Towards Balanced Astronaut-Oriented Design for Future EVA Space Technologies

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The realization of humanity's aspiration to establish permanent outposts on the Moon and beyond will necessitate a substantial increase in the complexity and frequency of Extravehicular Activities (EVAs). An innovative ecosystem comprising dependable, secure, and user-centric technologies will have to be developed to effectively assist and safeguard astronauts during these EVAs. Historical endeavors in the realm of space systems development have predominantly been shaped by science goals and engineering-driven safety considerations, typically resulting in solutions tailored towards a narrow range of carefully pre-planned procedures. The expanded scope of future EVA's will demand versatile tools capable of facilitating a diverse range of potentially unpredictable tasks. This paper asserts that addressing this situation requires the development of a balanced astronaut-oriented participatory design approach to effectively identify design requirements and develop prototypes for future EVA technologies. Drawing upon established methods in technology development, such as balanced human systems integration (bHSI), human systems exploration, and concurrent engineering, we propose the integration of astronauts and domain experts throughout the design process. Prior to technological development, significant emphasis should be placed on exploring initial design requirements and concepts. Through the adoption of an astronaut-oriented approach and the introduction of iterative feedback loops between all stakeholders at every stage of the development process, the adaptability of EVA tool designs can be assured. Derived from these principles, we propose a systematic balanced astronaut-oriented design framework aimed at enabling efficient, cost-effective, and targeted development of EVA technologies starting from the early design process. We illustrate the applicability of this approach by outlining a potential approach to the design of AR interfaces in support of future EVAs.

CCS Concepts: • **Human-centered computing → Interaction design theory, concepts and paradigms**.

Additional Key Words and Phrases: human-centered design, extravehicular activities, human systems integration, human systems exploration, lunar exploration, participatory design, augmented reality

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1 INTRODUCTION

The Artemis program is making significant strides towards returning astronauts to the Moon by 2025 [42]. Expanding on the legacy of the Apollo missions, its ultimate goal is to establish permanent lunar bases by the end of this decade. Considering this as well as the international interest in a sustainable human presence on Mars, long-term habitation in extraterrestrial environments may well become commonplace in the near future. Nevertheless, the successful implementation of such plans will depend on the development of a new ecosystem of reliable, safe and effective technologies designed in support of future astronauts and their extravehicular activities (EVAs).

Historically, the approach to developing space technologies has been driven by science goals and engineering methods. This has typically resulted in specialized and function-specific solutions designed to support narrowly defined and pre-planned activities. Apollo-era EVA technology, for instance, was tailored to facilitate the tasks performed by astronauts during their brief excursions on the lunar surface, such as the deployment of scientific experiments, scouting, geological observations and sampling procedures [30]. This hyper-specific planning is made possible by the fact that EVA operations follow a strict sequence of steps. Detailed checklists describe every action the astronauts need to take from the initial airlock egress all the way to the final removal and cleaning of their astronaut suits after re-entry [27].

The design of EVA solutions is thus often constrained by pre-established requirements, allowing limited scope for flexibility during the design phase. Instead, key design goals are typically identified prior to the ideation phase and tend to remain unchanged throughout the development process. As a result, end-user involvement is generally not required until later stages when physical prototypes are deployed for assessment, such as during simulated EVAs in neutral buoyancy facilities [3, 12, 43].

A human-centered design approach, based on more generalized functional requirements, can reduce development time by preventing late-stage redesigns, reduce the risk of human errors [44], potentially simplify training and enable the design of highly versatile tools. This will be especially important in light of planned long-term habitation missions to the Moon and Mars since the more time spent on the lunar surface, the more unexpected scenarios are likely to occur. Several scholars have proposed that user-centered design methods should be given a more prominent role in the development of forthcoming space technologies [35, 39]. As elaborated by Obrist et al. [34] such methods are uniquely qualified to “contribute a new perspective and knowledge on how to think about and design future interfaces in space” (p. 2) [34]. And as highlighted in NASA’s 2020 Extravehicular Activity Roadmap [37], we must explore new user requirements and reassess current ones.

Upcoming human missions to the Moon and Mars are projected to entail EVAs that are more frequent and prolonged than ever before [8]. Astronauts will have to exercise a higher degree of autonomy [43] while performing more complex tasks [25]. All this in the harsh lunar environment, with poor lighting conditions, impaired spatial orientation and reduced situational awareness [6, 18, 36].

In response, we advocate for the comprehensive engagement of end-users and other pertinent stakeholders in the design phase of upcoming EVA solutions, thereby introducing user-centered and interdisciplinary elements into conventional engineering processes. To this end, we propose a framework that prioritizes and balances the user’s and other stakeholders’ needs, starting from ideation to the deployment and testing of prototypes. To illustrate how such an approach might be operationalized, we outline a potential design process of Augmented Reality (AR) technology supporting future complex EVA activities on the lunar surface.

2 A (BALANCED) ASTRONAUT-ORIENTED APPROACH TO THE DESIGN AND DEVELOPMENT OF FUTURE EVA SPACE TECHNOLOGIES

Instead of relying on conventional engineering approaches to develop space technologies, we propose adopting a more comprehensive astronaut-oriented design process. Specifically, this process ought to involve establishing strong and systematic feedback loops between engineering teams, astronauts, and experts from a range of relevant domains, such as psychology, medicine, geology, and engineering, throughout the entire design phase. Although these stakeholders may not always have direct expertise in future EVA user requirements, their involvement in the design process will lead to more comprehensive and versatile solutions.

To inform our approach, we draw on a number of existing design methods in technology development, including Concurrent Engineering and Human Systems Integration (HSI):

Concurrent Engineering approaches are characterized by a simultaneous and collaborative design and development of technologies in a structured manner. By engaging multiple experts from diverse disciplines, the potential synergies and frictions between various project aspects can be evaluated from the outset. In the process, key considerations such as resource and system requirements, potential design solutions, and cost implications are formulated during collaborative sessions. Such an approach has been noted for contributing to a significantly faster development time and reduced costs when applied to the development of space technologies [5].

Human systems integration (HSI) is a managerial approach that focuses primarily on enhancing interaction between the user, (complex) technologies, and environmental and organizational factors. It seeks to help "coordinate, cooperate, and communicate in order to successfully carry out a particular function or mission” [37]. Balanced HSI thereby also highlights the importance of involving all relevant stakeholders throughout all phases of the development process. While converging on a balance between “requirements, ideas and methodologies” and other resources, including time, quality and financial resources [19], HSI takes into account not only the qualitative perspective of the user but also objective evaluations.

Notably, NASAs HSI handbook [37] warns that neglecting HSI practices during the early design phase could jeopardize mission success or even endanger the lives of future crews. HSI practices should thus be integrated into project planning and employed iteratively throughout the development life cycle. Exploring early design ideas and requirements can likewise be seen as a critical prerequisite for efficient development procedures. These exploratory activities enable the generation of original ideas and solutions, as well as the establishment of key design specifications, thus paving the way for testing and experimentation [20]. Correspondingly, the human-systems exploration method is frequently employed to systematically examine new combinations of “technology, humans, organizations and environments” in order to generate novel ideas during the early stages of technology development (p. 5) [20]. Following the aforementioned methods, we propose an astronaut-oriented approach to the development of EVA technologies that:

(1) **Involves astronauts and domain experts throughout the complete design process and balances the needs of all stakeholders.**
Astronauts and domain experts possess valuable knowledge about the challenging conditions during EVAs, such as the limited mobility of an EVA suit and the effects of reduced gravity. By involving stakeholders from different fields (e.g. psychology, medical personnel, mission planning team, etc.), it is possible to gain a diverse set of

perspectives. This way a comprehensive understanding of requirements and design solutions can be developed at an early stage of the design process.

(2) **Places a greater focus on the exploration of requirements and design ideas prior to technological development.**
By involving stakeholders in the early stages of the design process, prior to the development of a working prototype, the technological development can be steered in the right direction, ensuring an efficient and targeted development of design solutions for future EVA systems. This approach allows for the identification of needs and requirements, leading to a reduction in costs and development time during the implementation and testing of technological prototypes during the final step.

(3) **Creates iterative feedback loops between engineers, domain experts and astronauts.**
Feedback loops between stakeholders and engineers allow for a continuous adjustment of potential design ideas, requirements, and prototypes to dynamically meet new environmental constraints, new research findings, or other relevant factors, such as costs or time - constraints. This is relevant since mission profiles and therefore functional requirements are likely to change throughout the development cycle. Therefore, it is possible to achieve flexible development, continuous improvement, and a reduction in risks related to the development of future EVA tools [9].

Derived from those principles we propose a 4-stage model of EVA technology development. In the following section, we use the example of prospective AR technologies to illustrate how such a model might be put in place and the benefits that may follow from adopting an astronaut-oriented philosophy in support of future EVA operations.

3 (BALANCED) ASTRONAUT-ORIENTED AUGMENTED REALITY TECHNOLOGY FOR FUTURE EVAS

Augmented Reality (AR) technology has emerged as a promising solution for enhancing astronaut performance during future EVAs by overlaying the astronaut's field of view with contextually relevant computer-generated 3D information. Research suggests that this could help improve performance and safety for navigation [2], hazard detection [28], and assembly and maintenance tasks [11, 17].

Similar to other space technologies, current research on the design of prototypes for future AR technologies predominantly adopts a technology-driven or engineering-driven approach. Existing studies have exhibited a common pitfall by prioritizing the development of costly and time-consuming AR technologies without first establishing clear design ideas and requirements in early design stages prior to the development of working prototypes [1, 14, 17]. Furthermore, a significant number of studies rely heavily on existing technologies like the Microsoft HoloLens [2, 14, 22, 29], without any indication that these technologies fulfill any requirements for implementation in an EVA environment.

Diving into detailed design and prototyping before conducting a thorough and structured concept development process can lead to sub-optimal solutions which are based on wrong assumptions. Unstructured early concept development can potentially lead to overlooking solutions that may be better suited to future needs. It can even be the cause for costly redesigns at a later stage of development. In contrast, adopting user-centered methodologies and concept design methods in combination with the systems engineering approach can yield beneficial results, providing a better understanding of the problem area, the introduction of innovative concepts, and insights into technical requirements derived from the design and feedback process [38].

Studies in the field of AR for astronaut operations tend to start off by directly delving into the development of a prototype AR interface on a seemingly arbitrary or convenience-based choice of functionalities and technologies. In such cases, the concept development phase is often skipped entirely, with the AR interface design prototype seemingly being based on the researcher's preconceived idea for an AR application and previous research findings rather than on a structured concept development and validation phase. Previous work has attempted to address this with a structured ideation phase, and a categorization of potential functionalities found in a literature review [17]. However, the scope of this work is limited, and it does not address the need for comprehensive user-centered concept development.

The fragmented nature of research in this area means that no thorough analysis has been conducted to understand the wider implications of a potential AR system development for astronauts. Such a system would require a significant investment and one can expect that once developed, it will be in use for many years. So a comprehensive analysis of current and future stakeholders, potential application areas, technology developments and changing needs during the system's expected lifetime would yield invaluable insights that are essential for the validation of any detailed prototyping and testing campaign. Furthermore, such an analysis could allow a preliminary list of requirements to be drafted, which would enable a concept-based trade-off analysis of various fundamental approaches and system architectures to be conducted. After all, choices such as if the AR system should be suitable only for EVAs or if it should also work inside spacecraft are essential for the design of detailed prototypes.

A comprehensive concept development process would, for example, include feedback loops concerning preliminary design ideas (e.g. wireframes, sketches, Wizard of Oz mockup scenarios) from domain experts and astronauts [1, 2].

Another limitation of existing studies is the predominance of participants who lack experience with actual EVA conditions. For example, some studies [1, 14, 29] seemingly only involved non-astronauts and non-experts as participants. This constraint likely arises from the challenges associated with recruiting domain experts and astronauts as participants. However, the insights gained from studies that include respondents with direct experience in EVA conditions are invaluable for enhancing the effectiveness and usability of future AR technologies, as shown by, for instance, Rometsch et al. [39].

Lastly, In order to accurately evaluate the development of an AR system for extraterrestrial missions, it is crucial to conduct thorough testing of design prototypes under conditions that simulate the target environments, such as the geological conditions found on the Moon or Mars. Yet, most studies focus on prototype deployments in environments that lack such operational validity [1, 14, 29].

To solve this, analog facilities that mimic the conditions on surfaces such as the Moon or Mars have been utilized, by, for instance, Anandapadmanaban et al. [2] during NASA's BASALT campaign, which took place across several National Parks in the US, testing the navigational capabilities of their AR interface. However, these analog campaigns are infrequent, logistically complex and involve a limited number of participants and they can never reproduce the lunar environment perfectly. As a result, it is advisable for such testing to be done as a part of a thought-through testing and validation campaign, and that the AR interface is developed to a considerably advanced stage using more flexible and repeatable setups such as neutral buoyancy facilities [23] or VR environments [32] before investing in costly and demanding simulations of EVAs using analog campaigns.

In conclusion, the current design process of AR interfaces for future EVA missions is mostly inefficient and ineffective at comprehensively laying a foundation for a user-centered system development. The research findings also likely only have limited applicability by not giving adequate consideration to the high level of uncertainty derived from the still largely undefined mission criteria and unclear future needs of astronauts.

To address these issues, we suggest moving towards an astronaut-oriented approach, of which we provide an initial outline here. The proposed approach consists of a more comprehensive 4 - stage balanced astronaut-oriented design process (See Figure 1) that consists of iterative ideation, design prototyping, technical prototyping, and system usage stages. We furthermore propose various methods that could facilitate the design process at each stage. Following common design approaches [40], the process model of human systems exploration by Flemisch et al. [20], and the British Design Council's double diamond approach [16], each stage begins with an exploration of design possibilities involving all stakeholders (also known as the divergent process, discovery or analysis). At the end of each stage the information and needs of astronauts and domain experts are balanced and condensed into one key result or insight that serves as the foundation for the subsequent stage (also known as the convergent process, definition or synthesis). The iterative nature of these stages, as demonstrated by Rometsch et al. [38], is crucial [16].

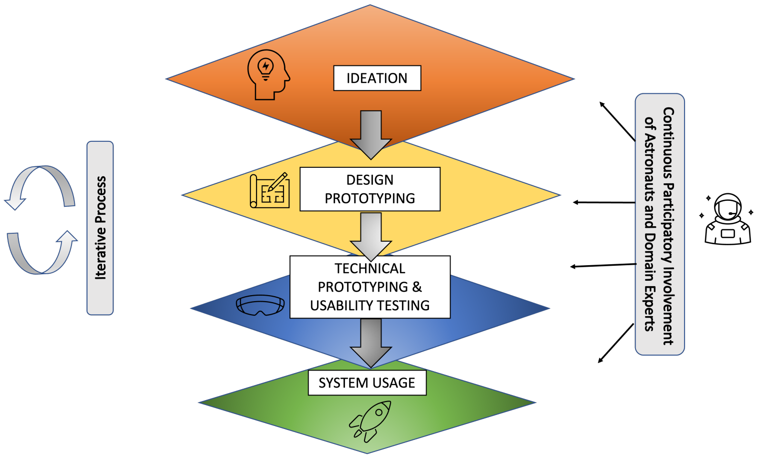

Fig. 1. Schematic diagram displaying an astronaut-oriented approach to the design of AR technologies for future EVAs, involving continuous participation of domain experts and astronauts in an iterative process

3.1 Ideation

We propose an increased focus on the identification of user needs and the inclusion of stakeholders at the very beginning of the development cycle (see Figure 1). The goal of the ideation stage is 1) the identification of technological and functional requirements through context, stakeholder and trend analysis and 2) the brainstorming about how these requirements could be met with or without AR technology.

In the ideation stage, the focus lies on generating a wide range of ideas and conceptualizing potential solutions to address the identified needs and challenges. It involves exploring different possibilities, thinking creatively, and expanding potential design possibilities [20]. Methods that can be used to foster collaboration and ideation in this phase are approaches such as interviews [10, 15, 39], focus groups [41], employing the Delphi method [13] and expert brainstorming sessions [17, 38], virtual testbeds [7] and design fiction [26] that all have been shown to be reliable and effective tools for the identification of requirements and novel design ideas in the space sector in past research (for a detailed description of each method, see references). Potential outcomes of the ideation stage may be a list of requirements, a mindmap or sketches about potential design ideas.

3.2 Design Prototyping

In contrast to the ideation stage, in the design prototyping stage, the astronauts and domain experts should be instructed to gather concrete design ideas for a specific AR design solution for a given environment (e.g. Lunar surface). During the design prototyping phase, selected design concepts from the ideation stage are transformed into tangible representations that can be tested, evaluated, and refined in a cost-effective and flexible manner. This involves creating prototypes that simulate the functionality, interactions, and visual aspects of the proposed design solutions. The proposed solutions can then be tested and evaluated by the same or other domain experts and astronauts in an iterative process. The output of the design prototyping stage is a collection of prototypes ranging from low-fidelity paper (for example, see Figure 2) or digital mockups to low-fidelity physical or virtual representations of the AR interface. Before continuing on to the technical prototyping phase, these prototypes are used to collect user feedback, evaluate usability, and refine the design. Methods to foster feedback and collaboration between researchers and experts in this phase are the creation of paper prototypes, the method of the Wizard of Oz [21, 24], or the implementation of design prototypes in a VR testbed [33], created in a participatory manner. Furthermore, methods proposed in the ideation stage (e.g. interviews, Delphi method, focus groups, etc.) can also allow for finding a consensus between domain experts, and astronauts to focus the development on one specific design prototype that should be followed in the technical prototyping stage.

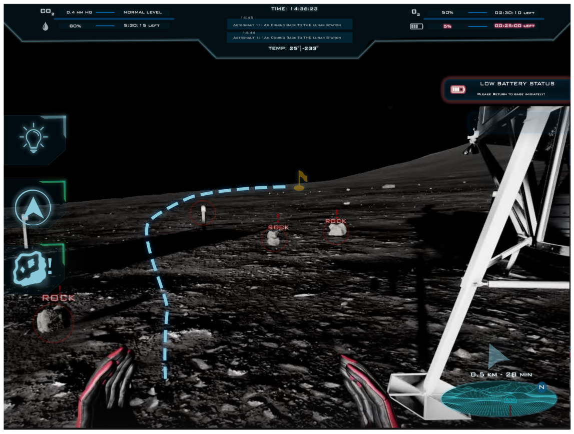

Fig. 2. A possible concrete design idea for an augmented reality interface that could be the outcome of the design prototyping stage

3.3 Technical Prototyping & (Usability) Testing

Unlike conventional research practices, the technical implementation of an AR system and usability testing are both conducted after a thoroughly conducted design of simpler prototypes and investigation of requirements in a participatory manner. Through iterative design and evaluation of AR system representations in a flexible and cost-efficient way, researchers could progressively identify a design solution that effectively meets astronauts' requirements.

During the technical prototyping stage, researchers should explore feasible options for technically implementing the proposed idea. On the one hand, researchers can test the AR system using existing technologies such as the Microsoft HoloLens. This enables researchers to assess usability and functionality within a familiar AR platform, limiting costs and ensuring flexibility in the development process.

On the other hand, researchers should also explore the integration of AR technology, for instance, directly into the astronaut suit. Here, technical prototypes should be developed as shown by e.g. [31]. This is especially important if current technological capabilities would limit the accurate (usability) testing of the design prototype.

For evaluating high-fidelity technical prototypes, analog campaigns should be employed as a method to simulate and evaluate the proposed AR system in relevant mission contexts (e.g. Lunar Surface, LEO, etc.) [2].

At the end of the technical prototyping stage, a final AR interface should be developed that meets all requirements defined in the ideation stage and that was refined through an extensive iterative and collaborative process between astronauts, domain experts and researchers or engineers. Moreover, the technical implementation, the design of the user interface, the infrastructure needed to use the device, should be successfully developed.

3.4 System Usage

The last stage of the design process is the usage of the AR system during actual EVAs. Here, the design process should still follow an iterative and participatory approach. Errors, novel requirements, constraints as well as feedback gathered from astronauts and domain experts should be furthermore integrated into the design process to ensure maximum safety, performance, and user-friendliness. Therefore, feedback gathered through, for instance, the usage of AR technology on the Moon can be quickly translated back into the design and improvement process.

4 FUTURE WORK

Considering upcoming missions to the Moon and beyond with a growing need for EVA systems and interfaces, our astronaut-oriented- approach could yield a flexible, cost and resource-efficient, as well as a systematic way of developing new EVA technologies that balance the requirements and needs of astronauts and other stakeholders throughout the design process.

In previous research, we already have successfully adopted the ideation stage of the proposed balanced astronaut-oriented design process for the development of AR technologies [7]. By leveraging a virtual testbed, we were able to create an accurate representation of the Lunar environment. This VR testbed served as a valuable platform for exploring potential operational scenarios, involving six astronauts and EVA experts. In our initial study, we were able to identify essential design requirements and use cases for AR technologies in the context of lunar exploration. Building on our prior work, we aim to further expand our understanding of astronauts' design requirements and needs during EVAs. To achieve this, we plan to conduct additional expert interviews, inviting a larger number of participants to engage in our VR environment. This will enable us to gather more comprehensive insights and refine our design approach accordingly.

Furthermore, we plan to implement and refine the ideas generated in close collaboration in a participatory manner with astronauts and domain experts. By utilizing the virtual testbed, we can iteratively enhance the design of AR features, incorporating valuable feedback from astronauts at our facility (design prototyping stage). Through these steps, we aim to deepen our understanding of the design requirements specific to astronauts' needs during lunar EVAs.

We would like to put emphasis on the fact that our proposed astronaut-oriented model should evolve over time. It is a product as much as the AR system is a product, which can be shaped and improved as one goes along - our intention is therefore not to adhere to a strict step-by-step process but rather to test the model and then improve it as we proceed.

In future work, we would therefore like to refine and test our proposed 4 stage model of balanced astronaut-oriented design targeting the development of space technologies for future lunar EVAs in collaboration with, for instance, concurrent design facilities, such as the one established at ESA - ESTEC [4].

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