Between Bulky Suits and Isolated, Deserted Landscape: Measuring the User Experience of Astronaut-Drone Interaction

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Fig. 1. An environment featuring extreme physical constraints impacts both physical and psychological well-being. These photographs, taken during our mission to the Mars Desert Research Station, illustrate some of these constraints—desert landscape, intense sunlight, use of bulky astronaut suits and protective gear—which collectively make the task of interacting with computer systems, such as controlling a drone more challenging. Understanding this user experience is our focus.

Isolated, Confined, and Extreme (ICE) environments, such as encountered in space exploration missions, pose unique physical and psychological challenges that influence user interactions with computer systems, yet remain considerably less documented compared to conventional settings. To investigate the impact of such environments on mobile interaction, we conducted an experiment involving a crew of analog astronauts operating a drone via a handheld controller in both a conventional Earth-based setting and an ICE environment represented by the extreme landscape of the Mars Desert Research Station. Our findings reveal how the user experience of mobile interaction evolves over multiple evaluation sessions conducted over a two-week period in the ICE environment, for which we analyze both pragmatic and hedonic dimensions, such as perceived efficiency, adaptability, novelty, usefulness, and trust. Based on our findings, we outline a set of implications for the design of mobile interaction intersecting space research through the distinctive lens of astronaut-drone interaction.

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ACM 2573-0142/2025/9-ARTMHCI005
https://doi.org/10.1145/3743712

CCS Concepts: • **Human-centered computing → Empirical studies in ubiquitous and mobile computing**; **Mobile devices**; *Field studies*; **Interaction paradigms**; **HCI design and evaluation methods**; • **Applied computing → Aerospace**.

Additional Key Words and Phrases: Human-drone interaction, Isolated confined extreme environments, Mars Desert Research Station, Mars planet, Mobile interaction, Space missions User experience

ACM Reference Format:
Jean Vanderdonckt, Radu-Daniel Vatavu, and Romain Maddox. 2025. Between Bulky Suits and Isolated, Deserted Landscape: Measuring the User Experience of Astronaut-Drone Interaction. *Proc. ACM Hum.-Comput. Interact.* 9, 5, Article MHCI005 (September 2025), 19 pages. https://doi.org/10.1145/3743712

1 Introduction

Mobile interaction involves users engaging with digital devices across dynamic environments, characterized by diverse physical and attentional demands arising from both the interactive devices themselves and the contexts of use. This interplay between users, devices, and the mobility context leads to a wide range of corresponding User eXperiences (UX), especially since mobile interaction spans a diversity of human activities, such as walking [4], jogging [57], cycling [47], driving [20], swimming [5], or even sleeping [26], being supported by mobile devices ranging from smartphones and smartwatches to glasses, rings, and assist robots operating from the body [12] or as flying assistants [17]. For example, the user experience of the assistance of smart glasses during cycling [21] has been characterized from the lens of its potential to improve road safety, offer entertainment, support gamification and optimize group cycling coordination. The user experience of jogging with a drone companion [52] is reflected in the benefits that drones bring to increase safety and engagement, while also posing potential distractions or creating situations of social awkwardness. As mobile devices evolve in form and function, they also create new opportunities for diverse context-dependent user experiences, which demand a systematic investigation.

However, not all environments and contexts of use are conventional, predictable, well-structured, or even accessible. Some pose extreme physical and psychological challenges that significantly affect daily living, work, and social collaboration, and are classified as *Isolated, Confined, and Extreme (ICE) environments* [29,62]. In such settings, interactions with computing devices are severely constrained by the need to wear protective gear, environmental conditions that limit or impair sensory perception, and physical restrictions that affect mobility and dexterity. Examples include space stations [19] and polar or desert research facilities [30], where individuals are confined to enclosed habitats for their safety, often isolated [2] or working in very small teams [27,62] due to spatial restrictions, and remain stationed for extended periods [28] without the possibility of leaving at will. In addition, the use of physically constraining equipment limits both sensory perception and physical movement. Figure 1 shows several photographs captured during our experiment conducted at the Mars Desert Research Station (MDRS),[1] a research facility to study human factors and test technologies for future Mars missions [16,46], allowing scientists to experience ICE conditions [54]. Note the bulky astronaut suits and protective gear, the isolated and deserted landscape, and the intense sunlight immediately striking in the photographs; also, not visible in these images are additional extreme factors, such as high humidity, requirements to adhere to strict safety protocols, and limited mobility affecting the activities of the analog astronauts. All of these factors make the conventional task of flying a drone a challenging experience, an aspect about which we currently know very little in ICE conditions, but its importance is critical for exploration, mapping, and resource monitoring on the planetary surface of extreme, vast, and inhospitable environments.

Unfortunately, research on ICE environments is scarce in the field of Human-Computer Interaction (HCI), despite their recognized importance for understanding human factors in other fields, such as psychology [29] or medicine [25]. However, extreme conditions, coupled with limited resources and altered sensory stimuli [63], create unique environments that influence the UX of being mobile and the performance of interacting with mobile

[1] Mars Desert Research Station.https://mdrs.marssociety.org

computer technology. These environments create distinctive contexts of use that impose extreme constraints, including psychological [29,53], physical [31,41,63], sensorimotor [60,63], social [42], cognitive [30], and technological [3,10,18]. In space research, these factors critically influence operational performance, crew collaboration, and overall mission success, creating contexts of use that are highly constrained, resource-limited, and with psychological stressors, for which HCI research provide both technological solutions and human-centered insights [43,44]. In contrast, the typical interpretation of a conventional context of use [11,13] for mobile interaction refers to situations where users employ mobile devices in environments that are far less constrained and without extreme factors. From this perspective, investigating mobile interaction in ICE environments, such as analog space missions (Fig. 1), presents unique opportunities to explore UX beyond conventional contexts of use.

In this paper, we report on the impact of a distinctive ICE environment, an analog Mars physical setting, on the UX of mobile interaction, specifically in the task of controlling a drone using a handheld controller. Given the recent SpaceCHI initiative [43,44] within the HCI community to support human physical and mental performance in extraterrestrial environments by "designing new types of interactive systems and computer interfaces that can support human living and working in space and elsewhere in the solar system" [43, p. 1], and its emphasis on the diverse range of topics within space exploration that require HCI knowledge and expertise, we chose this particular ICE setting in our research. We present the results of an experiment involving eight analog astronauts, who reported their UX of controlling a drone with a handheld device in both a conventional environment and the desert landscape surrounding the MDRS. Based on our findings, we outline implications for designing astronaut-drone interaction in ICE environments characterized by intense physical restrictions and reflect on the need for future research on understanding the UX of mobile interaction under ICE conditions.

2 Related Work

We review in this section prior research conducted on topics addressing the specific physical and psychological conditions of ICE environments. Although such work remains limited within the HCI community, we adopt an HCI perspective on work from psychology and human factors research, while focusing our discussion on aspects relevant to mobile interaction. In particular, we emphasize the intersection of mobile HCI with spatial research [43,44], the recent SpaceCHI initiative in HCI, which frames the scope of our experiment in Section 3.

2.1 A HCI Lens on ICE Environments

According to Van Puyvelde et al. [56], ICE environments shape the dynamics of organizational and interpersonal systems, influencing how individuals function while sojourning in such habitats. Inevitable symptoms caused by ICE conditions typically include sensory deprivation, disrupted sleep, fatigue, reduced group cohesion, and the displacement of negative emotions. These factors affect performance in daily activities, including work and, in particular, work involving the use of computer systems through the involved human factors, where both task performance [42] and user experience [29] can be negatively impacted. Regarding the latter, interaction with computers is significantly shaped by the characteristics of the environment that, along with users and devices, constitutes a critical component of the context of use [6,13]. From this perspective, applying an HCI lens to ICE environments aligns with the study of interactions in various physically situated settings, where environmental conditions dictate design requirements, influence user performance, and impact overall UX. The distinguishing aspect in ICE environments, compared to typical contexts of use, lies in the extreme conditions, both physical and psychological [2,19], under which interactions are carried out.

As missions to ICE environments continue to increase, so too does the demand for designing robust, effective, and dependable interactive systems designed to operate within such environments. Notable for our scope are missions involving space exploration. In this context, beyond the technical challenge of deploying "software on Mars" [18] lies the more complex one of enabling users to interact effectively with that software, where both users and systems need to operate under ICE conditions while still maintaining a UX that is rewarding, fulfilling, and trustworthy—qualities that are not always straightforward to achieve. For example, geospatial path planning software for planetary surface exploration [35] was found to reduce path cost errors, increase task performance, and save valuable time, but at the cost of reduced situational awareness and increased automation bias for users. In another example, a computer-based decision-support tool for astronaut self-scheduling during missions [48] was found to elicit increasing perceptions of system dependability and trust upon repeated use. Besides these empirical explorations, HCI-oriented inquiries regarding ICE environments have been addressed through design fiction [32], exploratory workshops [14], virtual reality simulations [38], and theoretical analysis, such as speculations about the applicability of interaction frameworks developed within an Earth perspective to extraplanetary environments [59].

2.2 Mobile HCI in Space Exploration and Extraplanetary Environments

SpaceCHI [43,44] is a recent initiative within the HCI community focusing on designing interactive systems to support human living and working in space and other regions of the solar system. In this context, HCI research is playing an increasingly important role in improving mission execution and crew well-being in space exploration [55], where mobile interactions are particularly relevant by involving devices ranging from smartphones to tablets, personal displays, and smart glasses. For example, tablets are used on the International Space Station[2] for tasks involving data logging, communication, experiment monitoring, and robotic control. In this context, many research contributions at the intersection of mobile interaction and SpaceCHI have been proposed, primarily addressing technical challenges. For example, in their "Smartphone's Guide to the Galaxy," Nelis et al. [37] reviewed smartphone-based applications for crew health monitoring and the detection of hazardous chemicals, proteins, or pathogens, addressing a practical problem through mobile devices as sensors. Another perspective has been that of control devices, *e.g.*, Arzberger et al. [1] adopted an astronaut-centered approach to design and evaluate a mobile interface for tablet-based robotic control on planetary surfaces. Furthermore, different form factors have been leveraged for designing specialized interactions. For example, orientation-responsive displays were explored by Fish [15], where facial recognition was leveraged to adapt screen orientation with the user's head position, creating an adaptive interface with displays in microgravity. By leveraging smart glasses, Karasinski et al. [24] developed a Microsoft HoloLens application to provide guidance to astronauts in locating tools or navigating destinations on the space station. Mackin et al. [33] introduced an Extra-Vehicular Activity information system with a cuff-mounted graphical interface and keypad, enabling astronauts to access procedures, capture images and video, while interacting in a hands-free manner. These examples illustrate the growing relevance of mobile devices in supporting context-sensitive interaction in space environments.

2.3 Takeaways

The HCI community has shown growing interest in contributing to humanity's efforts to reach, work, and live in ICE environments, such as those encountered in space exploration [55,65]. Within this context, our work focuses on the UX of mobile interactions under such extreme conditions. While existing contributions in mobile HCI at the intersection with SpaceCHI have primarily addressed technical challenges and aspects of user performance, the UX dimension has received comparatively little attention. However, the very nature of ICE environments challenges conventional UX principles developed for conventional interaction settings, yet research exploring how such conditions affect mobile interaction, beyond task efficiency, remains largely unaddressed. To this end, we designed and conducted a dedicated experiment in one of the best simulator on Earth of a Mars environment featuring both challenging physical conditions (*e.g.*, temperature and humidity) and psychological ones (*e.g.*, feelings of isolation and confinement); see Section 3.

[2] https://www.nasa.gov/international-space-station

3 Experiment

To gain insight into the user experience of mobile interaction in an ICE environment, we focused on a task involving drone control under extreme conditions. Operating a drone using a handheld controller requires both manual dexterity and sensory acuity, both of which can be impacted negatively by wearing a bulky astronaut suit and by exposure to high temperatures and humidity. In this section, we present our experiment that addresses specific UX dimensions.

3.1 Participants

We involved a crew consisting of eight analog astronauts who spent two weeks at the Mars Desert Research Station. (An analog astronaut is a trained individual who simulates the role of an actual astronaut during a crewed mission, engaging in activities such as living [56], eating [40], sleeping [66], walking [8], and working [32] in ways that replicate the expected conditions of a long-duration space mission in a geographically analogous setting [54].) The participants were young adults, aged 21 to 31 years (*M*=24.8, *SD*=2.6), with an equal gender distribution of four men and four women. They had diverse educational backgrounds, including applied mathematics, astronomy, biology, chemistry, computer science, geology, and engineering, all disciplines relevant to space missions. The size of the crew was limited by the spatial restrictions of the MDRS, which can accommodate a maximum of eight crew members simultaneously.

3.2 Physical Setting, Living and Working Conditions

The experiment was carried out at the Mars Desert Research Station, a Mars analog environment located in Hanksville, Utah, USA, which serves as an international research facility for studying human factors and testing technologies for future Mars missions [16,46], enabling scientists to experience ICE conditions [54]. The research station consists of several interconnected spaces, including the habitat, the Extra-Vehicular Activity (EVA) preparation room, and the science dome, which houses a laboratory; see Figure 3, top for an overview of MDRS and Figures 1, 4, and 5 for photographs taken during our mission with the participants in the ICE environment. The physical setting of MDRS necessitates specific adaptations in terms of living, working, and collaborating with others. For example, the average unproductive time amounts to approximately seventeen hours per day, a significant portion being devoted to daily chores and maintenance [9], leaving only about seven hours available to conduct scientific work. Mandatory safety protocols add to the complexity of conducting work and often interfere with daily life in the habitat. In addition, sharing the science laboratory among geologists, biologists, and engineers requires negotiation, compromises, and mutual cooperation. The outdoor environment offers realistic constraints for a simulated Mars mission, as the MDRS is located in the Bentonite Hills, a Jurassic-Cretaceous geologic landscape characterized by multi-colored bands of red, brown, and purple, and is subject to extreme temperature and humidity conditions that pose significant physical challenges. The architectural elements of the indoor habitat, such as porthole-style windows, amplify feelings of isolation, among other psychological challenges. Thus, the combination of physical and psychological constraints, along with limited productive time, makes analog space missions at MDRS demanding and highly relevant for studying ICE environments.

3.3 Training for the Mission

Before arriving at MDRS, all crew members underwent specialized physical training to prepare for the unique physical demands of their upcoming mission, designed to simulate conditions experienced in space and on Mars. This training included two key components, conducted at the European Space Agency's Neutral Buoyancy Facility,[3] involving microgravity resistance exercises in an aquatic environment (Figure 2, left), and the Euro Space

[3] https://www.esa.int/About_Us/EAC/Refreshing_the_Neutral_Buoyancy_Facility

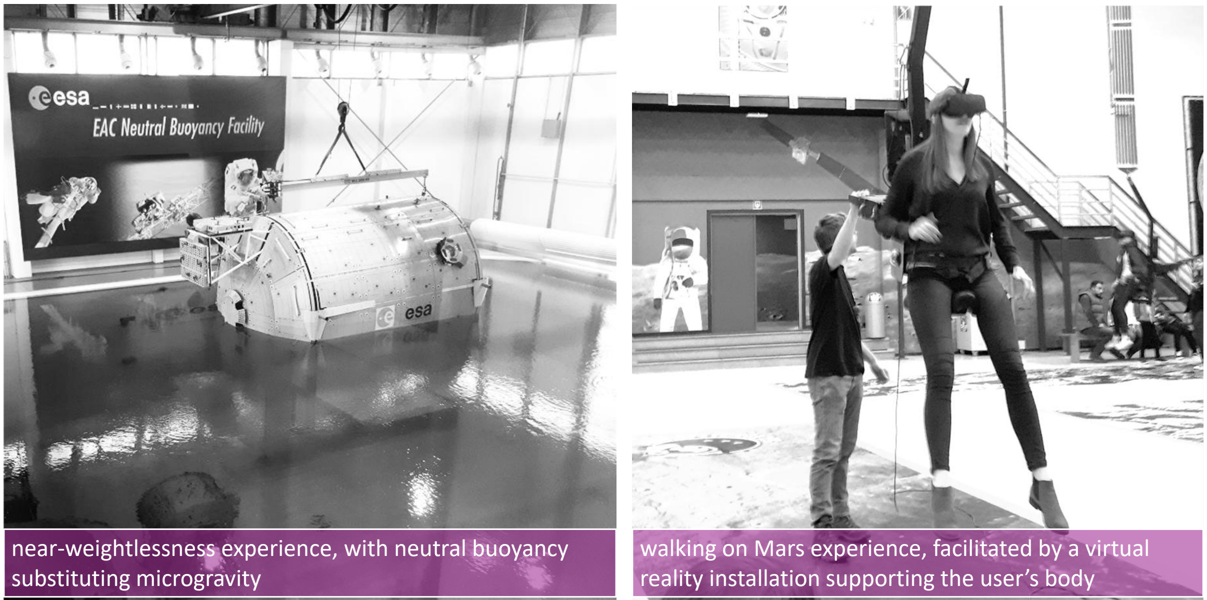

Fig. 2. Facilities used for analog astronaut training involving microgravity resistance in an aquatic environment (left photograph) and engaging in simulated VR-based Mars walking experiences (right photograph).

Center,[4] involving experiencing different gravity conditions through simulated Mars walks enabled by a virtual reality installation (Figure 2, right). In the first component, crew members were immersed in an underwater environment designed to mimic near-weightlessness, where neutral buoyancy substitutes for microgravity, offering them the opportunity to experience physical activities in the absence of gravity as would take place during extra-vehicular walks in space. In the second component of the training, crew members were immersed in a virtual environment designed to mimic Mars gravity conditions (about 38% of Earth's gravity) through an installation supporting the user's body while walking, an experience that enabled feeling each step different than when walking on Earth. We implemented these training procedures to increase the realism of the mission to our participants, preparing them both physically and psychologically for challenging conditions in an unconventional environment.

3.4 Task

To progressively build operational competence in crew members, a four-stage task guided them from initial training through free interaction to drone task specifics and the final UX evaluation, as follows:

- In the *discovery stage*, the participants received a tutorial on drone control, lasting between 5 and 15 minutes, and then interacted freely with the drone for another 10 to 15 minutes.
- In the *practice stage*, the participants were instructed to perform a representative task with the drone to become familiar with its operation, *e.g.*, fly the drone to a specific location, lasting about 20 minutes.
- During the *domain-specific stage*, the participants received instructions on how to complete specific tasks involving the drone, which took about 15 minutes; details next.
- Lastly, the *evaluation stage* consisted in the participants filling out a UX questionnaire.

[4] https://www.eurospacecenter.be/en

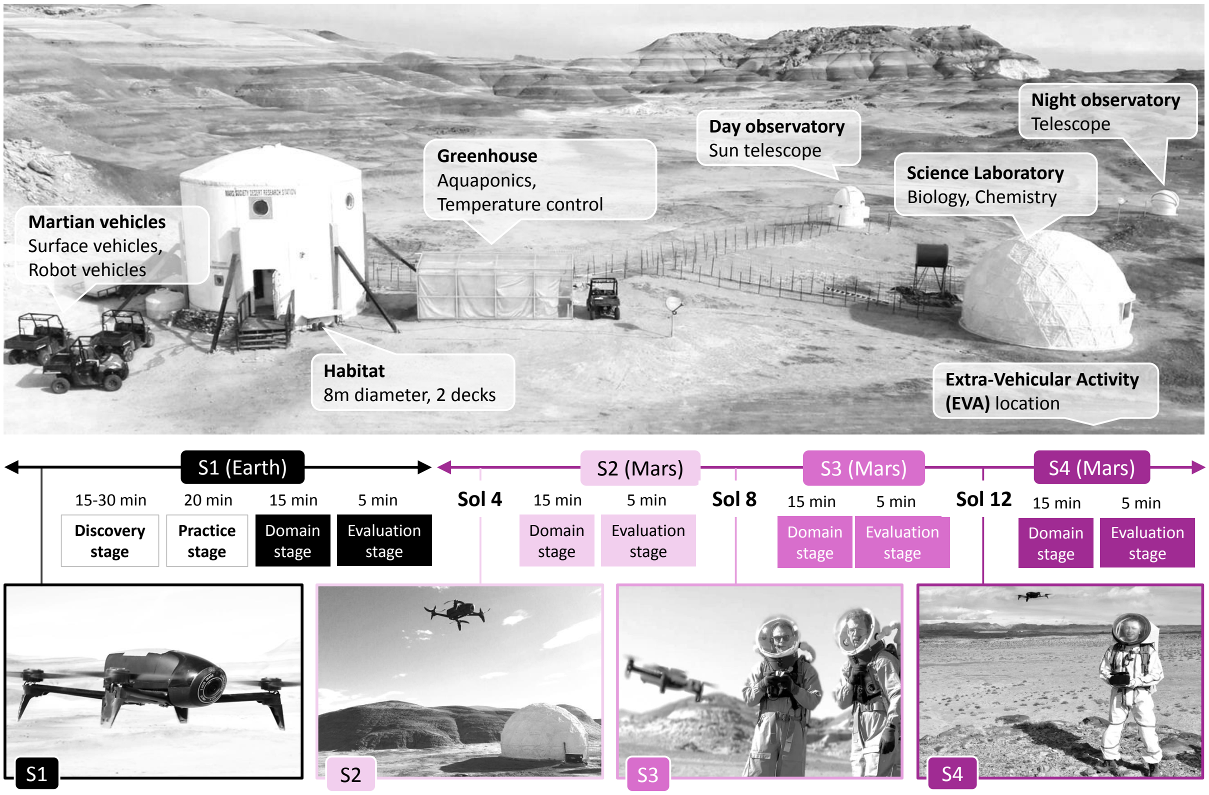

Fig. 3. *Top:* Overview of the Mars Desert Research Station, where evaluation sessions S2 to S4 of our experiment took place during the Mars analog mission. *Bottom:* Timeline of the experimental procedure, including the discovery and practice stages at session S1, followed by four repetitions of drone control tasks and corresponding UX evaluations conducted from S1 to S4.

The discovery and practice stages were conducted once before the mission in a conventional environment, serving as the baseline condition in our experiment. The following tasks, inspired from [7,39,45], were randomized per participant: *take off and landing* (basic drone control functions), *perform a flying tour* (a sequence of basic navigation actions centered around the astronaut), *perform a round trip* (a sequence of basic navigation actions relative to the astronaut's position), and *follow a series of stakes and return* (a more complex task involving obstacle navigation).

These tasks were performed four times during subsequent sessions, labeled as S1 to S4, as follows: S1 took place one week before the mission, S2 occurred after four Mars days (Sol 4), S3 took place after eight Mars days (Sol 8), and S4 occurred after twelve Mars days (Sol 12); see Figure 3, bottom. A Mars day, or Sol, represents a solar day on Mars, defined as the interval between two successive returns of the Sun to the same meridian as observed from the surface of Mars, *i.e.*, approximately 24 hours, 39 minutes, and 35 seconds in Earth time. This experimental design allowed us to evaluate UX repeatedly throughout the entire mission, including the effects of prolonged exposure to ICE conditions.

Fig. 4. Astronaut–drone interaction during our experiment through a handheld device. Note the requirement to wear an astronaut suit outside the habitat, which imposes physical constraints that affect sensory perception and manual dexterity.

3.5 Apparatus

We used the Parrot ANAFI USA drone, a robust, durable, and cost-effective device whose technical specifications make it well-suited for mission management and operation in ICE environments. For example, this drone model features a compact and lightweight design (500 g mass and folded size 252×104×84 mm) yet high-performance capabilities (maximum horizontal speed of 14.7 m/s, ascent speed of 4 m/s, and service ceiling of 5,000 m above mean sea level). Moreover, it can operate across a wide temperature range (−36°C to 50°C) and has no take-off temperature limitations. The ANAFI USA drone is operated using a handheld controller (1.14 kg and size 313×208×72 mm), which integrates a mobile device running FreeFlight 6, an application that allows astronauts to remotely access and control the drone's imaging system (1/2.4" sensors, 4K video resolution, 32x digital zoom, and a stabilized 3-camera IR/EO gimbal); see Figure 4 for photographs during the experiment, additional technical specifications available online,[5] and Figure 5 for photographs captured from the drone's camera. When connected to the drone, the application displays a live video feed from the drone's camera (with touch controls for focus and zoom), telemetry (altitude, distance, and speed indicators) and control overlays (take-off/land button, flight mode selector, camera settings). The mobile interface lets users define the flight mode (*e.g.*, manual, follow me, flight plan), the flight plan (by defining waypoints and camera angles, specifying points of interest that can be monitored throughout the flight), and take photos and videos. More details about the drone control application and user interface are available on the Parrot website[6] and through instructional videos online.[7]

[5]Parrot ANAFI USA, https://www.parrot.com/en/drones/anafi-usa
[6]Parrot drones - Applications and services, https://www.parrot.com/en/apps-and-services
[7]Using the FreeFlight 6 App on the Parrot ANAFI USA Drone, https://www.youtube.com/watch?v=2APFVjuEMeo

Fig. 5. Photographs captured using the drone. Top: Close-up and wide-angle views of the MDRS. Bottom: Close-up and wide-angle views of the crew members.

3.6 Evaluation

To evaluate the UX of mobile interaction involving the drone, we administered UEQ+, a modular extension of the User Experience Questionnaire (UEQ) [50], designed to measure various UX dimensions quickly and simply [51]. Moreover, UEQ+ covers both pragmatic and hedonic UX dimensions and is supported by readily available analysis instruments [36] for interpreting results [22]. We measured UX across the following dimensions or scales:

- *Attractiveness*: What is the overall impression of the system? Do users like or dislike it? Attractiveness is evaluated across four subscales corresponding to the following pairs of opposing adjectives: *annoying vs. enjoyable*, *bad vs. good*, *unpleasant vs. pleasant*, and *unfriendly vs. friendly*.
- *Efficiency*: Can users solve their tasks without unnecessary effort? Does the system react fast? Efficiency is evaluated across four subscales corresponding to the pairs of opposing adjectives *slow vs. fast*, *inefficient vs. efficient*, *impractical vs. practical*, and *cluttered vs. organized*.
- *Perspicuity*: How easy is it to learn how to use the system? Perspicuity is evaluated across four subscales corresponding to the pairs of opposing adjectives *not understandable vs. understandable*, *difficult to learn vs. easy to learn*, *complicated vs. easy*, and *clear vs. confusing*.
- *Dependability*: What impression does the system give to be in control of the interaction? Dependability is evaluated across the following four subscales: *unpredictable vs. predictable*, *obstructive vs. supportive*, *not secure vs. secure*, and *does not meet expectations vs. meets expectations*.
- *Stimulation*: Is it exciting and motivating to use the system? Is it fun to use? Stimulation is evaluated across four subscales corresponding to the following pairs of opposing adjectives: *inferior vs. valuable*, *boring vs. exciting*, *not interesting vs. interesting*, and *demotivating vs. motivating*.

- *Novelty*: Is the system design creative? Does it catch the user's interest? Novelty is evaluated across four subscales corresponding to the pairs of opposing adjectives *dull vs. creative*, *conventional vs. inventive*, *usual vs. leading edge*, and *conservative vs. innovative*.
- *Adaptability*: What is the impression that the system can be adapted to personal preferences or styles? Adaptability is evaluated across the following subscales: *not adjustable vs. adjustable*, *not changeable vs. changeable*, *inflexible vs. flexible*, and *not extendable vs. extendable*.
- *Trust*: What impression do users form that their data are safe and not misused to harm them? Trust is evaluated across four subscales corresponding to the following pairs of opposing adjectives: *insecure vs. secure*, *untrustworthy vs. trustworthy*, *unreliable vs. reliable*, and *non-transparent vs. transparent*.
- *Usefulness*: Does using the system bring advantages? Usefulness is evaluated across four subscales corresponding to the pairs of opposing adjectives *useless vs. useful*, *not helpful vs. helpful*, *not beneficial vs. beneficial*, and *not rewarding vs. rewarding*.
- *Value*: Does the system design look professional and high quality? Value is evaluated across the subscales *inferior vs. valuable*, *not presentable vs. presentable*, *tasteless vs. tasteful*, and *not elegant vs. elegant*.
- *Visual aesthetics*: Does the system look beautiful and appealing? Visual aesthetics is evaluated across four subscales corresponding to the pairs of opposing adjectives *ugly vs. beautiful*, *lacking style vs. stylish*, *unappealing vs. appealing*, and *unpleasant vs. pleasant*.
- *Intuitive use*: Can the system be used immediately without any training or help? Intuitive use is evaluated across the subscales *difficult vs. easy*, *illogical vs. logical*, *not plausible vs. plausible*, and *inconclusive vs. conclusive*.
- *Trustworthiness of content*: Is the information provided by the system is good quality and reliable? Trustworthiness of content is evaluated across the following four subscales of opposing adjectives: *useless vs. useful*, *implausible vs. plausible*, *untrustworthy vs. trustworthy*, and *inaccurate vs. accurate*.

According to UEQ+ [51], each scale s_i is decomposed into multiple subscales $s_{i,j}$. For example, *Attractiveness* (scale s_1) includes four subscales—*annoying vs. enjoyable* ($s_{1,1}$), *bad vs. good* ($s_{1,2}$), *unpleasant vs. pleasant* ($s_{1,3}$), and *unfriendly vs. friendly* ($s_{1,4}$)—each rated on a 7-point range with extremes corresponding to the two opposing adjectives. We denote by $SS_{i,j}$ the rating on subscale $s_{i,j}$ and by $SI_{i,j}$ the perceived importance of that scale, as reported by participants. Based on these individual scores, we calculate composite values for each main scale s_i:

- Scale-Mean-Score, $\text{SMS}(s_i)$, the average score obtained across all subscales $s_{i,j}$ of a scale s_i, ranging from -3 to $+3$, calculated as $\text{SMS}(s_i) = \frac{1}{4}\sum_{j=1}^{4} \text{SS}(SS_{i,j}) - 4$, where 4 represents the median point of each subscale.
- Scale-Mean-Importance, $\text{SMI}(s_i)$, the average importance of all subscales $s_{i,j}$ of a scale s_i, ranging from -3 to $+3$, calculated as $\text{SMI}(s_i) = \frac{1}{4}\sum_{j=1}^{4} \text{SS}(SI_{i,j}) - 4$.

To compare the UX, measured by specific scales, to a baseline such as the UX observed in the first session of the experiment, we follow Clarke *et al.*'s [10] definition of relative effort and define ratio measures:

$$\text{Scale-Mean-Ratio (SMR)} = \frac{\text{SMS}(s_i)}{\text{SMS}_{\text{baseline}}(s_i)}, \ \text{Scale-Importance-Ratio (SIR)} = \frac{\text{SMI}(s_i)}{\text{SMI}_{\text{baseline}}(s_i)} \tag{1}$$

Participants' answers were interpreted according to Schrepp and Thomaschewski's [51] guideline: "it is extremely unlikely to observe values above +2 or below −2 [...] the standard interpretation of the scale means that values between −0.8 and +0.8 represent a neutral evaluation of the corresponding scale, values superior to +0.8 represent a positive evaluation, and values inferior to −0.8 represent a negative evaluation."

To complement our UX evaluations, we also measured Task-Time, representing the time (in seconds) that participants took to complete each drone task, recorded using a stopwatch.

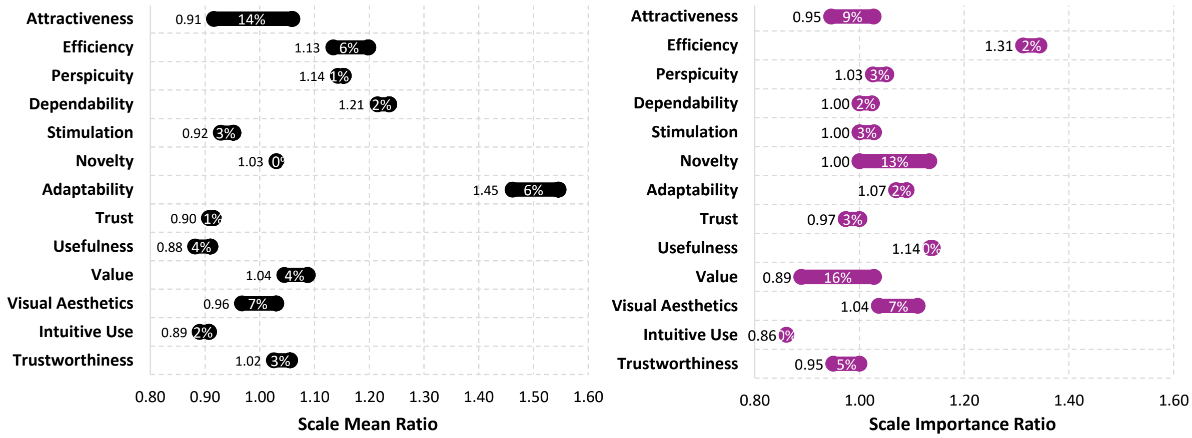

Fig. 6. Dumbbell plots of the evolution of the Scale-Mean-Ratio (left) and Scale-Importance-Ratio (right) across the various UX dimensions examined in our experiment for drone control in an ICE environment.

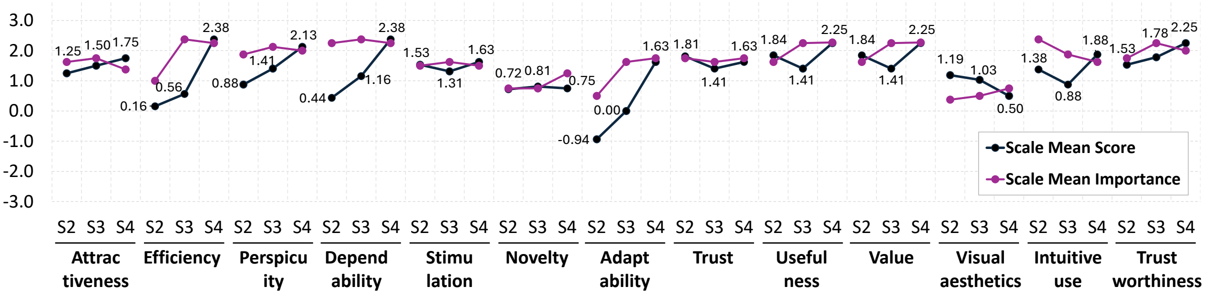

Fig. 7. Evolution of Scale-Mean-Ratio and Scale-Importance-Ratio across UX dimensions in the Mars sessions S2 to S4.

3.7 Results

Figure 6 presents the Scale-Mean-Ratio (left) and Scale-Importance-Ratio (right) represented as Dumbbell plots[8] to depict differences in UX across evaluation sessions S2 to S4 conducted in the Mars analog environment. In these plots, values below or above 1.0 indicate UX perceptions that are less or more positive, respectively, than the baseline condition represented by the Earth-like environment in S1. The majority of the scale ratios center around 1.0, *e.g.*, 0.91 for *Attractiveness* (Δ=14%) and 1.02 for *Trustworthiness* (Δ=3%), with a few exceptions represented by *Adaptability* (1.45, Δ=6%) and *Dependability* (1.21, Δ=1.21); see Figure 6, left. The scale importance ratios revealed a similar pattern with most values near 1.0, *e.g.*, 0.95 for both *Attractiveness* (Δ=9%) and *Trustworthiness* (Δ=5%); see Figure 6, right.

Figure 7 presents the Scale-Mean-Score and Scale-Mean-Importance across sessions S2 to S4 conducted in the Mars analog environment with most UX dimensions showing either stable or increasing trends over time. Three scales started in the neutral zone of $[-0.8, 0.8]$: *Efficiency* (M=0.16, SD=1.60), *Dependability* (M=0.44, SD=1.60), and *Novelty* (M=0.72, SD=1.5). The lowest reported UX score was for perceived *Adaptability* (−0.94 in S2) and the highest for *Efficiency* and *Dependability* (both 2.38 in session S4). Moreover, while scores at S2 ranged

[8]A data visualization method that illustrates changes between two points in time, conditions, or groups; se Chart Snapshot: Dumbbell Plots, https://datavizcatalogue.com/blog/chart-snapshot-dumbbell-plot.

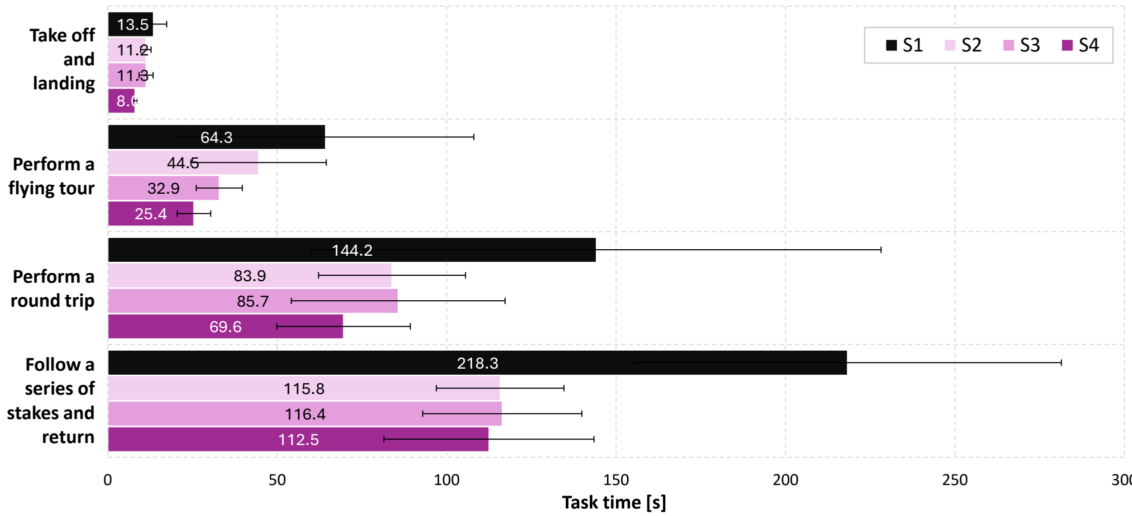

Fig. 8. Mean task completion times for each drone control task across sessions S1 to S4. Error bars represent 95% CIs.

within the interval [−0.94, 1.84], the last evaluation conducted in session S4 revealed scores within [0.19, 1.63], indicating a clear increasing trend on average. We observed three types of patterns across the individual scales: upward trends, downward trends, and stable trends. Upward trends were noted for *Attractiveness*, *Efficiency*, *Perspicuity*, *Dependability*, *Adaptability*, *Value*, and *Trustworthiness*, with scores increasing from S2 to S4. For example, *Efficiency* improved from 0.16 (S2) to 0.56 (S3) and reached 2.38 (S4). While some increases were smaller, such as for *Trustworthiness*, which rose from 1.53 (S2) to 2.25 (S4), they still show enhancement of UX across the different evaluation points. A notable case is *Adaptability*, which shifted from a negative perception (−0.94 in S2) to a strong positive evaluation (1.63 in S4). We identified only one descending trend: *Visual aesthetics* decreased from 1.19 (S2) to 1.03 (S3), then dropped further to 0.50 (S4). The only stable trends were represented by *Novelty*, with scores varying between 0.72 and 0.81, and *Stimulation*, with scores varying between 1.31 and 1.63 and little variation across the sessions. Some scales, such as *Trust* and *Intuitive Use*, exhibited a V-shaped pattern, where a decrease in scores in session S3 was followed by a rebound in S4. These results show that UX in the analog astronaut-drone interaction scenario improved across the majority of the evaluated dimensions, both pragmatic and hedonic. Upon repeated exposure, the analog astronauts adapted to and favorably appreciated the interaction despite the inhospitable environment, showing that task efficiency and system dependability can be complemented with perceived satisfaction and engagement when operating in ICE environments.

To complement our UX evaluations, we also measured the time it took participants to complete the drone control tasks. Figure 8 shows the distribution of TASK-TIME for the four control tasks performed across the sessions S1 to S4 with S1 acting as the baseline. A Kruskal-Wallis test revealed a statistically significant effect of task type on TASK-TIME ($H_{(3)}$=102.36, p<.001). For the *take off and landing* task, a Kruskal–Wallis test followed by a Nemenyi post-hoc pairwise comparison showed that task time in S4 was significantly lower than in S1 (R=14.06, p=.014) and S2 (R=12.31, p=.043). These results suggest that task performance improved over time, despite the restrictive conditions of the ICE environment. In this case, carry-over effects, such as learning and increased familiarity with the drone, appear to have offset the disadvantages of ICE conditions represented by fatigue and the physical burden of astronaut suits. Similarly, *perform a flying tour* showed a significant difference in task time between S4 and S1 (R=13.25, p=0.024) as did *follow a series of stakes and return* (R=13.75, p=0.018). For the *perform a round trip* task, performance time also decreased from S1 to S4, but the change was not statistically significant (R=10.75, p=0.12, *n.s.*).

4 Discussion

We draw on our findings to outline implications for mobile interaction design in ICE environments with a focus on space exploration, through the lens of drone control. We also discuss the limitations of our experiment and reflect on the need for more research to understand the UX of mobile interaction under ICE conditions.

4.1 Implications for Mobile Interaction in ICE Environments

Integrate mobile interactions into context-aware support tools for astronauts. The results of our experiment show the potential of flying assistants as mobile devices in ICE environments, offering dynamic, immersive experiences through aerial perspectives, geographic observation, and remote operation—all of which are essential yet often difficult for astronauts to achieve by other means. This extra mobility and supplementary visual perspective offered by a flying companion device are valuable in spatial stations and during extravehicular settings, extending the users' sensory perception at a distance, and we found it revealed by several of our UX dimensions with high scores and an increasing trend over multiple evaluation sessions, such as *Efficiency* (max 2.38), *Adaptability* (max 1.63), and *Dependability* (max 2.38); see Figure 7. However, drones also pose limitations being relatively bulky, depending on battery life, and requiring operational oversight. This suggests that flying assistants should be designed and deployed as context-aware, situational tools to readily support astronaut tasks without introducing undue burden or unnecessary risks. From this perspective, mobile interactions—through the involved mobile devices and the mobility context experienced by astronauts—emerge as a key component of support tools necessary to ensure mission success, user efficiency, and a rewarding experience despite the demanding conditions of ICE environments.

Explore diverse input modalities to enhance user engagement and task efficiency. The experiment revealed several desirable interaction qualities in terms of perceived *Intuitive use* (max 1.88), *Usefulness* (max 2.25), and *Efficiency* (max 2.38), making the drone a reasonable candidate for performing regular, essential tasks, such as equipment inspections, cargo transport, and environmental monitoring, thereby reducing the workload on astronauts. These involve precise landing, flying tours, round trips, navigating to specific waypoints, and providing different camera angles, all representing tasks performed in our experiment using a graphical user interface available on a handheld controller device with a touchscreen (Figure 4). However, other input modalities, such as gesture commands for drone control [7], could enable more expressive interactions. Interactions should also minimize the need for dexterity, as our astronauts operating in light and heavy spacesuits showed limited fine motor control. Furthermore, collaborative interaction, where multiple astronauts engage to control the drone precisely, might prove beneficial to task efficiency in ICE environments. For example, gestures designed for typical drone operations [7,39] could be performed in one step by one astronaut, as opposed to more complex tasks involving safety-critical operations that may need multi-step collaborative input. Insights in this regard are given by results regarding *Perspicuity* (starting at 0.88 and increasing to 2.38) and *Intuitive use* (starting at 1.38 and increasing to 1.88), both showing potential for future improvement by incorporating new input modalities. From this perspective, access to input modalities that can be switched at will according to the task specifics and user preference could support sustained performance in the constrained settings of ICE environments.

Provide multisensory feedback aligned with the conditions of the ICE environment. Since no single feedback modality is likely to satisfy all control needs, multisensory feedback may support more intuitive and immersive control mechanisms [63]. Although not implemented in our experiment, which focused on a graphical UI with visual feedback, several UX measures related to multisensory output show potential for further improvement, including *Attractiveness* (max 1.75), *Stimulation* (max 1.63), and *Intuitive use* (max 1.88). Beyond improving task performance and user experience, multisensory feedback has been shown valuable in microgravity conditions, where it helps spatial orientation and proprioception [31]. Incorporating visual [58], haptic [34], and auditory feedback could enhance the overall user experience by providing richer sensory cues, increasing user awareness, and compensating for the limited physical feedback in ICE environments, which we leave for future validation.

Balance pragmatic and hedonic UX dimensions. Pragmatic UX scales, such as *Efficiency*, *Perspicuity*, and *Dependability*, are particularly sensitive to the physical and psychological challenges posed by ICE environments: sensory deprivation, disrupted sleep, fatigue, etc. [56]. In our experiment, these scales started with values below 1 (*e.g.*, 0.16 for *Efficiency*) and gradually increased until the last session (*e.g.*, 2.38 for *Dependability*). Based on these findings, our recommendation is interaction techniques designed to mitigate the initial losses observed in these UX dimensions when confronted to ICE conditions. Furthermore, hedonic UX scales, such as *Stimulation* and *Novelty*, were perceived consistently across the mission duration (*e.g.*, *Stimulation* varied from 1.53 in S2 to 1.31 in S3 and to 1.63 in S4). Supporting such dimensions related to pleasure, enjoyment, and subjective satisfaction directly contributes to psychological well-being, fostering engagement and meaningful interactions for users in ICE environments. However, these dimensions are particularly challenging to address, given that the tasks performed in ICE environments are typically methodical and meticulous rather than hedonic-oriented. Improvement in UX across these dimensions requires developing new interaction techniques that support the hedonic aspects without compromising pragmatic performance.

Support interface adaptability to the ICE environment and the user. The *Adaptability* dimension showed the most notable evolution in our experiment, gradually increasing from a negative perception (−0.94 in S2) to neutral (0.00 in S3) and finally to a positive perception (1.63 in S4). In an ICE environment, adaptability reflects how both user capabilities and system functionality can adjust to variations in extreme conditions to maintain user efficiency. Adaptive interfaces that adjust based on user feedback, fatigue, or stress levels should aim to maintain the expected level of user experience as well. All adaptation parameters could be stored in a user profile to support customization of the interface, *e.g.*, through a specific color scheme suited for tasks performed during extra-vehicular activities and a distinct layout for in-habitat interaction [49], to accommodate individual tasks and user needs. More than in conventional environments, adaptability is tightly tied to designing context-aware, user-responsive systems that can dynamically accommodate both the operational demands and individual needs of astronauts in ICE environments.

4.2 Limitations

There are several validity threats—*external, internal, construct*, and *conclusion*— [61] that might have influenced the results of our drone control experiment, which we analyze below. Concerning *external validity*, our experiment was conducted in the MDRS, a state-of-the-art facility designed to replicate Mars-like conditions as closely as possible on Earth. However, despite the fidelity of this simulated setting, significant differences remain compared to the actual Martian environment, such as Mars' gravity being 38% of Earth's and a median surface temperature on Mars of −65°C. Thus, our empirical results should be interpreted with the understanding that they reflect a partial simulation of Mars. Regarding *internal validity*, the crew size was limited to eight astronauts due to logistical restrictions of the research station with direct implications about the generalizability of the findings and statistical power in our analysis, both of which should be interpreted with caution. Concerning *construct validity*, our within-subject approach could be restructured as a between-subject design in future studies to mitigate potential accommodation or learning effects that might influence the UX results of subsequent evaluation sessions. Concerning *conclusion validity*, we ensured all crew members received uniform training before their mission, including specialized procedures involving near-weightlessness and gravity simulations. However, this training was not comparable to the extensive and intensive preparation of real astronauts, which spans months of physical and psychological effort. Future work could address these threats with larger samples of analog astronauts and more realistic simulations of extraplanetary conditions, if available.

4.3 Future Work Opportunities

There are several opportunities for future work arising from our investigation, with both theoretical and practical implications for scientific explorations at the intersection of mobile HCI and space research. At the theoretical level, we acknowledge the need for conceptual frameworks to position, characterize, and guide mobile interaction design for ICE environments. To the best of our knowledge, the only attempt in this direction is Vanderdonckt et al. [59], who speculated on the applicability of interaction frameworks designed from an Earth-based perspective to extraplanetary environments, including ability-based design [64], reality-based interaction [23], or sensorimotor realities [60]. More foundational work is required in this area to advance conceptual and theoretical understanding. At the practical level, we recognize the need for further empirical evaluations conducted in ICE environments. These should include replications of our findings with a larger participant sample as well as evaluations involving other user interfaces, including those featuring natural interaction modalities [7], such as gesture and speech. Furthermore, expanding the range of evaluation measures in future studies to examine other factors relevant to ICE environments, such as perceived cognitive workload, *e.g.*, using the NASA TLX test, would provide insights into the relationship between user performance and experience. Lastly, investigating interaction design in ICE environments through the lens of crew dynamics, where collaboration is crucial in such settings, would be beneficial to ensure that interactions are not only adapted to individual user needs but account for crew performance towards effective collaboration in high-stakes environments.

5 Conclusion

We reported the results of an experiment involving a crew of analog astronauts to evaluate the mobile user experience of drone control in an ICE environment simulated at MDRS. Our findings indicated a generally favorable user experience with increasing trends across the two-week mission for the majority of both pragmatic and hedonic UX dimensions in our analysis. Among the implications of our findings, adaptable user interfaces designed to mitigate the physical and psychological constraints of ICE environments may further enhance mobile interaction in these contexts. Further research is needed to refine these insights and validate them in other extreme or extraterrestrial settings. Although mobile interaction in ICE environments shares certain characteristics with conventional settings, it must also respond to the unique and demanding conditions of unfamiliar and inhospitable environments. By acknowledging these differences and developing targeted technical solutions, we can ensure that astronauts are supported by robust and dependable interactive systems for safe, effective, and rewarding operations during extraterrestrial missions.

Acknowledgments

Jean Vanderdonckt and Radu-Daniel Vatavu acknowledge support from a grant of the Romanian Ministry of Research, Innovation and Digitization, CCCDI-UEFISCDI, PN-IV-P8-8.3-PM-RO-BE-2024-0003, within PNCDI IV and Wallonnie-Bruxelles International (WBI) Grant no. 650763 (WBI ref. PAD/CC/VP/TM - Roumanie - SUB/2024/650763)—project XXR (Novel Extended Reality Models and Software Framework for Interactive Environments with Extreme Conditions). Jean Vanderdonckt is also supported by the EU EIC Pathfinder-Awareness Inside challenge Symbiotik project (1 Oct. 2022-30 Sept. 2026) under Grant no. 101071147.

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