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Cosmic Troubleshooting: Exploring Third-Person View for Error Handling in Telerobotic Planetary Infrastructure Maintenance

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***Abstract*—This study investigates error handling intricacies in supervised autonomy orbit-to-ground teleoperation for space exploration robots, emphasizing scenarios with communication delays that render Earth-based ground control assistance unfeasible. In this setting, one major challenge lies in empowering the crew to independently mitigate robot errors that may occur as the robot plans its actions. To address this limitation of current supervised autonomy interfaces, we propose a third-person perspective and game design principles to improve environmental awareness in error situations. 16 experts with similar technical background as the target crew members tested the interface in a physical user study, while 42 people assessed it in an online study. We conclude that a third-person view brings significant improvements to mental workload, overall experience and the ability to identify and rectify planning errors.**

I. Introduction

Mars exploration is driven by the quest to uncover signs of life and understand planetary evolution. While robotic exploration has achieved successes [1], their efficiency is limited by the autonomy of the deployed systems. Semi-autonomous robots are projected to play a pivotal role in constructing habitats, establishing communication systems, and harvesting energy resources on Mars [2]. However, controlling these robots from Earth is hampered by up to 45-minute communication delays [1], [3]. A proposed solution involves astronauts in Mars orbit remotely operating these robots, which would allow for direct telepresence control [4] and high-bandwidth, supervised autonomous operations [5].

While autonomous robotic capabilities facilitate basic command execution (e.g., 'grasp this object'), they are limited in complex scenarios [6], [5]. A critical aspect of supervised autonomy is understanding robot capabilities and effectively handling planning errors [7]. As astronauts face challenges with confusing error messages the lengthy communication delay to Earth makes ground-based assistance impractical [3], [5]. In response to this, this paper centers on improving the understanding and resolution of errors that occur during robot operation planning. Utilizing *Rollin' Justin*, a dexterous humanoid robot experienced in space telerobotic missions [8], we investigate how to enhance astronaut situational awareness, error comprehension, and management through *User Experience (UX)* research and game design principles. Our goal is to minimize cognitive load and aid astronauts in navigating the complexities of human-robot autonomy interactions.

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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.

II. Related Works

Our literature review is focused on teleoperation and human-robot interaction with an emphasis on space robotics, UX and game design for improved situational awareness, and investigations on third-person view in telerobotics.

A. Teleoperation and Human-Robot Interaction

Robot teleoperation for space exploration faces challenges like high latencies, low communication bandwidth, and operator performance degradation [9], [10]. Extensive research has enhanced haptic teleoperation, such as in major projects like *Kontur-2* [11], *METERON* [12], and *Avatar-EXPLORE* [13]. Autonomous and supervised autonomous navigation, coupled with intuitive graphical user interfaces, has proven effective in reducing operator workload [14], [15], [16]. Furthermore, there is a sustained interest in exploring the role of human factors, such as limited system knowledge and reaction time, in the presence of error situations [17]. Recent HRI studies highlight various aspects of error communication and trust repair in human-robot interactions including generalized error management using natural human responses [18], strategies for unexpected robot failures [19], differences in social signals during error-free and erroneous situations [20], design principles for safety in HRI [21], comparisons of error-handling strategies in human-human and human-robot dialogues [22], approaches for repairing trust after robot errors [23], and investigation into human-robot trust repair strategies [24]. In contrast, remote human-robot interactions with substantial time delays heavily rely on supervised autonomy transported via Graphical User Interfaces (GUIs) [25], [26], [27]. Enhancing supervised autonomy is vital to making informed decisions and preventing errors [28], [29].

B. UX and Game Design Principles

To address these challenges, HRI research draws on UX and game design principles. Game design, similar to teleoperation, involves users navigating unfamiliar environments and mastering new controls, potentially aiding in situational awareness and error identification [30], [31]. GUIs anticipating robot actions and explaining them can prevent errors and

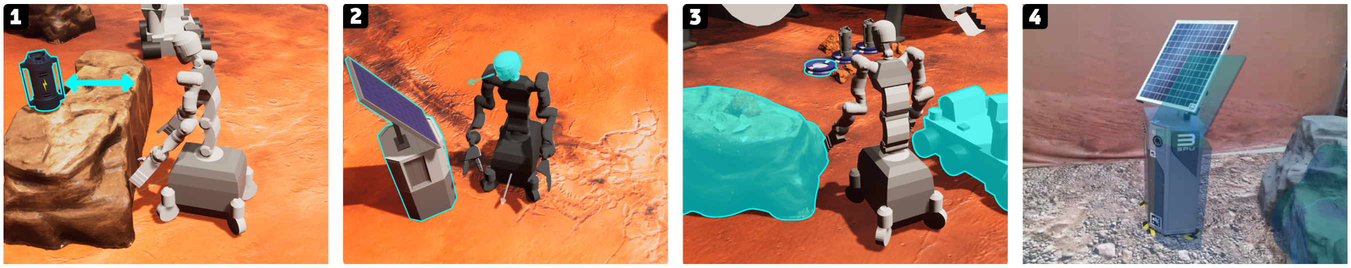


Fig. 1: Types of planning errors: 1) *Reachability*: arms unable to reach the target which requires different approach position. 2) *Orientation*: misaligned head and body lead to confusions in first person view. 3) *Collision*: obstacles in the way of the arms/base deny collision-free path planning. 4) *Localization*: the misaligned overlay suggests a bad localization. This error case becomes particularly obvious when the actual first-person image is superimposed with the internal robot model.

enhance the user experience [7], [32], [31]. Research has shown that game-inspired interventions can increase situational awareness in teleoperation [33] by using information cues [34], Augmented Reality layers [35], multi-modal interfaces [36], and reducing multitasking [37]. There is also work on preference learning to improve human-robot interaction and personalized experiences as known from customizable game interfaces [38].

C. Third-person View Studies in Telerobotics

Particularly promising are interventions focusing on the camera view of the user, a critical component of the teleoperation experience [9], [39], [40]. The potential of third-person perspectives, offering a broader view, has been recognized in games and teleoperation [41], [42], [43]. Possibilities for achieving this include mounting cameras on robotic arms or long poles [44], utilizing multiple ground robots [45] or Micro Aerial Vehicles (MAVs) [41], and approaches constructing full 3D models for a free viewpoint [46].

Several studies show that a third-person view can increase situational awareness in teleoperation scenarios. One, in particular, shows that navigation efficiency can be enhanced through the use of bird's eye and third-person perspectives [47]. Others have compared teleoperation performance of third-person view with an integrated first-person perspective projection [48]. Further, others observed that a third-person view can also improve direct control capabilities [49].

Although these examples provide important insights, a research gap remains: none of the referenced studies investigate how a third-person view enhances error handling in telerobotics which we consider a major issue, especially in complex settings. Most studies do not scale beyond direct telepresence control in simple scenarios (e.g. navigating an unknown environment), with simple actions (i.e. pick and place at most) and simple robots (e.g. robot cars), where as our work distinguishes itself by leveraging the power of supervised autonomy in a complex scenario (i.e. constructing and maintaining planetary infrastructure) for complex robots (i.e. a full scale humanoid), with complex tasks (e.g. cleaning solar panels and replacing hardware).

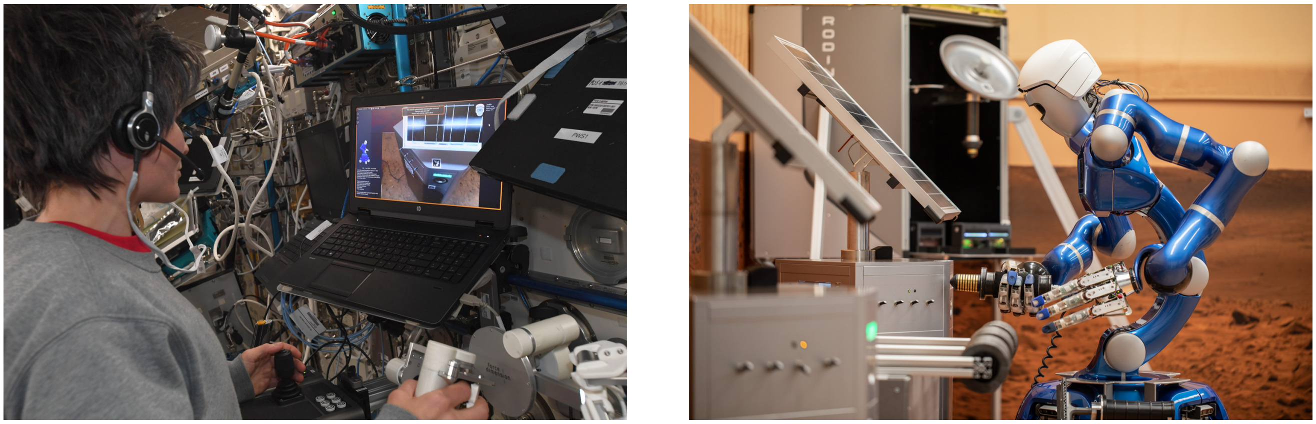
III. UX Investigations Facilitating Cosmic Troubleshooting

This work investigates whether game design principles, here third-person view in particular, are able to improve the UX of supervised autonomy teleoperation. The study includes both the redesign and testing of the GUI to operate Rollin' Justin in the Surface Avatar technology demonstration mission [25].

A. The Surface Avatar Experiment

The Surface Avatar experiment utilizes the the *International Space Station (ISS)* and a Mars mock-up at the *German Space Operations Center (GSOC)* to replicate potential future scenarios with astronauts teleoperating a robot from orbit. This testbed facilitates assessments and refinements of the interface, incorporating Mars-like conditions and tasks, including interaction with functional and non-functional module replicas. As depicted in Fig. 2a and Fig. 2b, astronauts engage with Rollin' Justin, adhering to scripted mission protocols for inspection, maintenance, and repair tasks [50], [8]. Communication channels simulate expected delays to ground control as in actual Mars missions, underlining the importance of autonomous error handling by astronauts in such scenarios.

While direct telepresence control is an option, 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 [24], [23]. In the scope of this study, our specific emphasis is on the four most commonly observed types of errors that a user may encounter in or before the planning phase (i.e. before execution) as visualized in Fig. 1:



(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.

Fig. 2: The Surface Avatar experiment setup combining direct telepresence control and supervised autonomy control. This study leverages this setup to control the robot, yet only the supervised autonomy mode is used to issue high-level commands.

1) Reachability: robot unable to reach manipulation goals.
2) Orientation: misaligned head/body cause confusions.
3) Collision: absence of a collision-free path to the goal.
4) Localization: inaccurate world perception by the robot.

B. Preliminary UX Research

We conducted ethnographic design research [51] at the DLR experimental site to inform the deign of the GUI [52] The primary researcher conducted individual semi-structured interviews, of about one hour each, with ($n = 9$) roboticists experienced in *Surface Avatar*, ranging from novices to experts, reflecting the aerospace engineering qualifications expected of future robot operators. The interviews are structured around established UX and HRI questionnaires, i.e. the *User Experience Questionnaire (UEQ)* [53] and the Godspeed questionnaire [54]). With this, the interviews were aimed to gain insights into the current UX of the robot and to understand of how users engage with the Surface Avatar interface, especially in scenarios that require interactive error handling. Furthermore, we analyzed and annotated two video-recorded sessions of the Surface Avatar experiment.

From this initial investigation, we identified six key aspects crucial to understand and manage robot planning errors:

1) How clear are the capabilities of the robot to the user?
2) How good is the spatial awareness of the user?
3) How positive is the experience with the interface?
4) How much ground support is needed by the user?
5) How effective are the assistive tools for the user?
6) How well are error messages understood by the user?

We thoroughly addressed each of these aspects and formulated potential approaches to improve upon them by drawing upon established principles in game design. Illustrated in Fig. 3, our exploration resulted in the generation of a comprehensive set of 33 concepts, aligned with three primary design principles distilled from both Game and UX design strategies: *Third-Person View*, *Debugging Dashboards*, and *Usability Add-ons*. These concepts were evaluated considering factors such as technical complexity and desirability, following the approach presented in [55]. The outcome reveals concepts that not only exhibit significant impact potential but also have a feasible path for implementation.

Consequently, we chose design features linked to the *Third-Person View* concept (located at the bottom right of Fig. 3). This concept aims to enhance situational awareness by providing users with an overview of the robot in its environment. While a *Debugging Dashboard* and *Usability Add-ons* were also promising, our focus here is on the Third-Person View.

C. Interface redesign

Leveraging the insights from the preliminary UX investigation, we developed a semi-functional interface building upon the existing GUI to test third-person view concept in Unreal Engine 5.1 [56], enabling control of a virtual robot. The prototype facilitates autonomous navigation, object interaction, manual head and base control, communication with ground control, a view of the robot's camera in the virtual environment, and a virtual third-person perspective (see Fig. 4).

For the virtual environment, the proof-of-concept implementation leverages the same software architecture as the real robot. For a detailed description of the software architecture please refer to [3]. In a nutshell, an object database stores prior knowledge, including detailed CAD data, while the current layout is derived from the robot's internal world representation. This representation is generated as the robot visually perceives its surroundings through the head-mounted camera system, enabling the recreation of a virtual environment. Consequently, actions initiated in the Third-Person View could potentially be mirrored on the physical robot in the future.

IV. User study design

The interface redesign serves as the foundation for two between-subjects experiments. The first experiment, an in-person user test with DLR staff, utilized the NASA TLX for assessing mental workload [57] and the UEQ for holistic user experience evaluation [58], complemented by a short

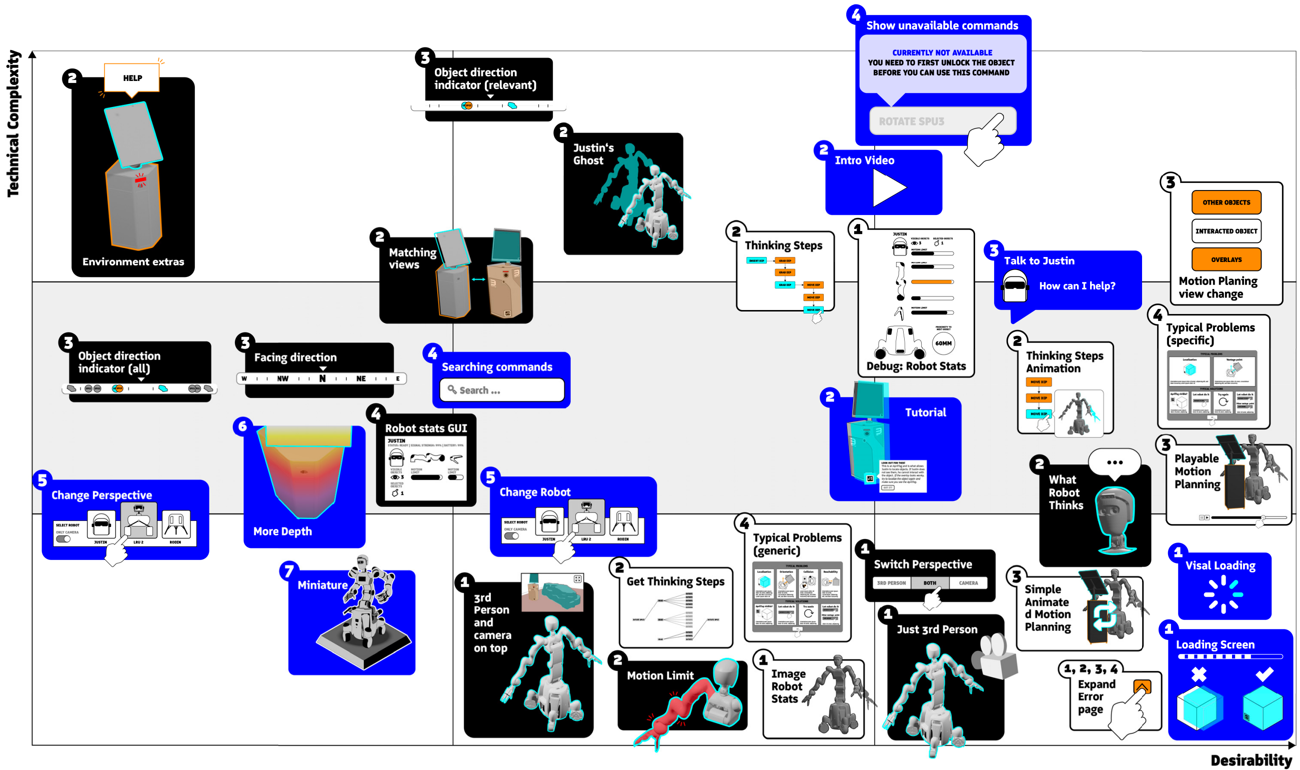
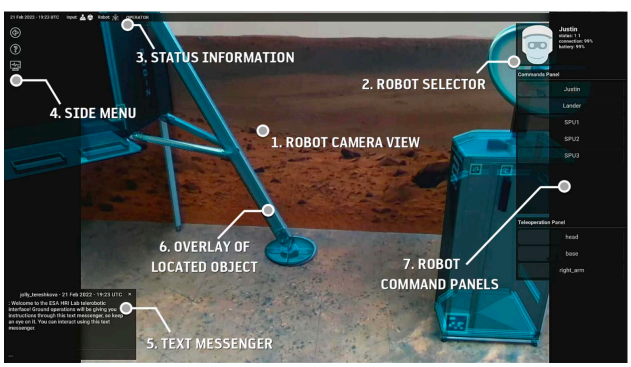
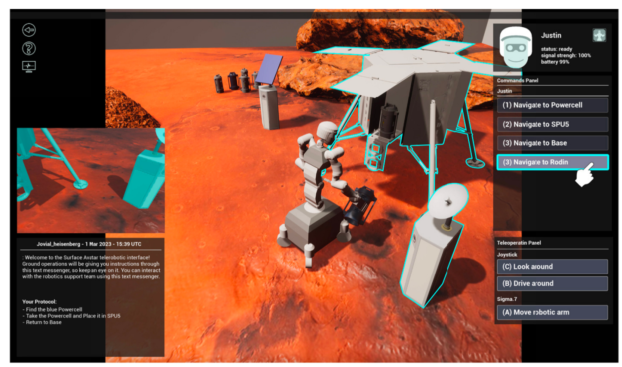


Fig. 3: Evaluation focused on the technical complexity and desirability of features: Black boxes represent *Third-Person View*, white for *Debugging Dashboard*, and blue for *Usability Add-ons*.



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



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

Fig. 4: Comparison of the existing GUI with the proposed redesign derived from Fig. 3 implemented with the Unreal Engine.

interview (Section IV-A). The second experiment, conducted online, required participants to troubleshoot robot errors based on interface screenshots from either the first or third-person perspective (Section IV-B).

A. In-person User Test

Participants in the in-person test engaged with a simulated Martian environment, featuring scans of the Martian landscape and models of various objects, as depicted in Fig. 5. The environment, designed to be mission plausible, includes different objects and rock formations. The task resembles a realistic Mars mission scenario: retrieving a power cell, installing it, and returning to the base, inducing planning errors like inaccessible power cells and collisions during navigation (see Fig. 1).

Each participant, sitting alone with a laptop, completed the entire task in either first or third-person view, taking approximately 15-20 minutes. We recorded the laptop screen, hand movements through an external camera, and audio. Following task completion, participants filled out the NASA TLX and UEQ questionnaires. Those in the third-person condition underwent a short interview about their experience, comparing it to previous encounters with the system. Participants were also shown potential game-based improvements for the system not discussed in this paper.

16 DLR employees participated in the test session, 8 in first-person and 8 in third-person mode. The group included

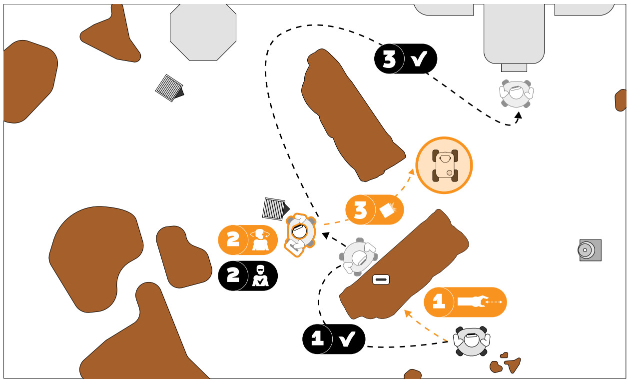


Fig. 5: The virtual world layout for testing displays correct routes in black and encountered errors in orange, involving: (1) Navigating to the power cell, (2) retrieving and installing the power cell in the SPU, and (3) returning to the base.

development team members (7/16), individuals with prior system experience (13/16), and those who had observed astronaut training (15/16). Some participants had no prior robot usage experience (3/16), evenly distributed between the prototype testing and comparison groups.

B. Online Experiment

The online experiment presented participants a series of non-interactive screenshots of the robot interface and tasking them with resolving errors encountered. After a brief introduction, each participant, either in first-person ($n = 21$) or third-person ($n = 21$) view, addressed a randomized sequence of 12 errors—three each for reachability, localization, collision, and orientation. Participants identified the error cause (recorded as correct or not) and selected appropriate actions from multiple-choice options. Actions were categorized as "Good" if contributing to problem resolution, "Bad" if potentially harmful or time-consuming, and "No effect" if irrelevant. To roughly match the age distribution of astronauts [59], we selected individuals aged 26 to 60, with moderate to high technology experience, in fields like engineering, science, health, biology, and related areas, reflecting profiles of astronauts and space-related personnel. Importantly, none of the participants from in-person sessions were involved in the online experiment.

V. Results

We explore four dimensions of first and third-person views:

1) overall cognitive load using NASA TLX (see Fig. 6a);
2) user experience via UEQ scores (see Fig. 6b);
3) online study error identification accuracy (see Fig. 7a);
4) online study frequency of "Bad" actions (see Fig. 7b).

We employed a Bonferroni-corrected [60] Mann-Whitney U test [61] ($p = 0.05/4 = 0.0125$) for analysis. To indicate differences, individual factor scores are visualized with 99% confidence intervals to avoid strong statistical claims.

A. In-person user study

Fig. 6a provides a comparison of NASA TLX factors between first- and third-person views. Mean scores across all factors were 41.0 ($n = 8$, $sd = 10$) for the first-person condition and 24.5 ($n = 8$, $sd = 8.3$) for the third-person condition, indicating a significant difference at $p = 0.0023$. 99% CIs suggest potential improvements in Temporal and Effort scores for the third-person view.

Fig. 6b shows a comparison of the UEQ factors in first- and third-person views. Mean scores 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, showing a significant difference at $p < 0.0001$. 99% CIs indicate potential improvements in all scores except Novelty for the third-person view. The user study reveals eight themes, five with significant participant opinions:

- All 8/8 noted improved situational awareness, expressing sentiments like *"this immersive experience, it's much more present[...] the perspective definitely helped."* [P6].
- 7/8 participants highlighted increased engagement like *"I would love to continue and solve some more tasks"* [P1].
- 7/8 participants found the third-person view positively influenced task difficulty, emphasizing *"a better awareness of where things are"* [P6].
- 6/8 participants appreciated the improved overview offered by the third-person view, because one can *"get a closer look or a different view"* [P4].
- 5/8 participants identified challenges in the robot's body orientation: *"Without error messages, finding out that the alignment of the head is important, is difficult."* [P2].

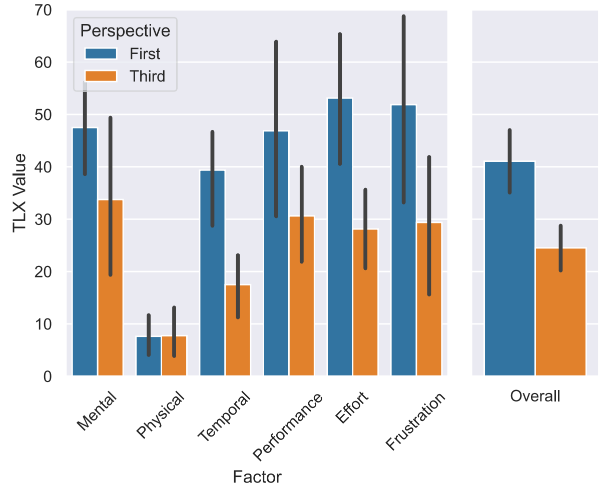
Additional themes include discomfort in first-person perspective for 2 participants (*"I get sick quickly"* [P5]) and a 3:2 split opinion on the suitability of the WASD control scheme from participants familiar with computer games. Participants suggested enhancements, unanimously favoring features like projecting a reachability map and highlighting potential collisions, with 7/8 expressing interest in highlighting misaligned robot body parts.

B. Online Experiment

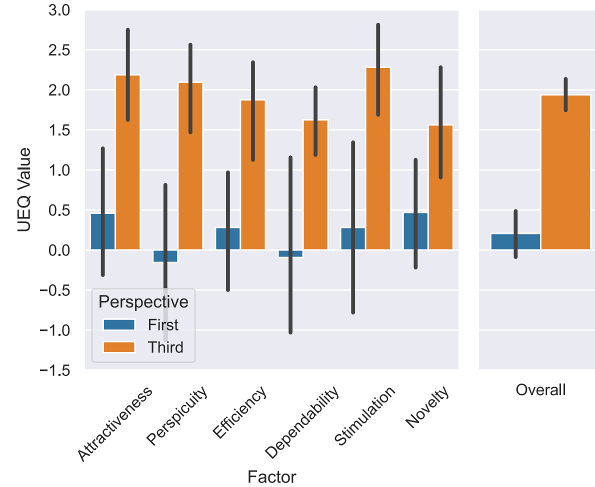
42 users participated in the online experiment, 21 in first-person view and 21 in third-person, with each attempting to solve 12 errors – 3 each of localization, reachability, collision, and orientation, shown in random order (Figure 7).

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 of the first-person rate (0.22), but this difference is not statistically significant ($p < 0.045$).

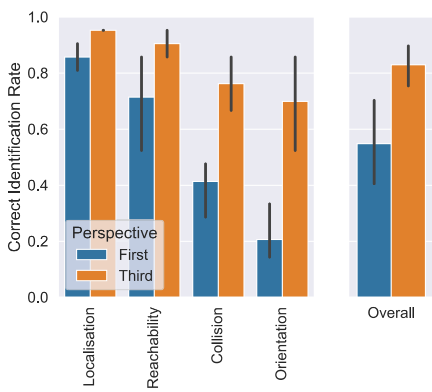


(a) The six factors and the overall average of the NASA TLX.

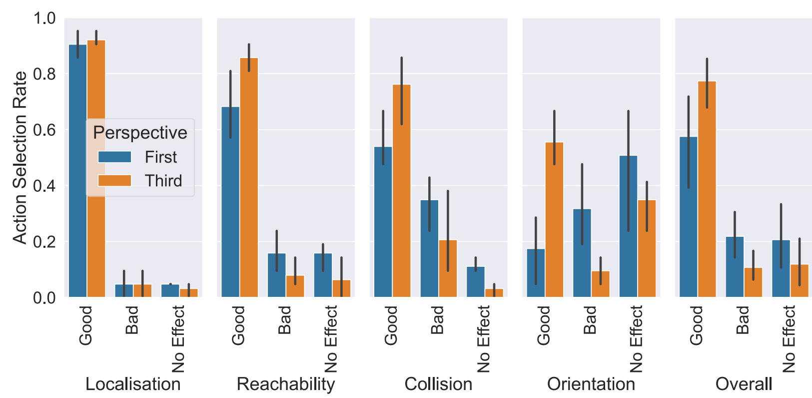


(b) The six factors and the overall average of the UEQ.

Fig. 6: First and third-person view scores with means and 99% CIs for NASA TLX cognitive load and UEQ user experience.



(a) Rates of correct error identification.



(b) Action selection in response to errors.

Fig. 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.

VI. Discussion

This study investigated preliminary ethnographic research that indicates astronauts operating robots face challenges due to poor situational awareness and limited error information. To address these issues, we redesigned the interface, aiming to reduce cognitive load and enhance error detection and resolution. Participants experienced lower cognitive load, a more positive user experience, and perceived tasks as less difficult. The third-person view enhances understanding of the robot orientation and surroundings, aiding decision-making and facilitating better communication of robot capabilities.

A. Feasibility

The implementation of a third-person view for a robot on Mars is achieved through a simulation that mirrors the internal world representation of the actual robot. This alignment with the current robotic system ensures seamless integration into the existing setup as it is currently used in the Surface Avatar experiment series [25]. In preparation for future Mars missions, ongoing research endeavors focus on refining the virtual environment, aiming for photorealistic representations achieved through matching of 2D images to 3D shapes [42]. This advancement not only enhances the fidelity of the third-person view but also enriches the immersive experience for the operator.

Moreover, third-person perspective can be augmented through additional camera installations. These cameras can be strategically positioned, whether fixed on the rover, mounted on a drone, or situated directly on the primary robot itself [44]. Fig. 1 showcases how a simulated overlay can be used to augment the view of the operator in a real camera feed for multi-camera setups for a comprehensive coverage of the environment, empowering operators with enhanced situational awareness and facilitating informed decision-making during mission-critical tasks. As an additional benefit to motivate the installation of multiple cameras on-site, recent work demonstrates the capability to merge multiple camera views into a single comprehensive 3D representation [62].

B. Theoretical views on human-robot perceived capabilities

Examining situations through different disciplinary perspectives offers valuable insights by providing alternative views on problems. In this context, the primary aim is to improve error handling efficiency, while also prompting considerations regarding how astronauts perceive their agency in relation to the robot. Dealing with increasingly autonomous technology necessitates creative approaches to delineating roles and responsibilities [63], such as speculative, design-led methods to explore the interplay between individuals and smart objects [64]. This question extends beyond interface functionalities to the nature of relationships that should exist between astronauts and robots.

VII. Conclusion and Future Work

This work has laid the groundwork for effective error mitigation strategies in supervised autonomy telerobotics through UX and game design principles. The initial investigations, as depicted in Figure 3, reveal a plethora of optimization possibilities, including straightforward options such as visualizing reachability limits, marking objects causing collisions, or offering detailed debug information, to more advanced changes where action controls are directly linked to the affected objects as known from computer games. In order to get more concrete validation of the findings from this work, we aim to employ our interface in the upcoming Surface Avatar ISS sessions to collect on-orbit user data. In this experiment series we are exploring the possibility of switching between first-person and third-person perspective depending on the context to further enhance the crew experience in preparation for future endeavours such as the Artemis mission of NASA.

Acknowledgment

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