Assessing the Use of Mixed Reality as a Valid Tool for Human-Robot Interaction Studies in the Context of Space Exploration

Enrico Guerra
Interactive Systems, University of Duisburg-Essen, Duisburg, Germany

Sebastian Thomas Büttner
Department of Computer Science and Communications, Westfälische Hochschule – Westphalian University of Applied Sciences, Gelsenkirchen, Germany

Alper Beşer
Interactive Systems, University of Duisburg-Essen, Duisburg, Germany

Michael Prilla
Interactive Systems, University of Duisburg-Essen, Duisburg, Germany

Abstract

Mixed Reality (MR) is a technology with strong potential for advancing research in Human-Robot Interaction (HRI) for space exploration. Apart from the efficiency and high flexibility MR can offer, we argue that its benefits for HRI research in space contexts lies particularly in its ability to aid human-in-the-loop development, offer realistic hybrid simulations, and foster broader participation in HRI research in the space exploration context. However, we believe that this is only plausible if MR-based simulations can yield comparable results to fully physical approaches in human-centred studies. In this position paper, we highlight several arguments in favour of MR as a tool for space HRI research, while emphasising the importance of the open question regarding its scientific validity. We believe MR could become a central tool for preparing for future human-robotic space exploration missions and significantly diversify research in this domain.

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1 Introduction

Robotic systems can be considered essential for space and planetary exploration, maintenance of space stations, and autonomous operations in deep space. For space missions involving humans, efficient collaboration between humans and robotic systems is vital to mission success [14, 18]. Consequently, human-robot interaction (HRI) studies are carried out to gain knowledge about the interaction between humans and robots. Conducting HRI studies is challenging for multiple reasons: First, the availability of the robot is limited, as the development of robotic systems for space missions might not be finished at the time the study is needed. This creates a "chicken-and-egg" dilemma: HRI study results are crucial for robot design, yet a robot is often prerequisite for comprehensive studies. Second, testing robotic systems in space is unfeasible, necessitating their evaluation in simulated or artificial environments.

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Indeed, this problem has been extensively explored in Human-Computer Interaction (HCI) research, particularly through the study and use of various speculative design methodologies, including speculative enactments [11] and design fiction [27]. Mixed reality (MR) technologies, however, offer a powerful approach in addition to these existing speculative approaches. By enabling HRI studies with highly interactive and immersive virtual robot prototypes in blended real-virtual spaces, MR allows participants to engage in situated, embodied interactions that were previously difficult to achieve without physical hardware. According to the reality-virtuality continuum of Milgram [31], we understand MR as all variations of technologies that can merge real and virtual objects in the view of a user, including but not limiting the scope to the most prominent variant of augmented reality (AR).

While MR offers enormous potential in HRI research, there is still limited knowledge about the validity of using simulated robots in HRI studies. However, our ongoing work particularly researching the validity of HRI studies with virtual robots indicates that MR studies produce almost identical results to studies done with real robots. Based on this experience we argue that MR studies are a feasible alternative to HRI studies with real robots.

In this position paper, we argue that MR should be more widely used in HRI studies in the context of space exploration. Here, we first provide information on the established methods of HRI studies in the spaceflight domain in Section 2. Based on this, we highlight the potential of MR in Section 3. In Section 4, we summarise the current state of research in terms of validity of HRI studies including our own work that indicates that MR studies are valid, before we conclude the position paper in Section 5.

2 Established Methods in the Spaceflight Domain

To understand the methodological gap that MR could address, it seems helpful to review current approaches used to evaluate human-system and human-robot interactions in the context of space exploration. A common approach has been the use of so-called *analogue missions*. These missions replicate certain conditions found on planetary bodies such as the Moon or Mars [32]. This replication is achieved by conducting missions at locations on Earth that have specific similarities to extraterrestrial environments, such as the lunar surface. Analogue missions can be seen as essential means for performing tests on aspects regarding scientific, technological, and operational challenges of planned space missions [39]. This includes investigating specific human-centred questions and challenges such as insights into efficient astronaut-robot interactions techniques for surface operations [5]. While these analogue missions are seen as instrumental, they are rarely designed with systematic HRI research in mind. Academic studies explicitly investigating astronaut-robot interaction in such environments remain scarce, and the existing efforts are mostly driven by space agencies with a focus on engineering evaluation or mission preparation [18].

As much as these analogue campaigns are critical to prepare for future human-robotic exploration mission on extraterrestrial surfaces, they also come with some notable challenges. They require extensive planning and coordination, often involving complex logistics due to their remote and harsh locations. These sites–such as the Barringer Crater in Arizona [5] or the volcanic terrains in Spain and Italy [41]–are chosen for their similarity to extraterrestrial surfaces, but can be rather difficult to access and operate in. Alternatively, analogue facilities and lab-based physical simulations offer more accessible alternatives to remote analogue missions. Analogue facilities, such as ESA's LUNA [12] or neutral buoyancy facilities [33], replicate extraterrestrial conditions in controlled environments and can be used more flexibly and frequently. Similarly, high-fidelity physical tests conducted in laboratory settings can simulate planetary operations without requiring complex field deployments [14]. Even with these approaches, however, scientific HRI studies remain scarce. The existing body of HRI research in the space domain appears rather minimal and fragmented [37]; partly perhaps due to the aforementioned institutional context of these initiatives, which are often led by space agencies with operational rather than academic goals.

In recent years, however, Virtual Reality (VR) has increasingly been proposed as an additional helpful tool [7, 38, 10]. When designed effectively, VR-based simulations provide a cost-effective, flexible, and highly accessible alternative to analogue sites, facilities, or entirely physical lab-based test scenarios. Due to these aspects of VR, it can be used for better design evaluations [36], evaluations of concepts of operation [10], or the familiarisation of astronauts with robotic devices on the International Space Station (ISS) [7]. However, this approach comes with trade-offs, as certain aspects of realism are inevitably reduced–even when the virtual environment is meticulously crafted. In particular, tactile elements such as realistic haptic feedback, as well as the physicality required for natural interaction, remain difficult to reproduce in fully virtual settings.

In contrast, we argue that MR can offer a compelling middle ground, combining the flexibility and accessibility of virtual simulations with the physical realism, situational context, and physical fidelity of real-world test scenarios. In some cases, it may even enhance these aspects further by adding contextual realism or environmental augmentation. Some researchers in the field of HRI even suggest that interactions with virtual robots presented through AR could yield results similar to interactions with physical robots [19, 25, 16, 30].

3 The Potentials of Mixed Reality

This section provides an overview of why MR presents a highly beneficial technology for HRI in the research domain of space exploration. We first provide an overall look at the general advantages immersive, or Extended Reality, technologies can provide, before focusing on key benefits that are specific to HRI in space-related HRI scenarios.

3.1 General Benefits: Enhancing Efficiency and User-Centric Design

Immersive technologies such as VR and AR provide significant cost-efficiency advantages by enabling simulation and virtual prototyping throughout the design process [8, 24]. Instead of investing in multiple physical prototypes, engineers can develop and test virtual models. These digital iterations not only streamline the development cycle but also drastically reduce both material expenses and labour costs [8, 24, 4, 28].

Moreover, the iterative nature of digital prototyping allows for the early involvement of end-users. Usability and user experience tests can be conducted in the initial stages of development, even when the physical hardware does not exist yet. This early feedback loop facilitates the rapid identification and elimination of potential design flaws, thereby reducing the risk of costly errors later in the project timeline [6, 15]. While this might theoretically be also possible with desktop simulations, MR offers a distinct advantage in HRI contexts through higher immersion and more natural, embodied interactions. For example, instead of exploring a 3D rover model with a mouse and keyboard, MR allows users to physically engage with an augmented rover chassis, potentially using their hands for more intuitive control. This direct, physical interaction within a blended real-virtual space yields unique insights into spatial understanding and user experience, which can be pivotal for HRI research and justify the adoption of MR. Research suggests that user studies conducted with immersive virtual prototypes yield results that are comparable to those obtained using physical prototypes, validating the effectiveness of these digital approaches [8, 21].

Another considerable advantage of early virtual prototyping is its role in end-user training. As soon as the design phase is complete, virtual systems can be deployed to train users–even if the final physical systems are not yet available. This ensures that personnel are well-prepared and familiar with the system, reducing the learning curve when the physical hardware is eventually introduced. Additionally, the ability to simulate operational scenarios in virtual environments provides a safe and cost-effective platform for testing the system's performance in dangerous, remote, or expensive-to-replicate conditions [13]. Users can gain valuable experience in decision-making during high-risk scenarios, thereby enhancing overall mission readiness and system reliability [20].

In summary, immersive technologies not only reduce development costs and time but also improve the overall quality and safety of system design through early user involvement and flexible training environments. While these mentioned aspects apply broadly to many domains, the following section focuses specifically on the unique potential of MR for HRI in the context of space exploration.

3.2 Specific Benefits of Mixed Reality in the Human Spaceflight Domain

Several key benefits for HRI in space exploration stem from the fundamental capability of MR of combining virtual and real-world elements into a shared interactive space. The following are some of the most pertinent and encouraging advantages of MR, in our opinion as HRI researchers. While this is not an exhaustive list, it outlines key affordances that could meaningfully enhance how HRI is studied and designed in space-related domains with the help of MR.

3.2.1 Human-in-the-Loop: Enhancing HRI in Hybrid Robotic Systems

One of the major benefits of MR which is particularly relevant for HRI is its ability to facilitate interaction with virtual or partially virtual robotic systems. While VR can also simulate such interaction (only the fully virtual ones, however), the combination with real-world context sets MR apart. It not only enables safe yet potentially more natural interaction with a virtual robot compared to fully immersive VR environments; it also allows for the augmentation of physical robotic components [40].

For instance, a physical (maybe even low-fidelity) rover chassis might be enriched with a virtual manipulator or scientific instruments. Multiple variations of these virtual components could then be tested using an experimental setting following a between- or within-subjects design. This allows researchers to test and iterate robotic designs with human input and interaction well before the physical hardware is finalised. MR thus enables early human-in-the-loop development of robotic systems intended for future missions, helping to integrate human-centred design principles from the very beginning. That would also allow for early testing of astronaut-robot interaction techniques, workflows, or task protocols.

A limitation that can be pointed out in this regard could be that the interaction with, for example, a virtual manipulator of a rover would still be virtual; thus there would be a lack of haptic feedback or tactile aspects (during a handover for example) that would differ from the experience one would have when utilizing physical components. However, MR's ability to merge the physical and the virtual leaves it up to the experimenter where a tangible interface is needed and where a virtual one may suffice.

3.2.2 Realistic Hybrid Environment Simulations

Another major strength of MR that we see is the ability to carry out virtual HRI simulations within a realistic physical context. Real-world conditions such as lighting conditions, acoustics or various environmental details are therefore already available without having to be reproduced in a completely virtual environment. This can be particularly relevant for analogue facilities such as LUNA, where the physical setting can be preserved while being enriched with virtual content. In this way, the realism of the physical environment is preserved, while simultaneously benefiting from the flexibility of a virtual simulation.

That way, MR enables the creation of hybrid test beds that blend physical analogue environments with virtual additions. Such environments can offer the potential to approximate lunar surface conditions and mission scenarios in ways that would be difficult, or outright impossible, to achieve with physical means alone on Earth. Examples include the behaviour of passive objects under lunar gravity, which are not directly interacted with but still shape the environmental context [35]; challenging lighting conditions such as deep, sharply defined shadows cast on the Moon's surface [35]; the simulation of lunar dust behaviour, including how dust clouds form, move, and settle on equipment and surfaces; or the addition of a distant lunar horizon, which can evoke a greater sense of spatial scale and immersion.

As previously mentioned, recreating such conditions physically would be prohibitively complex or entirely unfeasible. MR thus provides a valuable opportunity to incorporate these otherwise inaccessible features into HRI research scenarios, paving the way for exploring and evaluating mission-critical factors under more realistic conditions for space missions.

3.2.3 Broader Accessibility and Flexible Simulation Setups with Adaptable Levels of Virtuality

By supporting simulations in physical, and therefore often more realistic, environments, and by allowing for the augmentation of physical elements with virtual content, AR holds considerable potential for increasing the accessibility of HRI research in the human spaceflight domain to a broader range of institutions and researchers. As MR and AR offers the ability to dynamically add virtual elements to physical objects [17] and therefore potentially adding details to the objects, institutes and research groups could enhance low-fidelity physical mock-ups or basic robotic systems with virtual elements. This can enable them to study partial aspects of future mission scenarios without full-scale hardware. While VR could support a similar notion, its limitation lies in largely omitting these aforementioned physical aspects.

Importantly, MR allows for more flexibility in simulation setups: researchers can decide which components should be physical and which virtual, depending on the development stage and the specific aspects of interaction being studied. This adaptability is further supported by emerging technologies and, at the time of writing this paper, the most cutting-edge devices such as the Apple Vision Pro [3], Meta Quest 3 [29], or Varjo XR-4 [42], which allow for dynamically adjusting the degree of virtuality. Such technologies can enable hybrid laboratory setups in which certain elements are physically present while others are virtual. They also allow for enhancing physical lab environments with additional visual context, such as features of the lunar or Martian surface, without fully abandoning physical interaction, as would be the case in VR.

Establishing such hybrid lab settings would, from our point of view, foster greater participation in HRI research targeting the human spaceflight domain. Such increased participation would allow, as already suggested in the earlier specific aspects of future human-robot exploration missions on the Moon or Mars to be examined in greater depth by domain experts. This includes factors that may significantly influence the quality of interaction between humans and robots–both positively and negatively–such as trust, usability, mental workload, cognitive fatigue, or acceptance.

4 The Question of Validity

While the previously outlined aspects of mixed reality may indeed offer significant value, we believe this potential is largely contingent on one critical condition: MR studies, experiments, and test scenarios must yield the same–or at least comparable–results as fully physical scenarios with physical robots or even in real operational contexts. This raises the fundamental question of *ecological validity*, which, in this context, means if the results of an HRI study done in MR would be similar to those from a real-world situation involving a physical robot [9].

4.1 Empirical Perspective

Previous research has correctly identified the most straightforward way of investigating this question: by conducting identical studies with real robots and with simulated robots. Interestingly, most comparative studies carry out their experiments using VR-simulated robots, such as Nenna et al. [34] investigating mental workload during a pick-and-place task; Li et al. [26] and Kamide et al. [23] comparing general human perception in regards to the proximity of an operating robot or Villani et al. [43] mainly investigating mental workload during a human-robot navigation task.

To our knowledge, the only two empirical comparative studies using physical and AR-simulated robot are the ones by Han et al. [19] and Mielke et al. [30]. Han et al. compared physical and AR-based robot gestures and found no significant differences in accuracy, anthropomorphism, or social attributes such as likeability, warmth, and perceived competence. Mielke et al., on the other hand, showed that human-robot tasks like pick-and-place scenarios can yield comparable results between real and virtualized setups in regards to workload and task ease.

We as a research group have set ourselves the goal to investigate the question of valid AR simulations in HRI, too. For this purpose, we conducted two identical experiments that investigated human trust in industrial robots. One of the experiments used a physical robot [2] and one used an AR-simulated robot [1] in a real environment. From these two studies, early insights can be drawn. In the studies, a human and a robot carried out collaborative handover tasks in the context of industrial disassembly of hazardous components. We measured the perception of trust, predictability, faith, dependability, safety, and adaptability multiple times during the studies, resulting in 98 data points to be compared. A statistical comparisons showed no significant differences between the physical and the AR condition for most of the data points measured. However, a small number of the data points showed significant differences, which might be attributed to situations, in which a robot fails in executing a physical task (in the study, differences showed in the variable trust, when the robot failed to remove a rusty screw). The results were all based on non-parametric Mann-Whitney-U tests at a significance level of $\alpha = 0.05$.

While this shows that interaction with AR simulated robots may indeed yield similar results as interactions with physical robots and can therefore provide ecological validity, the question may remain how these indications can be transferred to human space exploration.

4.2 Implications for Space Exploration

While previous results from MR-based HRI studies indicate that virtual simulations can deliver valid results, the transferability of these findings to the space exploration context is anything but self-evident. Space missions involve very specific environmental conditions, work requirements, and psychological stress that differ greatly from typical laboratory scenarios. This raises the question of how ecological validity can be meaningfully assured or at least approximated in the field of space research.

We see two potential complementary approaches to address this challenge and to try to better understand the question of validity of MR-based HRI studies in the context of spaceflight:

(1) General lab studies as indicators: Studies such as the ones that have been described in Section 4.1, will likely emerge in a higher frequency in the future. These studies, that happen in classic lab settings with a fully physical counterparts that can be feasible to make identical to the MR-simulated condition, can be initial indicators for validity. The more variety these studies show (concerning different interaction techniques or dependent variables), the clearer the picture becomes. Regarding important variables in the HRI context like workload, performance, or trust, such empirical research can deliver valuable insights for astronaut-robot interaction, thus providing a degree of plausibility of MR-based research. Nevertheless, such findings should be interpreted with caution, as typical HRI scenarios in space exploration are significantly more complex and context-dependent.

(2) Comparative studies with a focus on space exploration: A more targeted approach involves designing MR-enhanced HRI lab studies that resemble conditions and tasks relevant to space exploration. For instance, experiments could compare the interaction with a low-fidelity physical robotic mock-up augmented with virtual elements to the interaction with fully physical robotic systems, while carrying out a scenario relevant human-robot activities on the lunar surface such as scouting and exploration, cooperative construction activities, or even emergency assistance scenarios [22]. Additionally, the influence of a virtualised environment–for example, a simulated lunar surface–could be evaluated against physically reconstructed analogues like ESA's LUNA facility. While such studies are more complex to design and execute, we believe that they offer the most promise for shedding light on the validity of MR in human-centred space research. Moreover, they may approximate the transferability of MR findings to real-world space missions.

Combining both approaches can provide a stronger foundation for understanding and investigating the ecological validity of MR in space-related HRI research. Moreover, this direction may help open the door to a broader participation in space research, allowing more institutions to engage in realistic HRI simulation and design efforts without needing access to physical hardware or analogue mission infrastructure.

5 Conclusion

Mixed Reality holds substantial promise for advancing HRI research in the context of space exploration. By enabling hybrid simulations that combine physical realism with virtual flexibility, MR allows for early-stage testing, human-in-the-loop evaluations of robotic systems, and potentially broader participation in HRI research in the spaceflight domain.

However, we believe that this potential is only fully realised if MR-based studies can yield comparable results to those obtained through more established, physical experiments. In this paper, we argue that this scientific validity is essential for establishing MR as a reliable tool for space-related HRI research.

Thus, the future utility of MR in HRI research in the context of space exploration hinges on its demonstrated, ecological validity. This requires systematic comparative studies in which MR-based interactions are directly evaluated against their physical counterparts. Such comparisons should ideally be carried out in scenarios specific to space exploration. However, comparative studies in general HRI context could deliver valuable implications for space exploration-related scenarios, too. Key variables like trust, workload, and human-robot performance should then be empirically examined. If pursued rigorously, this line of research could establish MR as a scientifically validated and broadly accessible tool for astronaut-robot interaction and, as a long-term perspective, enabling deeper insights into human-centred space mission design by making the participation more inclusive.

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