XR Testing Framework for Human-System Interaction Design Validation

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The current standard for human-system integration testing for the development of space hardware makes large use of high-fidelity mockups to test operational scenarios and human interactions with the hardware. This process is iterated at different development stages with the utilization of large amounts of time and resources which limits the speed at which designs/products can be developed.

Immersive technologies can help overcome this limitation by minimizing the dependency on physical prototyping of assets and help condense the iterative evaluation/implementation process optimizing the transition from design to human-in-the-loop testing.

In this study, we present the current development stage of a testing framework to be used in Human-System Interaction design validation. This study has been developed at Sasakawa International Center for Space Architecture's immersive laboratory as a breakthrough towards the implementation of those technologies in space hardware testing.

To validate this framework, we use the Lunar Surface Infrastructure Project, a pilot project developed at SICSA and sponsored by The Boeing Company. The aim of this project is to design a minimal lunar infrastructure that allows 4 astronauts to carry out an exploration class mission on the lunar surface, of 14 days duration. The scope of the project includes the design of a Class I pre integrated habitat, an unpressurized teleoperated/autonomous rover and the development of surface operations scenarios (ConOps).

Our XR (Extended Reality) testing framework makes use of the Task Load Index by NASA (TLX) to assess the task workload and the System Usability Scale (SUS) to study the usability of the immersive technology system for these applications. On top of those two qualitative evaluation methods, we will use biometric data to validate the qualitative evaluations through quantitative feedback interpretation. The biometric data are collected using a suite of wearable sensors developed by Astradyne SRL.

A test campaign will take place in the first quarter of 2023, using the XR assets of the Immersive Laboratory at SICSA. The data will be collected and used to evaluate the current habitat and rover design of the Lunar Surface Infrastructure Project using the proposed testing framework. The findings of the evaluation phase will so be used to further develop the project.

I. Nomenclature

XR	=	Extended Reality
VR	=	Virtual Reality
AR	=	Augmented Reality
$SICSA$	=	Sasakawa International Center for Space Architecture

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ESA	=	European Space Agency
ISS	=	International Space Station
$NASA$	=	National Air and Space Administration
LSS	=	Lunar Surface Study
LTV	=	Lunar Terrain Vehicle
TLX	=	Task Load Index
SUS	=	System Usability Study
$mSUS$	=	modified System Usability Study
CAL	=	Cold Atom Lab

II. Introduction

Extended Reality (XR) is an umbrella term encompassing augmented reality (AR), virtual reality (VR), and mixed reality (MR) [1]. Extended Reality (XR) technologies have reached a level of development unforeseen just a decade ago. Such advancements resulted from a paradigm shift in approaches to design human-machine interfaces by companies like Meta[2]. Although space agencies around the world were using the technology for scientific and training applications for some time, rapid hardware advancements and costs reductions became possible with development of commercial applications[3]. Virtual Reality (VR) headsets with advanced capabilities are now available not only for industries and academia but also for other customers at very accessible prices. In addition, the open source nature of the two main XR applications development software, Unreal and Unity3D, stimulated technology development further leading to its broader applications including in commercial space industry. But while the number of applications has been growing exponentially, there are stakeholders who struggle finding perceptible advantages of such applications, which leads to using trial-and-error processes that consume resources without providing feasible results[4].

Given its enormous potential, XR technology has been increasingly applied and studied in a plethora of fields, ranging from tourism [5], education [6], retailing [7], gaming [1] and healthcare [8] to manufacturing [9].

Sasakawa International Center for Space Architecture (SICSA) is an international research laboratory of the University of Houston's College of Engineering that focuses on research for human space exploration and design of habitats, bases and infrastructures in space and on other planets. Every year SICSA produces different designs for orbital stations, lunar and Martian outposts and other human spaceflight-related research. These studies call for development of effective evaluation and validation tools and techniques. XR technologies have a great potential to became a fundamental tool for such purpose and with support of The Boeing Company, SICSA has initiated an in-depth research on feasibility of using XR as a part of design validation methodology. After conducting analysis on different implementation strategies for space industry, we have identified significant gaps in standardization of XR utilization, and in XR impact measuring approaches during the testing. This paper presents SICSA-developed framework that aims to fill these research gaps, building a foundation for scientific standards with measurable indicators. Potentially, it may lead to identifying tangible advantages of using XR to test and validate space hardware.

NASA's System Design Process recognizes 4 main phases. The first phase is identification of stakeholder expectations, needs, goals, objectives, constraints and success criteria. The second phase is requirements definition where they are derived, allocated, and validated. The third is the logical decomposition phase where the requirements are broken down for developing methodology architecture. Finally, in the fourth phase - design solution definition - designs are actually developed, compared to the ConOps, and evaluated to see if they meet the success criteria. The process can be iterated until the design meets the success criteria as shown in figure 1.

Our research revealed several challenges in the fourth phase of the described design process that need to be addressed in order to improve efficacy of the whole process. The identified challenges include:

- Testing for design iterations is often limited by resources (time and cost) due to the need for building expensive and time-consuming physical mockups.
- Design evaluation is subjective and there are no current quantitative means for obtaining objective evaluations.
- There is no defined strategy for implementation of testing results into design iteration propositions.
- Low potential for design iterations due to mockup construction complexity.
- Mockup testing is possible only after the design phase is mostly complete.

The presented here XR testing framework was developed as means to improve the design solution definition phase and within research and design studies sponsored by The Boeing Company during 2020-2021 and 2021-2022 academic years. The next stage of the project is under development during 2022-2023 academic year is also sponsored by The

Boeing Company and aims to complete XR lab assembly and demonstration of the developed earlier methodology that is proposed to become an augmentation to the existing System Design Process (not a replacement), as shown in figure 2.

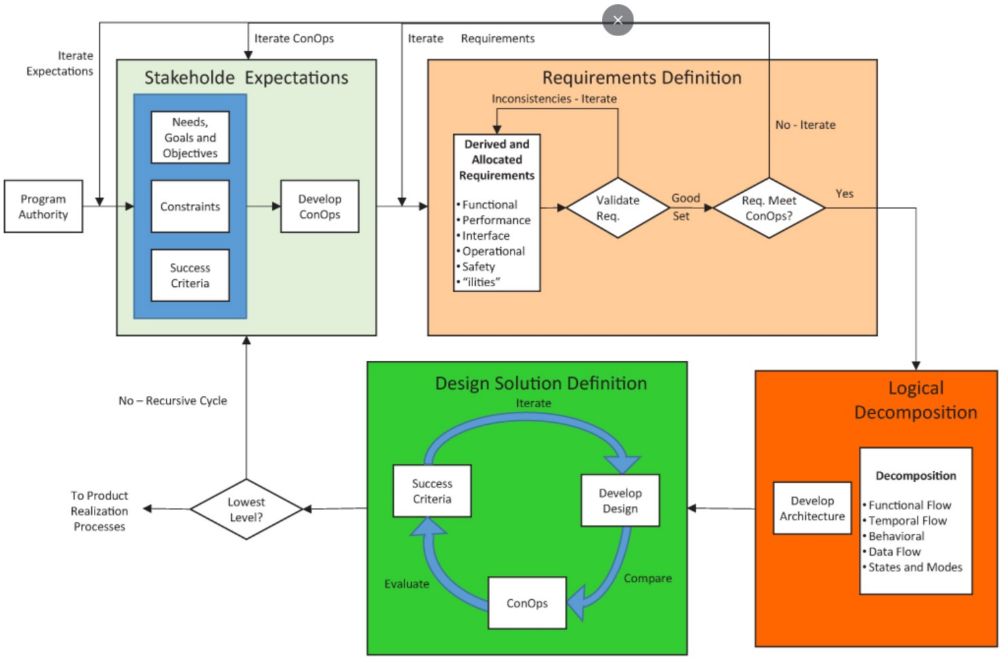

Fig. 1 Interrelationships among the System Design Processes of NASA

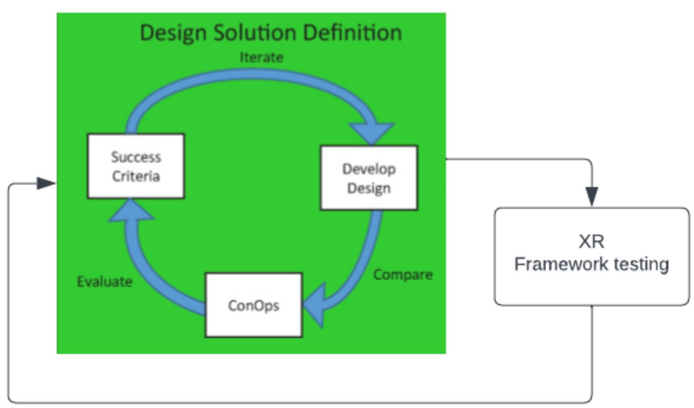

Fig. 2 Design solution definition phase adaptation

III. Project Goals and Objectives

In 2020-2021 and 2021-2022 studies our team was tasked to develop and evaluate several options of lunar surface architectures, habitat design and logistics operations. To fulfil these task, we proposed application of Extended Reality (XR) technologies with integrated low-fidelity mockups as a design evaluation methodology. Multi-user methodology would test the environment with the mission-defined number of crew and under mission-specific scenarios. Recommendations may be made both at the module level and space station level as the overall design architecture of Orbital Reef is in an early state.

The project aimed to fulfil the following research objectives:

- Identification of the most efficient methods of XR for testing and validating high level design concepts of the Orbital Reef modules
- Identification of possible design interventions and development of evaluation criteria (or Figures Of Merit)
- Refinement of systems and design requirements, the most important design considerations and defining the major design challenges
- Create a framework to grow new XR capabilities for the space sector.
- Define a standard evaluation system to validate and implement design assumptions using XR testing.
- Define a multi-mission procedure testing framework based on highly immersive XR technologies.

IV. Methodology

A phased approach was used for achieving project goals and objectives. Such approach makes application of XR in the design process easier through breaking it down into achievable steps. The initial research helped us to understand requirements and strategies for implementation of immersive technologies during the design process. This phase included allocation of funds, specifications and procurement of hardware and studying possible hardware utilization that resulted in producing technical research papers. The goal was creating a framework to be adaptable for diverse needs of aerospace companies that already use or plan to use VR/AR in their design workflow.

A. Phase I: XR Framework design

This paper is the third report about studies performed in 2020-2022 and follows two papers that have been published earlier. The first work titled "A Framework for use of Immersive Technologies for Human-System Integration Testing of Space Hardware"[10] published in 2021 and the second "Extended Reality (XR) as a validation method for digital modeling of space habitats" [11] published in 2023. This research is based on current standards for human-system integration in space hardware that rely on time consuming and cost intensive utilization of high-fidelity mockups for testing operational scenarios and human interactions [12]. To minimize the dependency on physical prototyping and maximize efficiency of iterative evaluation/implementation processes, a new means for design testing and evaluating required for optimization of transitions from CAD modeling to human-in-the-loop testing and immersive technologies can be used for achieving this goal.

Virtual Reality and Augmented Reality have been used on the International Space Station (ISS) in various ways: teleoperations with robotic arms and space vehicles using VR with interfaces based on haptics and simulated touch and motion in the "Pilote" [13] study; augmenting bicycle exercise routines with VR interfaces; assisting with maintenance of assets on board; supporting running experiments such as the Cold Atom Lab (CAL) where the ground crew can see what astronauts see and direct them using annotations in the form of texts or drawings on the astronaut's visor; examining perception of time; recreating the ISS experience for people on Earth; studying manipulation of objects in space with the "GRIP" study; studying body awareness in micro-gravity with "VECTRON" and "GRASP" studies. Hardware used on the ISS includes Sidekick developed by NASA and Microsoft, which uses the Hololens augmented reality headset and the Oculus Rift.

For implementation of XR in the design and development processes, a new framework has to be designed to allow application of immersive technologies for operational and hardware testing on Earth.

B. Phase II: XR Framework testing

An XR laboratory is set up at the Sasakawa International Center for Space Architecture (SICSA), University of Houston. The intent of this laboratory is to establish a state of the art XR facility for developing and testing various XR based methodologies and provide students, faculty and researchers with a platform for utilization of immersive technologies and design for space.

This laboratory comprises of a 2.5m(l) x 2.5m(b) x 3.5m(h) "cage" and a control station as shown in figure 3. The cage can house a human subject wired up to a VR headset and with biofeedback sensors, sensors for the VR system, and lights. The workstation is placed next to the cage from where an operator runs the VR simulation and lights and collects the biofeedback data. The location of the control station next to the cage also allows for the experiment runner to observe operations directly.

A test campaign for development of the framework was based on the SICSA studies for Boeing in 2020-2021. Four different tasks were designed using the ConOps of the Lunar Surface Study (LSS) as a reference mission. The four tasks were designed to validate key architectural design choices developed by SICSA for the Lunar Habitat and lunar mobility vehicle - Lunar Terrain Vehicle (LTV).

The test begins with an entry survey and training. Next, a subject proceeds to don the VR set and biofeedback systems. Then, a subject enters the simulation to perform four tasks. After each task, a subject temporarily lifts the headset to answer some questions about the task. Finally, a subject is debriefed and answers exit survey. The purpose of the entry and exit surveys is to collect meta data on the subject.

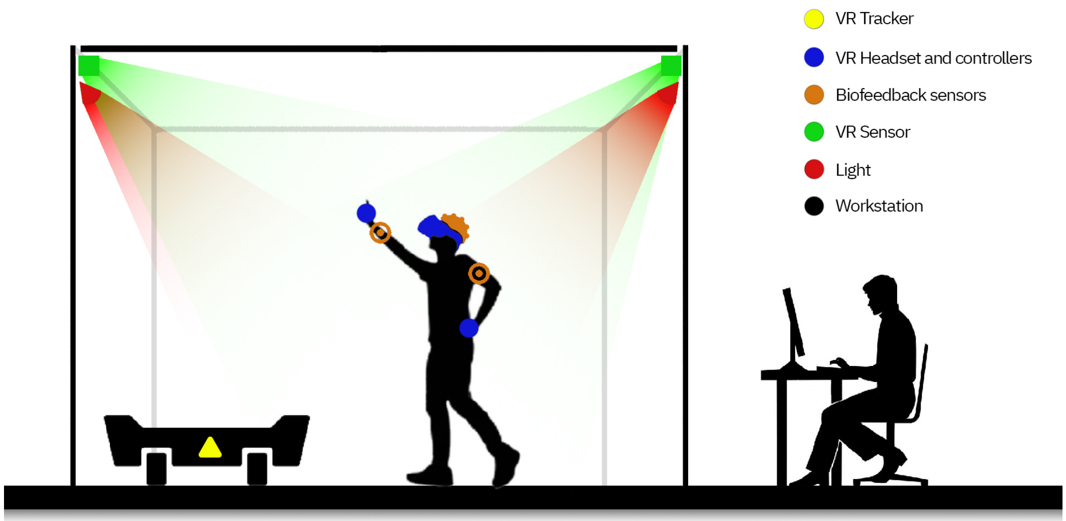

Fig. 3 Schematic diagram of the components of the experiment setup

C. Phase III: XR Framework deployment

The framework is meant to be utilized by aerospace companies and educational institutions intended to integrate immersive technologies in their design process. A subsequent technical paper will be written and presented to produce a "manual" for adoption of immersive technologies.

V. Framework Evaluation Methodology

XR is a fundamental tool for the space sector, but as many new technologies do, it requires time for extension of its possibilities to be fully understood. Even though the first NASA experiments of using XR started in the late 80s, as of today, its use is relegated to empirical testing, with no standardized protocols for obtaining measurable data that can impact a design process. As it is already stated in the section IV, many private space companies and space agencies are researching effective utilization of this technology for human factors evaluation in space applications. The main outcome of the presented here XR framework is providing scientifically proven protocols for XR applications, described with qualitative and quantitative evaluations that can impact the design process.

This section describes an evaluation process of the XR testing phase and its use for synthesis of derived design criteria. The XR framework was designed to test space hardware performance along with human factors accommodating design. Therefore, the evaluation phase was broken down into two major topics: Human performance evaluation and Hardware performance evaluation. The collected data points sequentially interpolated to obtain a final inclusive evaluation of the process. Additionally, the framework is flexible enough to allow reading the data independently for obtaining more precise outcomes from the process.

A. Hardware performance evaluation

Hardware performance with human factors evaluation is described as the measurement of hardware capability to perform the tasks that it was designed for and when operated by a user. That is a fundamental evaluation metrics because

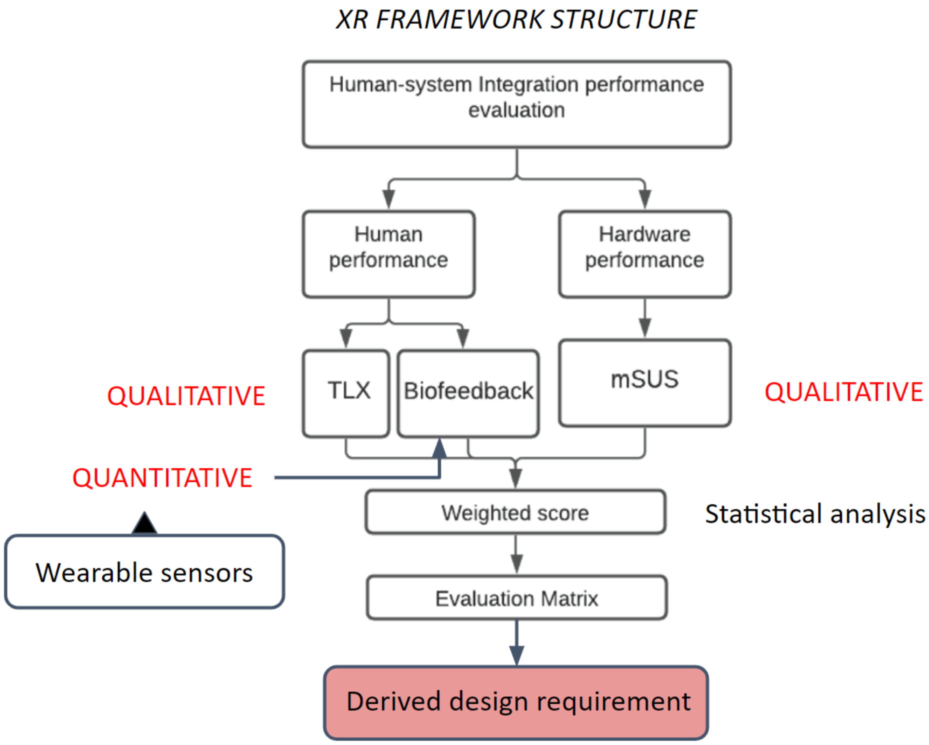

Fig. 4 The final iteration of the XR framework

it is directly connected to design features of the hardware. This evaluation phase allows defining specific aspects of hardware designs that are responsible for performance deficiencies. In the XR framework, the hardware performance is evaluated with the mSUS (modified System Usability Scale) an adaptation of the largely used SUS. The mSUS is a qualitative evaluation method based on a user dispensed survey. The survey is organized in 10 questions to be answered on a 5-level scale from Strongly Disagree to Strongly Agree. The 10 questions administered after the test scenario performed by the user. Questions are designed to cover system's specific usability aspects.

B. Human performance evaluation

Human performance evaluation aims to assess physiological and psychological states of the user while using the hardware for performing a specific task. It is important for two reasons: it identifies specific design features that pose a challenge or risk for accomplishing an objective; and it acts as a control group for Hardware performance evaluation since a deep discrepancy between the results can usually be traced back to a faulty data collection phase or to an evaluation impairment from the user. Human performance evaluation collected in two different ways: through TLX (Task Load Index) and biofeedback reading. The TLX is a NASA designed survey dispensed to users for self-evaluation of their own performance while using a target hardware to perform a specific task. The Task Load Index was created at NASA Ames Research Center in 1980 by Sandra Hart. By incorporating a multi-dimensional rating procedure, NASA TLX derives an overall workload score based on a weighted average of ratings on six different subscales that include: Physical Demand, Temporal Demand, Performance, Effort and Frustration. The NASA TLX has been successfully used in a wide range of applications since its introduction, and it is still used today in a wide range of Human-Machine Interaction testing. The TLX survey assesses work load on five 7-point scales with increments of high, medium and low estimates for each point resulting in 21 gradations on the scales. The survey composed of 6 questions.

C. Global evaluation

The XR framework is not a pure quantitative evaluation tool, designed to give numerical ratings per specific design options. Instead its purpose is to provide insights on specific aspects that impact positively or negatively design efficiency.

An expected framework application is to test one of more design options for a hardware component or human-machine interface and express a number of qualitative insights on different aspects that affect design usability and/or efficiency.

Thus, framework evaluation process interpolates the data collected from three sources:

- NASA TLX
- mSUS
- Biofeedback sensors

While the first two are to be considered 'indicators', the biofeedback data from wearable sensors are used as control data for some of the TLX indicators. The biofeedback sensors provide the only objective data used in the framework, and are important to overcome possible false inputs that can occur in the user self-evaluation process.

In a summary, indicators from the three data sources include:

- 6 questions from the NASA TLX survey
- 10 questions from the mSUS survey
- 14 different physiological measurements from the Biofeedback sensors

Even if arranged in two different surveys, 16 questions are to be reorganized in 6 categories that identify different areas in which hardware design affects the task success rate. TLX, mSUS and biofeedback sensors use different scales, requiring to standardize the partial results in a scale of 0-100 to enable comparison of different indicators. The six categories are:

- Physical effort
- Mental effort
- Task performance
- Hardware usability
- Hardware complexity
- Hardware intuitiveness

Analysis of quantitative results in each of the described areas allows to define specific optimization criteria for enhancing overall efficiency of the design and usability by different categories of users. In case of experiments that involve testing different design options for the same hardware, it is possible to add partial results from the six evaluation areas to obtain a general rating for evaluating each option against others. An outcome of the evaluation process is a quantitative evaluation in 0-100 for each of design areas. It is up to a designer to use those indicators to improve specific aspects of the hardware design if desired. For example, a poor score in the hardware usability should trigger a specific concern regarding a human interface, especially if it is correlated with a high physical effort and a low task performance score.

VI. Framework Testing

The framework needs to be tested through a sequence of experiments aimed to evaluate certain design aspects of the reference mission - the Lunar surface architecture studies performed by SICSA research team for The Boeing Company. Since development of the design evaluation methodology is a continuous effort related to sponsored research, the selection of subjects depends on availability of funds, students and faculty, and volunteers from other subject pools.

The study aims to recruit 20 subjects (ideally 10 men and 10 women) within the age range of 22-70 years. The number is arbitrary and reflects on desirable amount of data that can be handled by SICSA research staff. The subjects to be chosen from different professions including designers, astronauts, potential space tourists, and flight operation engineers. The hearing ability, mental state, and health conditions of the test subjects are self-admittedly normal. Furthermore, the test subjects should not undergone any previous VR, EEG and other biofeedback related training. [14] [15] For this study, we are not considering the difference in brainwave performance between males and females that several studies maintain. [16]

During initiation of the experiment, at the entry phase, subjects to perform an entry survey where meta data collected to identify subjects' details.

Next, in the calibration phase, test subjects asked to wear biofeedback sensors and perform baseline tests to establish baseline readings for each subject. This also helps to make subjects to familiarize themselves with sensors to prevent potential discomfort during the test and influencing accuracy of experiment results.

Then, in a training phase, subjects wear VR sets and introduced to the simulation. During this phase, each subject to perform 4 tasks that related to the selected reference mission, Lunar Surface Architecture study conducted by SICSA and sponsored by The Boeing Company.

- Task 1: Drive the LTV in EVA mode.
- Task 2: Access the habitat crew airlock from an EVA mode.
- Task 3: Unload the cargo airlock from the Cargo box in IVA mode.
- Task 4: Re-purpose the interior habitat configuration in IVA mode.

Each subject performs a survey after each task with a VR device off but keeping biofeedback sensors on. Subjects answer questions that inform TLX and mSUS surveys on a specific task they just completed.

After the fourth and final survey, a subject is debriefed and an exit survey taken to collect high-level meta data of the experiment. This concludes the test. A schematic diagram showcasing the structure of the test run is shown in the figure 5

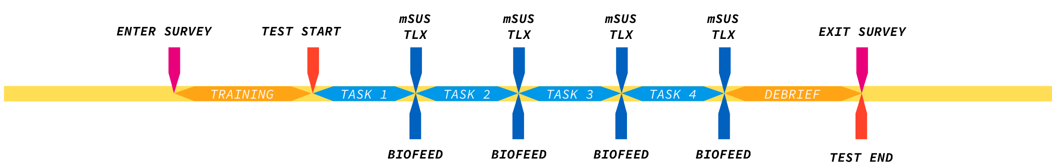

Fig. 5 The final iteration of the XR framework

The tasks were designed in a previous study [17] to test four different design features of both the LSS (Lunar Surface Study) and LTV (Lunar Terrain Vehicle), to validate their respective initial design assumptions. The length of each task is approximately 3 minutes and the length of the whole test run is an average of 25 minutes.

VII. Conclusion and Next Steps

This paper aims to describe the design process of a performance evaluation method for human-System Integration for Space applications developed at SICSA. The proposed method utilizes traditional qualitative and quantitative metrics while enhancing immersion into testing environment, and increasing performance fidelity through VR utilization. Immersive technologies allow a higher level of simulation accuracy along with enabling a better understanding of design constraints and human-machine interaction failure points. Following the completion of the functional mockup and the virtual simulation environment assembly, a testing campaign is planned to validate research assumptions. In addition, design testing and evaluation using the presented in this paper methodology, will be integrated into Master of Science in Space Architecture curricula allowing students incorporate XR framework in their research and design methodologies. The results of master thesis projects evaluations will contribute to XR methodology maturation. The XR framework is based on proven NASA testing standards and shows the potential to become an additional new standard for XR technologies utilization across the space sector including space agencies and private companies.

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References

[1] Rauschnabel, P. A., Felix, R., Hinsch, C., Shahab, H., and Alt, F., "What is XR? Towards a Framework for Augmented and Virtual Reality," *Computers in Human Behavior*, Vol. 133, 2022, p. 107289. https://doi.org/10.1016/j.chb.2022.107289, URL https://www.sciencedirect.com/science/article/pii/S074756322200111X.

[2] "Planning and shooting guidelines," , ???? URL https://creator.oculus.com/getting-started/planning-and-shooting-guidelines-for-immersive-media-video-production/.

[3] Anthes, C., Garcia-Hernandez, R. J., Wiedemann, M., and Kranzlmuller, D., "State of the art of virtual reality technology," *2016 IEEE Aerospace Conference*, 2016, pp. 1–19. https://doi.org/10.1109/AERO.2016.7500674, URL http://ieeexplore.ieee.org/document/7500674/, conference Name: 2016 IEEE Aerospace Conference ISBN: 9781467376761 Place: Big Sky, MT, USA Publisher: IEEE.

[4] Castillo, M., "The Scientific Method: A Need for Something Better?" *American Journal of Neuroradiology*, Vol. 34, No. 9, 2013, pp. 1669–1671. https://doi.org/10.3174/ajnr.A3401, URL https://www.ajnr.org/content/34/9/1669, publisher: American Journal of Neuroradiology Section: Editorials.

[5] Jiang, S., Moyle, B., Yung, R., Tao, L., and Scott, N., "Augmented reality and the enhancement of memorable tourism experiences at heritage sites," *Current Issues in Tourism*, Vol. 26, No. 2, 2023, pp. 242–257. https://doi.org/10.1080/13683500.2022.2026303, URL https://doi.org/10.1080/13683500.2022.2026303, publisher: Routledge _eprint: https://doi.org/10.1080/13683500.2022.2026303.

[6] Alnagrat, A., Ismail, R. C., Idrus, S. Z. S., and Alfaqi, R. M. A., "A Review of Extended Reality (XR) Technologies in the Future of Human Education: Current Trend and Future Opportunity," *Journal of Human Centered Technology*, Vol. 1, No. 2, 2022, pp. 81–96. https://doi.org/10.11113/humentech.v1n2.27, URL https://humentech.utm.my/index.php/humentech/article/view/27, number: 2.

[7] Alcañiz, M., Bigné, E., and Guixeres, J., "Virtual Reality in Marketing: A Framework, Review, and Research Agenda," *Frontiers in Psychology*, Vol. 10, 2019. URL https://www.frontiersin.org/articles/10.3389/fpsyg.2019.01530.

[8] Mathew, P. S., and Pillai, A. S., "Role of Immersive (XR) Technologies in Improving Healthcare Competencies: A Review," *Virtual and Augmented Reality in Education, Art, and Museums*, IGI Global, 2020, pp. 23–46. https://doi.org/10.4018/978-1-7998-1796-3.ch002, URL https://www.igi-global.com/chapter/role-of-immersive-xr-technologies-in-improving-healthcare-competencies/www.igi-global.com/chapter/role-of-immersive-xr-technologies-in-improving-healthcare-competencies/241592.

[9] Doolani, S., Wessels, C., Kanal, V., Sevastopoulos, C., Jaiswal, A., Nambiappan, H., and Makedon, F., "A Review of Extended Reality (XR) Technologies for Manufacturing Training," *Technologies*, Vol. 8, No. 4, 2020, p. 77. https://doi.org/10.3390/technologies8040077, URL https://www.mdpi.com/2227-7080/8/4/77, number: 4 Publisher: Multidisciplinary Digital Publishing Institute.

[10] Netti, V., Guzman, L., and Rajkumar, A., *A Framework for use of immersive technologies for human-system integration testing of space hardware*, 2021.

[11] Netti, V., Bannova, O., Kaur, J., and Spolzino, R., "Mixed Reality (XR) as a Validation Method for Digital Modeling of Space Habitats," 2023, pp. 885–892. https://doi.org/10.1061/9780784484470.074, URL https://ascelibrary.org/doi/10.1061/9780784484470.074, publisher: American Society of Civil Engineers.

[12] Rippy, L. O., "NASA Human Systems Integration Handbook," , Nov. 2021. URL https://ntrs.nasa.gov/citations/20210010952, nTRS Author Affiliations: Langley Research Center NTRS Report/Patent Number: NASA/SP-20210010952 NTRS Document ID: 20210010952 NTRS Research Center: Langley Research Center (LaRC).

[13] Ennis, S., Rometsch, F., Saling, F., Fischer, B., Mittler, P., Ferra, L., Vizzi, C., Casini, A. E. M., Marnat, M., Thevenot, C., and Boyer, L., "Astronaut training on-board the International Space Station using a standalone Virtual Reality headset," Dubai, United Arab Emirates, 2021. URL https://elib.dlr.de/147953/, iSSN: 0074-1795.

[14] Kim, H.-G., Cheon, E.-J., Bai, D., Lee, Y., and Koo, B. H., "Stress and Heart Rate Variability: A Meta-Analysis and Review of the Literature," *Psychiatry investigation*, Vol. 15, 2018. https://doi.org/10.30773/pi.2017.08.17.

[15] Liu, N.-H., Chiang, C.-Y., and Chu, H.-C., "Recognizing the Degree of Human Attention Using EEG Signals from Mobile Sensors," *Sensors (Basel, Switzerland)*, Vol. 13, 2013, pp. 10273–86. https://doi.org/10.3390/s130810273.

[16] Kim, H., Kim, Y.-S., Mahmood, M., Kwon, S., Zavanelli, N., Kim, H. S., Rim, Y., and Epps, F., "Fully Integrated, Stretchable, Wireless Skin-Conformal Bioelectronics for Continuous Stress Monitoring in Daily Life," *Advanced Science*, Vol. 7, 2020, p. 2000810. https://doi.org/10.1002/advs.202000810.

[17] Spolzino, R., Kaur, J., Netti, V., and Bannova, O., "Minimal Lunar Infrastructure to Facilitate the Construction of Sustainable Structures," 2023, pp. 935–945. https://doi.org/10.1061/9780784484470.078, URL https://ascelibrary.org/doi/10.1061/9780784484470.078, publisher: American Society of Civil Engineers.