M Bracken, Melissa McGuire, Christina McQuirck, Aron Kisdi, Jonathan Murphy, Bjorn Cole, and Pezhman Zarifian. 2015. Model-based systems engineering in concurrent engineering centers. In *AIAA SPACE 2015 Conference and Exposition*. 4437.

[14] Juniper C Jairala, Robert Durkin, Ralph J Marak, Stepahnie A Sipila, Zane A Ney, Scott E Parazynski, and Arthur H Thomason. 2012. EVA Development and Verification Testing at NASA's Neutral Buoyancy Laboratory. In *42nd International Conference on Environmental Systems (ICES).*

[15] Hyeong Yeop Kang, Geonsun Lee, Dae Seok Kang, Ohung Kwon, Jun Yeup Cho, Ho-Jung Choi, and Jung Hyun Han. 2019. Jumping Further: Forward Jumps in a Gravity-reduced Immersive Virtual Environment. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. 699–707. https://doi.org/10.1109/VR.2019.8798251

[16] Lin-gun Liu. 2022. Water on/in Mars and the Moon. *Terrestrial, Atmospheric and Oceanic Sciences* 33, 1 (2022), 3.

[17] Erin Mahoney. 2022. NASA to practice Artemis Moonwalking, roving in Arizona desert. https://www.nasa.gov/feature/nasa-to-practice-artemis-moonwalking-roving-operations-in-arizona-desert

[18] Kelli Mars. 2020. 50 years ago: Three months until Apollo 14. https://www.nasa.gov/feature/50-years-ago-three-months-until-apollo-14

[19] Paul Milgram and Fumio Kishino. 1994. A taxonomy of mixed reality visual displays. *IEICE TRANSACTIONS on Information and Systems* 77, 12 (1994), 1321–1329.

[20] Thomas P Moore. 1989. US space flight experience. Physical exertion and metabolic demand of extravehicular activity: Past, present, and future. In *NASA, Johnson Space Center, Workshop on Exercise Prescription for Long-Duration Space Flight*.

[21] Takeshi Naemura, Takuya Nitta, Atsushi Mimura, and Hiroshi Harashima. 2002. Virtual shadows in mixed reality environment using flashlight-like devices. *Transactions of the Virtual Reality Society of Japan* 7, 2 (2002), 227–237.

[22] Tommy Nilsson, Flavie Rometsch, Leonie Becker, Florian Dufresne, Paul Demedeiros, Enrico Guerra, Andrea Emanuele Maria Casini, Anna Vock, Florian Gaeremynck, and Aidan Cowley. 2023. Using Virtual Reality to Shape Humanity's Return to the Moon: Key Takeaways from a Design Study. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. 1–16.

[23] Derek Nowrouzezahrai, Stefan Geiger, Kenny Mitchell, Robert Sumner, Wojciech Jarosz, and Markus Gross. 2011. Light factorization for mixed-frequency shadows in augmented reality. In *2011 10th IEEE International Symposium on Mixed and Augmented Reality*. IEEE, 173–179.

[24] Vladimir Pletser. 2004. Short duration microgravity experiments in physical and life sciences during parabolic flights: the first 30 ESA campaigns. *Acta Astronautica* 55, 10 (2004), 829–854.

[25] Marc Reagan and David Coan. 2017. Enabling Human Exploration Through Integrated Operational Testing. In *Extravehicular Activity Technology Workshop*.

[26] Flavie AASDT Rometsch, Andrea EM Casini, Anne Drepper, Aidan Cowley, Joost CF de Winter, and Jian Guo. 2022. Design and evaluation of an Augmented Reality tool for future human space exploration aided by an Internet of Things architecture. *Advances in Space Research* 70, 8 (2022), 2145–2166.

[27] Francesco Sauro, Jo De Waele, Samuel J Payler, Marco Vattano, Francesco Maria Sauro, Leonardo Turchi, and Loredana Bessone. 2021. Speleology as an analogue to space exploration: The ESA CAVES training programme. *Acta Astronautica* 184 (2021), 150–166.

[28] Jürgen Schlutz, Aidan Cowley, Andrea EM Casini, Petra Mittler, Martial Costantini, Stephen Ennis, Lionel Ferra, and Beate Fischer. 2021. The ESA/DLR LUNA Analogue Facility Preparing for Lunar Exploration: Status and Latest Developments. In *Global Space Exploration Conference 2021 (GLEX 2021)*.

[29] Mark Shelhamer. 2016. Parabolic flight as a spaceflight analog. *Journal of applied physiology* 120, 12 (2016), 1442–1448.

[30] Marshall Smith, Douglas Craig, Nicole Herrmann, Erin Mahoney, Jonathan Krezel, Nate McIntyre, and Kandyce Goodliff. 2020. The Artemis Program: An Overview of NASA's Activities to Return Humans to the Moon. *2020 IEEE Aerospace Conference*, 1–10. https://doi.org/10.1109/AERO47225.2020.9172323

[31] Valentina Sumini, Manuel Muccillo, Jamie Milliken, Ariel Ekblaw, and Joseph Paradiso. 2020. SpaceHuman: A Soft Robotic Prosthetic for Space Exploration. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–8.

[32] Paul Valle. 2017. Reduced gravity testing of robots (and humans) using the active response gravity offload system. In *International Conference on Intelligent Robots and Systems*.