Cosmic Troubleshooting

Exploring Game Design Principles to Facilitate Error Handling in Robot Teleoperation in Space.

Anonymous Author(s)

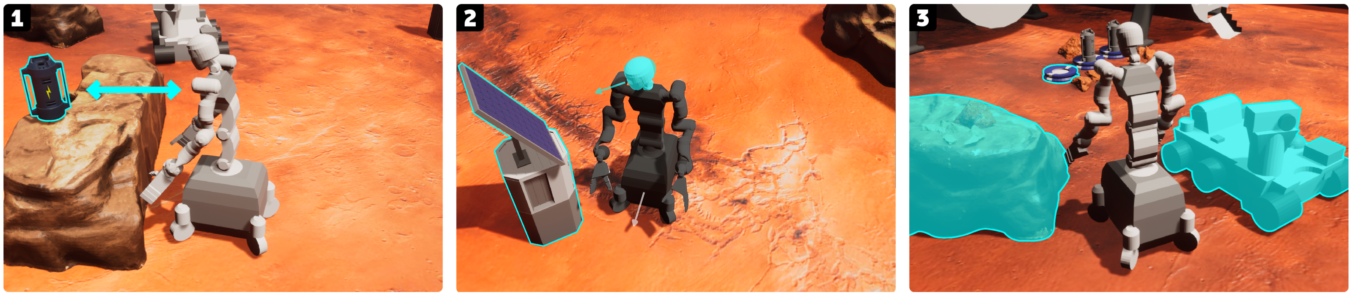

Figure 1: Simulated views from a virtual third-person perspective showing three planning errors encountered by Rollin Justin: 1) *Reachability* - the robot's arms cannot reach the target, and may need to approach from a different position; 2) *Orientation* - the robot's head and body point in different directions, leading to potential collisions, which may be fixed by adopting an 'idle' position; 3) *Collision* - obstacles obstruct the shortest path to the targeted object, necessitating manual navigation or repositioning to address the potential collision risk.

ABSTRACT

This work investigates the design space of error handling for teleoperation of robots used in space exploration. Among the challenges for teleoperation in planetary and lunar surface exploration are: a lack of knowledge of the environment and time delays in communication. It can be difficult for astronauts to gain proper situational awareness, and to understand the autonomous capabilities of the robot in context. These problems persist in current interfaces as they provide a limited view and minimal explanation of errors. This results in poor error handling, over-reliance on ground control intervention, time inefficiencies, and ultimately, high mental workload. In this paper, we explore possibilities for redesigning the teleoperation interface, in particular through the use of a third-person view. 16 experts tested the interface in a physical user study, while 42 people assessed it in an online study. We conclude that the third-person view brings significant improvements to operators' mental workload, overall experience and their ability to identify errors.

CCS CONCEPTS

• **Human-centered computing** → **Graphical user interfaces**; **User studies**; • **Applied computing** → **Aerospace**; • **Computer systems organization** → **Robotics**.

KEYWORDS

Teleoperation, Space Robotics, Error Handling, Game Design, User Experience

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1 INTRODUCTION

The exploration of Mars is currently interested in the search for signs of past and present and gaining insights into planetary evolution to enhance our understanding of Earth [31], although other possibilities exist, such as space mining [35]. Despite the successes of robotic exploration [56], there remains a desire for a human presence on Mars. However, crewed exploration of Mars faces many challenges in the hazardous environment of space, as well as the extreme distance and communication delay from the support crew on Earth. These conditions all add to the technical, physiological and psychological difficulties of crewed deep-space travel. [55, 61].

To facilitate human presence on Mars, there is a need to set up and maintain infrastructure on the planet's surface. As suggested by the Global Exploration Roadmap [31] and several other studies [40, 69–71], semi-autonomous robots are envisioned to handle physical tasks in building habitats, setup communication infrastructure, and providing the means to harvest energy resources. These robots are typically operated through remote control from Earth [56] which results in communication delays of up to 45 minutes [40, 69].

A promising solution to address this challenge involves astronauts in orbit around Mars controlling the robots instead. This would enable high-bandwidth communication for supervised autonomous operation [69] as well as direct telepresence control [59].

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This idea has been proposed in several other studies [9, 13, 41, 58]. Autonomous robotic capabilities allows astronauts to control the robots with simple commands such as 'navigate to this location' rather than manual control via joysticks, but it is still limited in complex situations [5, 69]. To alleviate cognitive load while retaining manual control in complex task/multi-modal command situations, shared autonomy is introduced, blending human and robot control [46].

When working with shared autonomy understanding robot capabilities is vital, particularly when errors occur [33]. Astronauts often encounter issues where error messages can be confusing [71], and the up to 45-minute communication delay between Mars and Earth means ground-based assistance is impractical[40, 69]. The primary focus of this paper is on enhancing the comprehension and resolution of errors that manifest during the planning phase of robot operations as shown in Figure 1. We work with *Rollin' Justin*, a dexterous mobile humanoid robot, which as served in several space telerobotic demonstration missions [70]. This project leverages *User Experience (UX)* research and game design principles to enhance astronaut situational awareness, error comprehension, and management. The ultimate objective is to reduce the astronauts' cognitive burden and support their understanding of the trade-offs between human and robot autonomies.

The core contributions of this work include (i) a user experience investigation on crew awareness, comprehension, and management of telerobotic planning errors, (ii) a prototypical implementation of a third-person interface leveraging UX and game design principles, and (iii) a comprehensive user study investigating cognitive load measurements, user experience scores, correct identification of errors, and the quality of actions taken to resolve the errors.

2 RELATED WORKS

2.1 Teleoperation and error handling in space

Robot teleoperation for space exploration faces a number of challenges, such as lag and latency, low communication bandwidths, and degraded operator performance (due to spacecraft conditions and extraterrestrial surface conditions) [52, 61], which remain open problems for *Human Robot Interaction* (HRI) research. Extensive research into enabling effective haptic teleoperation has been conducted within major space robotics projects such as *Kontur-2* [2, 76], *METERON* [12, 13, 65–68], *Avatar-EXPLORE* [19] and Surface telerobotics experiments by NASA [6, 7]. For instance, the use of force feedback was shown to improve performance in the teleoperation of users under the environmental stressors of microgravity [59]. Relieving operators from the teleoperation task, by enabling either autonomous [6, 7] or supervised autonomous [44] navigation, was also found to be effective in reducing the operators' mental workload, especially when coupled with the use of an intuitive graphical user interface [44].

Despite developments in the field around autonomous and supervised autonomous operation, issues remain when human operators encounter errors in the robot's (tele)operation. While some studies develop techniques for mitigating errors related to robot's tracking of localization [49] and its synchronization with user commands [36], little progress has been made in addressing the human factors around robot errors, such as operators limited knowledge of the system, their reaction time, and the potential for misunderstanding the situation in ways that negatively affect the robot operation [24]. This is in contrast to HRI more broadly, where error handling is an important area of study [11, 28, 29, 33, 34, 77, 83]. There is a general agreement that a robot should at least be able to identify errors and be equipped with strategies to address them [29], if not anticipate errors [14] and repair trust once an error occurs [3, 21, 22, 25, 73]. However, most of the existing approaches in error handling and trust repair are not directly usable in the context of teleoperation of robots in space as they rely on human-robot co-preseence and are entangled in social interactions that allow the robot to leverage human social strategies for error communication and trust repair [11, 21, 77].

We are interested here in space exploration, where we assume i) the human and the robot are situated in two distant locations and ii) there is significant time delay between human commands and robot actions. This means that no social channels can be leveraged to explain the situations and mitigate the effects of errors. The typical interaction scheme in this situation is haptic controllers and GUIs. There is a continuing challenge to make these controls intuitive and self explanatory to astronauts in demanding situations [10, 42, 45], as wellas to develop the *situational awareness* (SA) that allows users to make informed decisions and prevent errors [16, 26, 33].

2.2 UX & game design for situational awareness

These difficulties have led to a growing body of HRI research that builds on established knowledge from the fields of user experience (UX) and game design to to address aspects of intuitiveness, explainability, and situational awareness in teleoperation. Gaming often involves users navigating unfamiliar worlds and mastering new controls and interaction possibilities [38], and has been shown to enhance cognitive abilities such as neural processing, problem-solving, and spatial skills through the choice of game mechanics [1]. Control of virtual avatars has similar characteristics to remote teleoperation, indicating that game design techniques may assist in developing situational awareness as well as identifying and addressing robot errors [63]. Developing GUIs that can anticipate robot actions and explain them to users can prevent errors and enhance the user experience [33, 63]. HRI research has demonstrated ways that game and UX elements can be used to increase situational awareness in teleoperaton: using information cues, whether as icons on a traditional GUI [17], Augmented Reality info layers [46, 52] or multimodal interfaces [23]; reducing multitasking [62]; limiting the amount of information to display [60]; enabling active communication from the device to the user [39]; and showing position information and planned movement [81].

The game-inspired interventions that hold the most potential for space teleoperation , but still underinvestigated, are the ones focusing on the camera view of the user. Studies have shown how improving video transmission quality [52]), adjusting cameras to light conditions [64], and providing more viewpoints [51] have a strong impact on the quality of teleoperation. The visual connection between the user an the robot is a key component of the teleoperation experience. Improving video transmission quality [52] and adjusting cameras to light conditions [64] have been shown to have a strong impact on the quality of teleoperation. Another approach, common in games, is to provide other viewpoints [51], in particular 'third person' perspectives, where the avatar is visible to the player. While a first-person view can hinder situational awareness [79] as it provides a limited field of view of the environment, a third-person perspective offers a broader view of the robot's surroundings [27], allows for better control and fewer collisions [57], requires a minor workload [8], and improves tasks performance overall. While this may seem challenging, there are possibilities such as: mounting cameras on robotic arms [74] or long sticks [74]; using multiple ground robots [53, 82] or Micro Aerial Vehicles (MAVs) as capturing cameras [27]; and more generally Simlultaneous Localisation and Mapping (SLAM) approaches that construct full 3D models providing a free viewpoint [79].

Together, this points to the possibility of using a wide range of techniques from game design to improve the experience and quality of teleoperation in space exploration. There are potentials to better communicate about robot errors and capabilities, as well as to improve the situational awareness that operators develop. In this context, we are interested in techniques that can be applied to distant operation with low bandwidth and high latency, and in particular techniques that improve system learnability, user experience and mental workload.

3 A USER EXPERIENCE INVESTIGATION OF COSMIC TROUBLESHOOTING

This work investigates whether game design elements can bring significant improvements to the user experience of robot teleoperation in space. Specifically, we explore how to provide better situational awareness, improve error handling, and reduce the operator's mental workload, through interface design. To conduct our research on HRI for space telerobotics, we analyzed, redesigned, and tested an early version of the telecommand GUI developed for *Rollin' Justin*, a humanoid robot employed in the [redacted] technology demonstration mission [45].

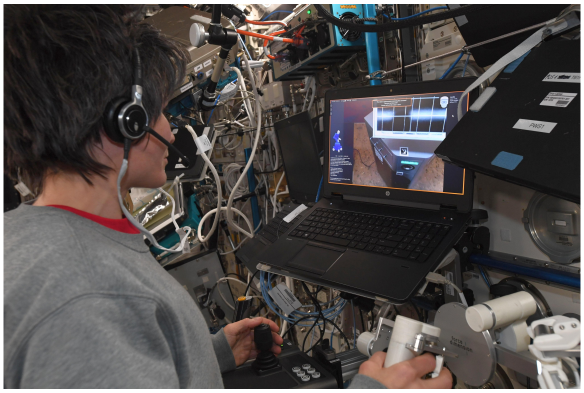
3.1 The Surface Avatar experiment

To realistically replicate a potential future exploration scenario involving astronauts in orbit and a robot on the surface, the Surface Avatar experiment uses the ISS and a simulated Marian environment on Earth as a testbed. Astronauts aboard the *International Space Station* (ISS) are instructed to teleoperate the robot from their orbital location, allowing for realistic assessments and subsequent refinements of the interface as shown in Figure 2a. The terrestrial part of the experiment is situated at the [redacted], near [redacted], operated by [redacted]. Our experiments strive to recreate Mars-like conditions, accomplished through the replication of a Martian environment [43]. Within the experiments, both functional and non-functional module replicas are deployed on the test grounds. For instance, solar panel units that astronauts can interact with through *Rollin' Justin* are set up, as shown in Figure 2b. While engaging with *Rollin' Justin*, astronauts adhere to standard protocols typically followed during Mars missions, including procedures for inspection, maintenance, and repair tasks [70]. The communication channels between ISS and Earth allow for communication times of just a few seconds, enabling astronauts to request assistance from ground control at any time. However, in an actual Mars scenario, increased time delays make real-time communication impossible, leaving astronauts with error situations on their own.

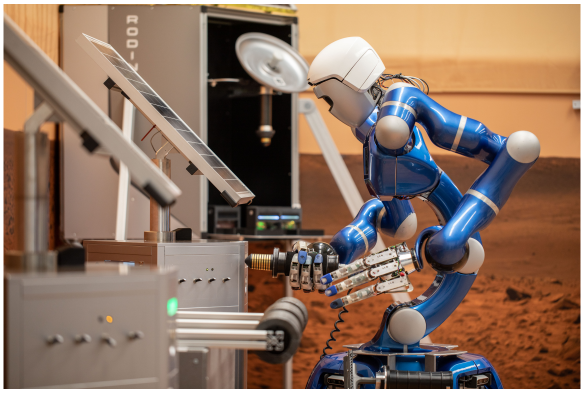
Whenever feasible, Rollin' Justin is operated under the paradigm of supervised autonomy. In this mode, an astronaut issues a high-level goal, and the robot subsequently plans and executes a sequence of actions to accomplish that goal. During supervised autonomy operation, Rollin' Justin may encounter two primary categories of errors: First, planning errors occur when the robot is unable to devise a plan that satisfies the operator's request. In this case, the robot will stay still, and then report that it was unable to comply with the request. Second, execution errors manifest when the robot finds a plan but faces challenges while executing it. Examples include collisions with the environment, issues with object handling, or hardware and software malfunctions [21, 83]. In the scope of this study, our specific emphasis is on planning errors. We postulate that by enhancing UX design, users can more effectively address and navigate through planning errors as they arise.

3.2 Preliminary UX Research

Applying a Research through Design [75] approach grounded on UX research, we first conducted preliminary research to understand the context and issues of robot teleoperation. We conducted preliminary field research, at the [redacted] experimental site, to



(a) A crew member using the current interface on-orbit aboard the ISS.



(b) The robot Rollin' Justin in the mock-up environment on-ground.

Figure 2: The Surface Avatar experiment setup

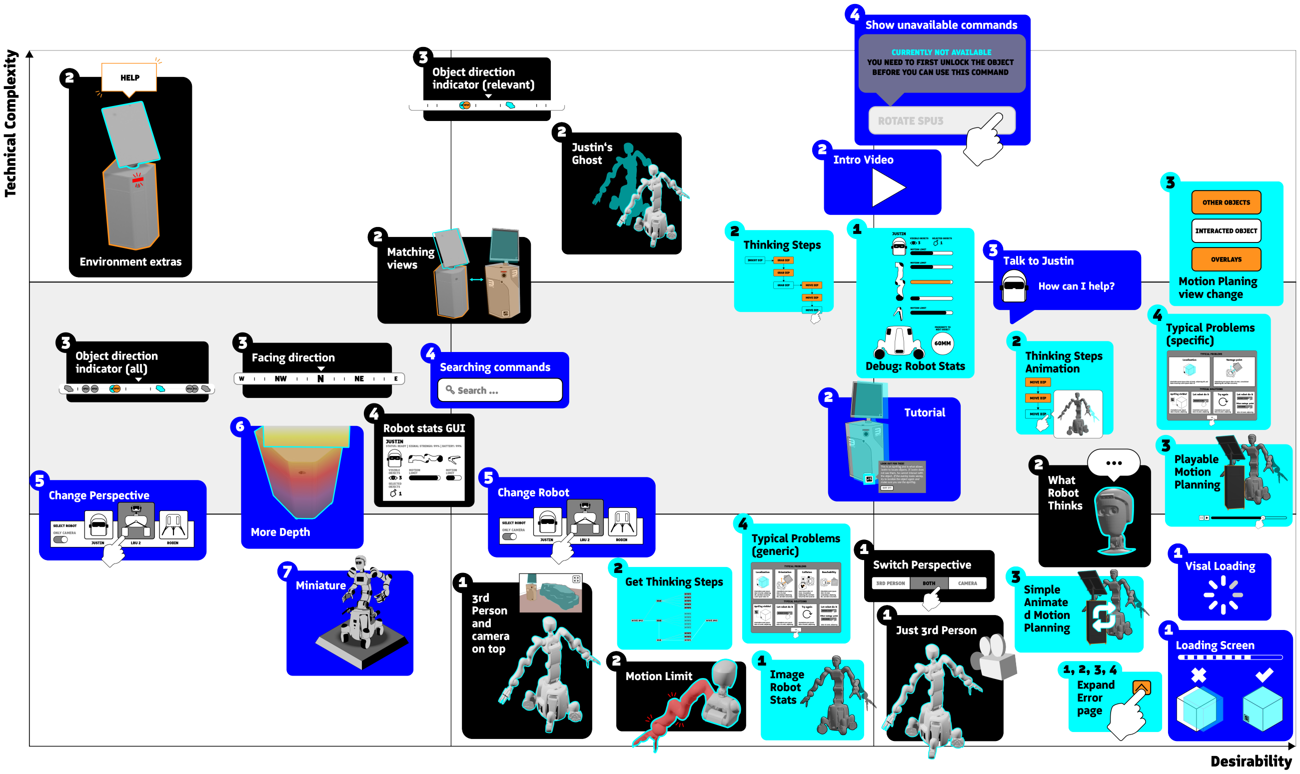


Figure 3: Evaluation of concepts and respective features based on technical complexity and desirability: Black boxes are all features of the *Third-Person View*, cyan boxes are all part of the *Debugging Dashboard* concept and the blue boxes all belong to the *Usability Add-ons*

understand the operating context and identify key issues that could impact participants' error-handling capabilities throughout their teleoperation journey.

The primary researcher engaged with roboticists working in the field ($n = 9$), that we selected for their previous experience with *Surface Avatar*, varying from first-timers to more experienced operators. In the individual sessions, which lasted about 1 hour each, the researcher combined semi-structured interviews with more structured questionnaires (such as the user experience [72] and the Godspeed [4] questionnaires) to understand the perception of the robot and to gain a holistic understanding of the general usage of the Surface Avatar system, with a specific emphasis on error handling scenarios. Furthermore, we observed and annotated two video-recorded sessions of the Surface Avatar experiment, each involving a different astronaut using the existing interface. From this initial investigation, we distil a list of six primary factors that contribute to human understanding and management of robot planning errors:

- *Understanding of robot operation and capabilities*
- *Operator spatial awareness*
- *Experience with the interface and control scheme*
- *Amount of ground support required*
- *Usage of assitive tools*
- *Quality and understanding of error messages*

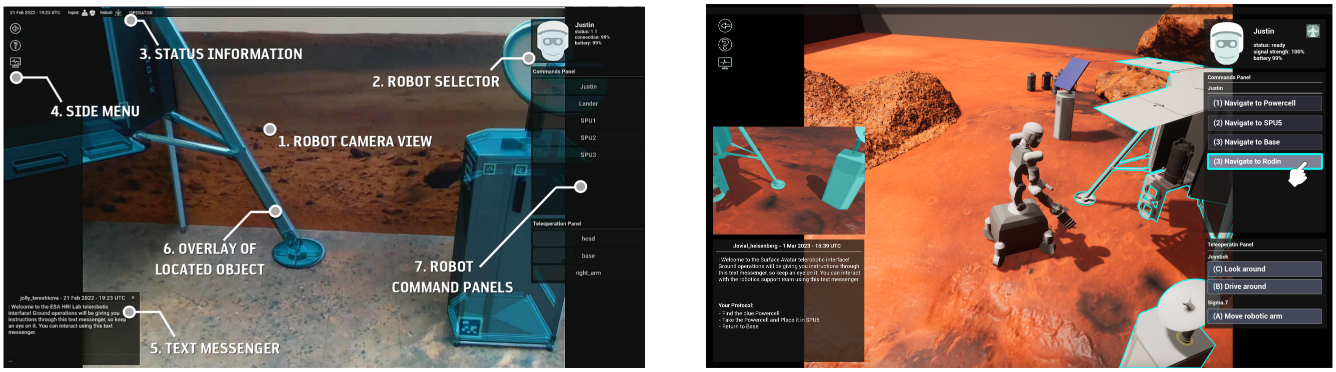
While coherent with existing literature [24], most of these challenges do not find explicit solutions in previous works.

Thereafter, we engaged with each of these factors and ideated possible solutions by leveraging existing knowledge about game design principles. As shown in Figure Figure 3, we generated a total of 33 concepts, all ideated following three main design principles distilled from Game and UX design strategies, which are: the *Third-Person View*, the *Debugging Dashboard*, and the *Usability Add-ons*. The concepts were reviewed and weighted and then plotted according to complexity and desirability (as in [54]) to find the potentially most impactful yet feasible concept.

As a result, we selected design features associated with the *Third-Person View* concept at the bottom right of the table (see Figure 3, which would allow the user to gain an overview of their surroundings by seeing the robot in its environment, with the aim of improving situational awareness. Other design features part of the other two overarching concepts, the *Debugging Dashboard* and the *Usability Add-ons*, were also deemed very promising and further developed, but this paper focuses on the features for Third-Person View as it is the one that was tested more thoroughly.

3.3 Interface redesign

Using Unreal Engine [20], we developed the third-person view concept into a semi-functioning interface that allowed the control of a



jolly_tereshkova - 21 Feb 2022 - 19:23 UTC
: Welcome to the ESA HRI Lab telerobotic interface! Ground operations will be giving you instructions through this text messenger, so keep an eye on it. You can interact using this text messenger.

Jovial_heisenberg - 1 Mar 2023 - 15:39 UTC
: Welcome to the Surface Avatar telerobotic interface! Ground operations will be giving you instructions through this text messenger, so keep an eye on it. You can interact with the robotics support team using this text messenger.

Your Protocol:
- Find the blue Powercell
- Take the Powercell and Place it in SPU5
- Return to Base

(a) The existing GUI showing the video stream of the head-mounted camera

(b) The new GUI concept showcasing a Third-Person View rendered in Unreal

Figure 4: Comparison of the existing GUI with the proposed concepts implemented with the Unreal Engine

virtual version of the robot. The prototype allows for autonomous navigation, object interaction, manual head, and base control, contact with ground control (operators providing support from Earth), a view of the robot's camera in the virtual environment, and a virtual third-person perspective with the freedom to change perspectives, see Figure 4. The new user interface is designed building on the existing GUI, except for the teleoperation of the arm, which remained in its original place but did not have functional interaction.

To create the virtual environment, the proof-of-concept implementation can build upon the same software architecture as the one used on the real robot [40]. An object database stores prior knowledge about the environment and all assets known to the robot including detailed CAD data. The current layout of the environment, including the exact positions of objects, is derived from the internal world representation of the robot, which is generated as the robot visually perceives its surroundings. Utilizing this information, the robot can recreate a virtual environment. Consequently, actions initiated in the Third-Person View could potentially be mirrored on the physical robot eventually.

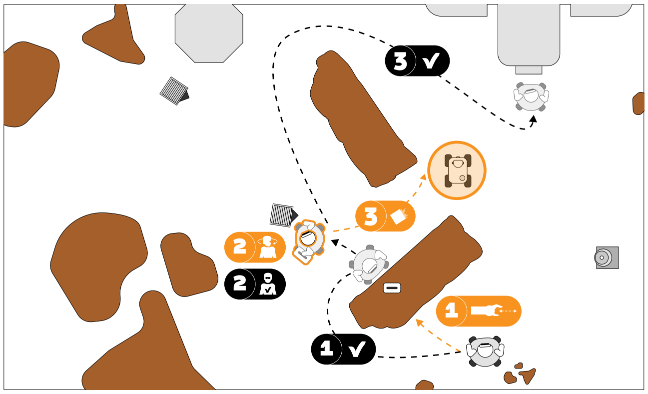


Figure 5: Layout of the virtual world for testing showing correct routes users had to take to finish protocol in black and encountered errors in orange: (1) Going to the power cell, (2) taking the power cell and installing it in the SPU, (3) returning back to the base.

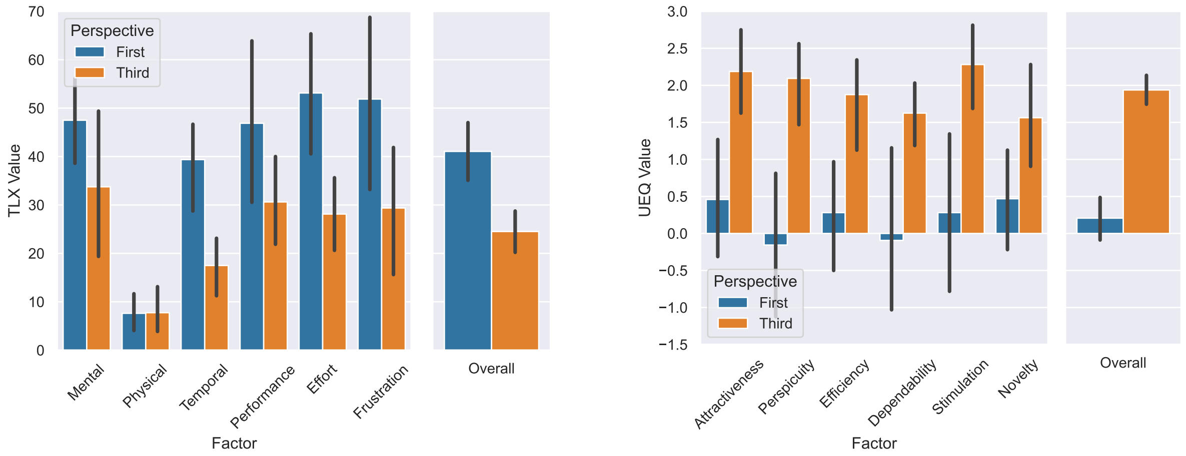
4 USER STUDY DESIGN

The interface redesign from Section 3.3 creates the basis of two between-subjects experiments to explore differences between the traditional first-person view, and the possibilities offered by a reconstructed third-person view of the environment. We carried out two experiments. The first experiment was conducted as an in-person user test with [redacted] staff, which we assessed with the NASA TLX and the UEQ as well as a short interview (Section 4.1). The NASA TLX is a subjective tool used to assess mental workload during task performance [32] and the UEQ scales offer a holistic evaluation of user experience [37]. The second experiment was conducted online and asked participants to solve robot errors based on interface screenshots from either first or third-person perspective (Section 4.2).

4.1 In-person User Test

For the in-person test, participants interacted with a simulated environment featuring scans of the Martian landscape with models of rock formation and objects such as rovers, habitats, or solar panels (Figure 5). This environment was designed with reference to the simulation setup at [redacted] to be mission plausible but contained a different set of objects and a different configuration of rock formations to avoid familiarity. A mission protocol was created to reflect a realistic Mars mission task: finding a power cell, installing it, and returning to the base. The task was designed to induce several planning errors such as inaccessible power cells and collisions during navigation (see Figure 1).

Each participant sat alone with a laptop and carried out the whole task in either first or third-person view, taking roughly 15-20 minutes. We recorded i) the laptop screen, including a visual record of keypresses; ii) hand movements through an external camera; iii) audio. After completion of the task, participants filled out the NASA TLX and the UEQ questionnaires. With participants in the third-person condition, we carried out a short, semi-structured interview about their experience and how it compares to their previous experiences with the system. They were also shown a



(a) The 6 factors and overall average of the NASA TLX

(b) The 6 factors and overall average of the UEQ user experience questionnaire

Figure 6: Comparison of scores for first and third-person views showing means and 99% CIs for the NASA TLX cognitive load measurement and the UEQ user experience questionnaire.

range of potential interface changes based on game interfaces in order to solicit suggestions for improvements, but these are not covered in this paper.

For the test sessions, 16 employees from the [redacted] were recruited, 8 in first-person and 8 in third-person mode. This included members of the development team (7/16), individuals with prior dry-run experience using the existing system (13/16), and those who had observed astronaut training (15/16). Some participants had no previous usage experience with the robot (3/16). These were evenly distributed among the prototype testing- and the comparison group.

4.2 Online Experiment

The online experiment involved showing participants non-interactive screenshots of the robot interface and asking them to solve the error it was experiencing. After a short introduction, each participant worked with either a first-person ($n = 21$) or a third-person ($n = 21$) view and was shown a randomized sequence of 12 errors – three each for reachability, localization, collision, and orientation. In all cases, they were both asked to determine the cause of the error (recorded as correct or not) and choose appropriate actions to fix the error via multiple choice. For each action to fix errors, we classified the suggested action as "Good" if it contributed to problem resolution; "Bad" if it would actively harm the situation – this included asking for help or teleoperating the arm, both of which were time-consuming and unnecessary for the given scenarios; or "No effect" if they did not affect problem resolution. Our goal was to enlist individuals aged between 26 and 60, possessing moderate to high levels of technology experience, and belonging to occupational categories such as engineering, science, health, biology, and related fields. This selection criteria aimed to closely mirror the profiles of astronauts and individuals engaged in space-related actions. Notably, none of the participants in the in-person test sessions were involved in the online experiment.

4.3 Ethics

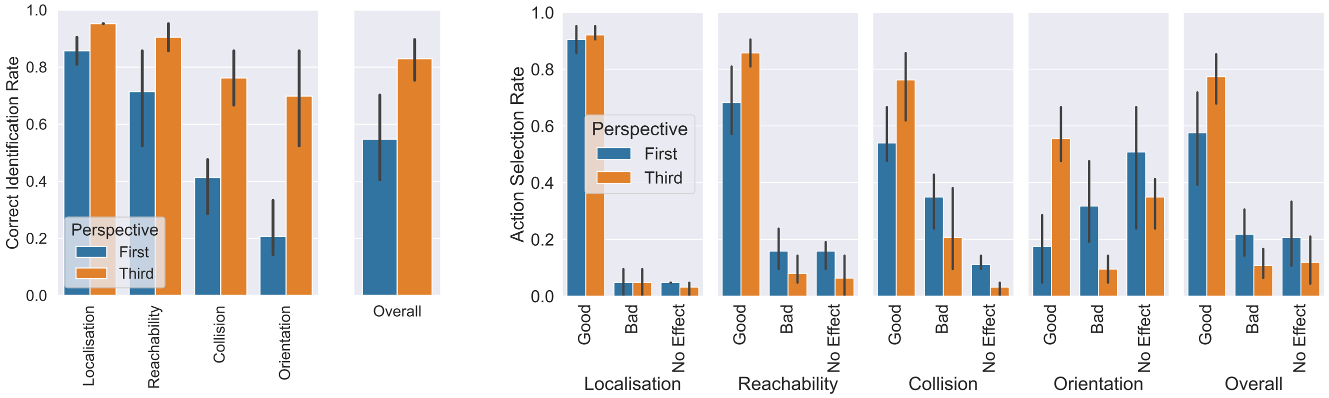
The research carried out in this study has received approval from the Human Research Ethics Committee (HREC) at TU Delft. All research procedures strictly adhere to the approved data management plan, and participants were asked to give their informed consent by signing a consent form. Participants volunteered for the study without receiving any form of compensation.

5 RESULTS

From the quantitative results, we tested four broad hypotheses for differences between the following quantities in first and third-person views: i) overall NASA cognitive load measurements; ii) overall user experience scores from the UEQ; iii) correct identification of errors in the online study iv) Bad actions taken to fix errors in the online study. These hypotheses were tested using a Bonferroni corrected [18] Mann-Whitney U test [50] at $p = 0.05/4 = 0.0125$ using `mannwhitneyu` from the `scipy.stats` Python library. Individual factor scores were plotted with 99% confidence intervals (each test has 6 factors, $1 - 0.05/6 = 0.99$) to give indications of potential differences without making strong statistical claims.

5.1 In-person user study

Figure 6a gives a visual comparison of factors measured by the NASA TLX [32] in first- and third-person views. The means averaged across all factors were 41.0 ($n = 8, sd = 10$) for the first-person condition and 24.5 ($n = 8, sd8.3$) for the third-person condition. This shows a significant difference at $p = 0.0023$. 99% CIs for the



(a) Rates of correct error identification

(b) Action selection in response to errors

Figure 7: Identification and action choices in response to errors in first- and third-person perspective ($n = 21$ in each condition), from 12 example errors – three each of localization, reachability, collision, and orientation, presented in a randomized order.

individual factors indicate a potential improvement in Temporal and Effort scores.

Figure 6b gives a visual comparison of factors measured by the UEQ user experience questionnaire [37] in first- and third-person views. The means averaged across all factors were 0.21 ($n = 8, sd = 0.98$) for the first-person condition and 1.4 ($n = 8, sd 0.64$) for the third-person condition. This shows a significant difference at $p < 0.0001$. 99% CIs for the individual factors indicate a potential for improvements in all scores except Novelty.

5.1.1 Qualitative Results. After the interviews, we clustered quotes into 8 themes. Of these, we present the 5 clusters in which more than 5 of the participants expressed opinions:

- all 8/8 participants felt an improvement of situational awareness: *"this immersive experience, it's much more present. [...] if you see the robot all the time, then you know exactly how it looks and if something looks unhealthy. Then it's directly present to you. And that's why I think that's super valuable. [...] And the perspective definitely helped."* [P6].
- 7/8 participants referred to their level of engagement: *"I would love to continue and solve some more tasks"* [P1].
- 7/8 participants mentioned the impact that the third-person view had on the task difficulty: *"So, I think that because you saw more, it was easier than if I had only seen the camera, because I have a better awareness of where things are around me, what the robot is like, where can I navigate to"* [P6].
- 6/8 participants mentioned that the third-person view gave an improved overview of what was going on: *"because it is very important if you want to get a closer look or a different view of things and even meanwhile, just have your robot and you can see at which orientation position it is. I really like that"* [P4].
- 5/8 participants mentioned that the body orientation of the robot was still a challenge, e.g. *"Without error messages, finding out that the alignment of the head is important is difficult."* [P2].

Other themes that were mentioned included feeling that they *"get sick quickly when it's in the first-person perspective"* [P5] (2 participants), and a disagreement about whether the WASD control scheme was good (3 in favor, 2 against) based on experience with computer games.

In addition to reflecting on the experience, participants suggested improvements based on features that were presented to them during the interview. For instance, all participants were in favor of projecting a reachability map and highlighting potentially colliding objects in the world, and 7/8 showed interest in highlighting misaligned body parts of the robot.

5.2 Online Experiment

42 users participated in the online experiment, 21 in first-person view and 21 in third-person, with each attempting to solve 12 errors – 3 each of localization, reachability, collision, and orientation, shown in random order (Figure 7). Figure 7a shows the rate of correct error identification. The average rate of correct error identification was 0.83 in the third-person view, versus 0.55 in the first-person, which is significantly different ($p < 0.0053$). The bar chart indicates that this effect is strongest for collision and orientation errors. Figure 7b shows the proportions of 'Good', 'Bad' and 'No Effect' actions. The sample mean of the rate of bad actions in the third-person is 0.11, half that of the first-person rate (0.22), but this difference is not statistically significant ($p < 0.045$).

6 DISCUSSION

In this study, we investigated the user experience of teleoperation of robots in space and the complexity of handling errors in this context. Conducting preliminary ethnographic research we found that astronauts operating robots encounter difficulties mostly due to poor situational awareness and limited info about the type of errors occurring. We engaged with these limitations in the redesign of the teleoperation interface and tested whether this brings a significant improvement in operators' user experience, in terms of cognitive load, error identification, and error correction actions.

Our results suggest noteworthy improvements between the existing interface and our redesign. Participants experienced a significantly lower cognitive load, reported a more positive overall user experience, and perceived the tasks as less difficult, possibly due to the enhanced spatial awareness our interface provided.

In particular, the virtual environment excels in providing a clear understanding of the robot's orientation and its relation to the surroundings, improving decision-making, while removing the factor of time delays, and providing a ground for communicating the limitations of the robots capabilities.

6.1 Feasibility

The simulation we developed for testing aligns with the current robotic system, utilizing its 3D world representation to discern object locations. Consequently, implementation in the existing [redacted] test setup could be feasible and would allow for agile future investigations into astronauts' user experience of robot teleoperations. However, scenarios exist where the camera perspective is indispensable, especially for detailed manual control or assessing damaged objects. Camera views are vital in dynamic contexts, where maintaining an accurate virtual representation is challenging, e.g. the actual Mars surface. For future Mars missions, and consequently a more complex environment, current research is already working on how to implement such a virtual environment, even considering photorealistic representations by accurately matching 2D images to 3D shapes [57]. In the meantime, previous research [74] has shown a simple solution for integrating a third-person view by mounting a camera on a robotic arm or attaching it to a long stick, which preserves the live feedback aspect.

6.2 Bridging disciplines

This work builds upon existing research on situational awareness, widely recognized in the teleoperation context, and adds a distinctively user-centred and experience-focused perspective into matters of error handling and teleoperation efficiency. The contribution of this work, however, extends far beyond providing empirical evidence of the benefits of using a third-person view in teleoperation interfaces. Our experience revealed how established disciplines like UX and game design have much to offer when HRI research "gets into the field".

Several existing works [47, 48, 80] already argue for the value of integrating designerly practices in HRI research and call for a richer understanding of how design produces knowledge [47]. Our work further provides an in-depth articulation of what professional design practices can bring into practical matters of HRI research, such as aspects of control, cognitive load, and efficiency in operation. We look at design as a tool to navigate the complexities of our world and create seamless HRI experiences. The designer acts as a bridge between intricate contexts, people, and robots.

Beyond arguing for the value that design has to offer to HRI, our wish is for the field to look at the very *bridging of disciplines as the site for discovery and methodological innovation. How does an anthropologist look at the performance of human-robot collaboration? How might a historian shed light on possible HRI futures?* The HRI field is notoriously multidisciplinary [30], but much still needs to be done to enable genuinely cross-disciplinary collaborations, so *what vocabularies do we need to really enable such plurality of disciplinary perspectives?*

6.3 Theoretical views on human-robot perceived capabilities

Part of the value of looking at situations from other disciplinary perspectives is the use of alternate lenses to understand the problems. In this case, while better, more efficient error handling is the initial goal, behind that sits the question of how astronauts understand the boundaries of agency between themselves and the robot. Other work has used speculative, design-led approaches to understand the inter-agencies between people and smart objects, e.g. [78], which tries to understand how relations form around autonomous technologies. Working with increasingly agential and autonomous technology requires creative approaches to understanding and navigating who should do what [e.g. 15]. Overall, the question here touches not just on the functionalities of the interface, but on what relations should form between the astronauts and the robot.

7 CONCLUSION AND FUTURE WORK

By leveraging concepts from gaming, gestalt principles, and existing research, this work has laid the groundwork for effective error mitigation strategies in teleoperation systems in space. There was a richness of possibilities discovered through the initial investigations (see Figure 3) that can make the GUI more intuitive and approachable. These range from simple possibilities such as displaying the bounds of reachability of the robot, through highlighting objects that are causing collisions, or providing detailed debug information, to interface changes that situate action controls on the objects they affect – as seen in many computer games. The reachability map in particular is likely to be added to the next version of the GUI for Rollin Justin. In order to get more concrete validation of the findings from this work, we aim to employ some of the features we introduced here in the upcoming Surface Avatar Prime ISS sessions to analyze the on-orbit user data. Overall, we have shown that importing these ideas can improve the quality of life of astronauts, and help them to better make use of the robot's capabilities for autonomous action.

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