MULTIMODAL OPERATIONS FOR ROVER TELEOPERATION: HAPTIC DRIVING AND MANIPULATION WITH A 7-DOF DEVICE

Rute Luz[1], **Thomas Krueger**[2], **Aaron Pereira**[3], **Emiel Den Exter**[2], **Jacob Beck**[2], **Thibaud Chupin**[2], **José Luís Silva**[4], **and Rodrigo Ventura**[1]

[1]*Institute for Systems and Robotics, Instituto Superior Técnico, University of Lisbon, Lisboa, Portugal*
[2]*European Space Agency ESTEC, Noordwijk, The Netherlands*
[3]*Solid Sustainability Research, Leiden, The Netherlands*
[4]*ITI/LARSyS, Instituto Universitário de Lisboa (ISCTE-IUL), ISTAR, Portugal*

ABSTRACT

Teleoperating rovers in unstructured environments (e.g., Lunar or Martian surface) is often challenging for the human operator. These scenarios frequently lead to a high mental workload, erroneous perceptions of the environment, and faulty decision-making. We present the system architecture of a novel haptic teleoperation interface to improve the interaction with remotely operated rovers in the domain of planetary exploration. With the proposed approach, the operator can control both the robotic arm and the rover's locomotion with a 7-DoF force feedback device (sigma.7) depending on the operation mode (manipulation or locomotion). Moreover, while standard haptic devices for teleoperation only display one type of stimuli (e.g., contact forces), the proposed interface displays three distinct haptic stimuli: (1) force (during manipulation tasks, e.g., rock-picking), (2) proprioceptive (emulate the inclination of the rover while traversing rough terrains), and (3) vibration (convey traction losses during locomotion). Finally, we present a qualitative discussion from preliminary test with users operating the Interact rover with our multimodal teleoperation concept.

Key words: haptics, robotics, teleoperation, multimodal feedback, traction, proprioception, vibration.

1. INTRODUCTION

Robotic exploration of planetary surfaces can significantly benefit from human-in-the-loop operations enabled by low-latency telerobotics ($<$ 1 second) [1]. In this scenario, the overall success of teleoperated tasks strongly relies on the interaction methods available to the human operator. Previous experiments on the International Space Station (ISS) [2, 3] showed that supervisory autonomy approaches are an effective interaction method where astronauts can maintain appropriate Situational Awareness (SA) with a low effort and workload while ensuring overall mission success [4, 5].

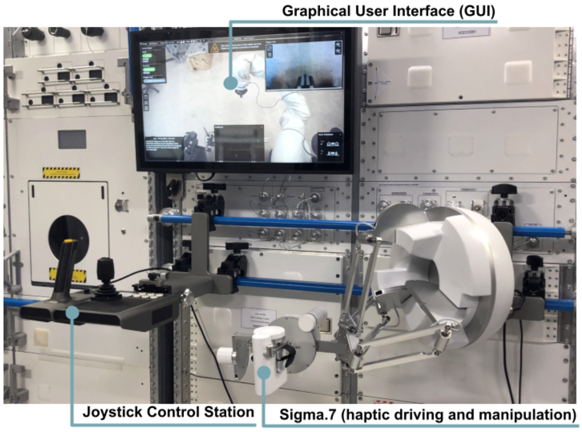


Figure 1: Teleoperation setup currently installed on the ISS: sigma.7 device, a GUI, and a custom joystick control station with stabilisation handle and enable button (left), 3-axis joystick, and buttons.

However, in unstructured environments with poor lighting conditions (e.g., the Lunar surface), state-of-the-art autonomy components still fail to solve unexpected events (e.g. stuck rover wheels) [6]. Such cases often require human intervention through direct teleoperation. Moreover, even when a high level of autonomy tools (e.g. waypoint navigation) are available during teleoperation, operators often request an additional low-level control to perform fine adjustments and controls of the robotic systems [7, 8].

Here, the success of this interaction modality is highly dependent on the operator's perception of the environment and the robot (SA) to make adequate and timely decisions. Thus, the iterative design of the operator control units (GUIs and input and feedback devices) is crucial to ensure the success of teleoperated tasks. In this paper, we build upon systematic iterations of the teleoperation system currently deployed on the ISS (see Fig. 1) and lessons learned during several testing campaigns [9, 10, 11, 12, 13].

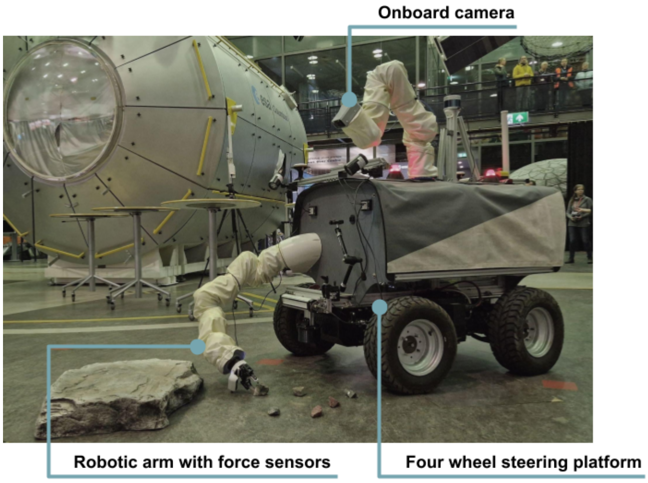


Figure 2: Interact rover (four-wheel-steering) and setup for manipulation and driving operation with sigma.7 during preliminary tests of the integrated system.

Direct teleoperation of ground rovers, particularly locomotion tasks, has been mainly limited to joysticks and dedicated Graphical User Interfaces (GUIs). At the same time, manipulation tasks often resort to dedicated force feedback devices to enhance the remote operation of robotic arms [9]. Moreover, enhancing the operator's interaction during driving tasks with haptic feedback can significantly improve the human detection of faults [1], reduce task difficulty and create a greater sense of operator immersion in the remote environment [14]. Therefore, it is essential to investigate adaptable and efficient teleoperation interfaces for robotic systems with several multimodal operation capabilities.

In this paper, we present a multimodal teleoperation concept that integrates the haptic operation of a robotic manipulator [10] with a novel haptic driving approach [15] to control the locomotion of a ground rover (Interact rover in Fig. 2) using a 7-DoF haptic input device (sigma.7 in Fig. 1). The sigma.7 device was previously used to control a robotic manipulator on ground from the ISS with force feedback, during the ANALOG-1 experiments [9, 10]. During these experiments, the astronaut controlled the locomotion of the rover and the camera's movement with a 3-axis joystick without force feedback. Additionally, he received telemetry information through the Graphical User Interface (GUI).

Feedback from the astronaut included the remark that using the 7-DoF device (sigma.7) for telenavigation would eliminate the need to switch back and forth from the 3-DoF joystick, thus reducing the operator's workload [9]. We build upon this setup and introduce a novel interaction method to drive the rover with the 7-DoF haptic device, enhance the operator's situational awareness during driving operations, reduce the workload associated with switching between devices, and reduce information density on the GUI.

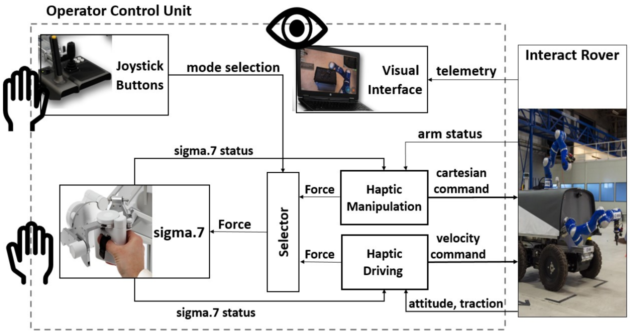


Figure 3: System architecture of the multimodal teleoperation concept: haptic driving [15] and manipulation [9] using sigma.7.

2. MULTIMODAL TELEOPERATION CONCEPT

2.1. System Architecture

Our proposed system architecture is illustrated in Fig. 3. With the presented approach, the operator can select two multimodal operations implemented for the sigma.7 device: (1) haptic manipulation (e.g., rock-picking shown in Fig. 2), where the operator controls the robotic manipulator of the Interact rover and receives haptic feedback regarding contact forces between the end-effector and the remote environment, and (2) haptic driving, where the operator controls the rover's locomotion and can feel, on the hand, the haptic feedback regarding the rover's inclination (pitch and roll) and traction losses (vibration). Additionally, the GUI provides visual information regarding telemetry from the rover and confirmation regarding the currently active operation mode (see Fig.4 and 5).

The communication between the rover and Operator Control Unit (OCU) was implemented using the Data Distribution Service (DDS™) standard and RTI Connext® software to implement this standard. Finally, all functional blocks of the OCU, except the GUI, resorted to MATLAB Simulink®. Integrating the sigma.7 device into the teleoperation control was performed with a custom-built Simulink block that wraps functionalities of the Force Dimension SDK[1].

Finally, we separately developed and evaluated the components "Haptic Manipulation" (Section 2.3) and "Haptic Driving" (Section 2.4) of the system architecture (Fig. 3). In this paper, we present the integration of the "Haptic Driving" component into the system architecture used in the ANALOG-1 experiments. We replace the previous control of the rover with the standard joystick with the haptic driving module to control the rover and receive haptic feedback regarding its state. The first iteration of haptic driving was introduced and systematically evaluated in [15]. In this paper, we expand this validated component by integrating haptic feedback regarding traction

---

[1] https://www.forcedimension.com/software/sdk [last accessed September 2023]

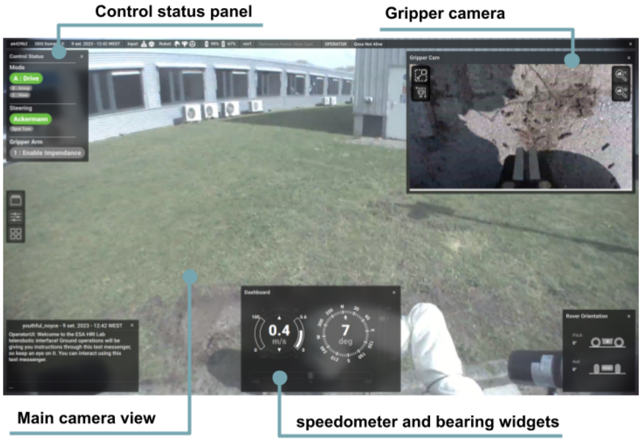


Figure 4: GUI for teleoperation with confirmation of the operation mode.

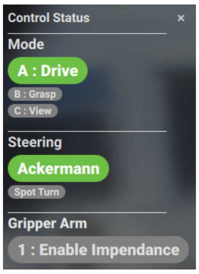


Figure 5: Highlight of the control status panel: visual confirmation of the operation mode (drive, grasp or view)

losses (section 2.4.2) and dead-band awareness (section 2.4.3).

2.2. System Hardware

The hardware of the proposed teleoperation architecture is shown in Figs. 1 and 2. The teleoperation setup is currently deployed in the ISS and includes: (1) a laptop with a Graphical User Interface (GUI), where the astronaut receives telemetry and can interact with the interface to visualize the relevant information and trigger robot actions (e.g., autonomous rock picking), (2) a costume made joystick control station with a standard joystick and 7 buttons, including an “enable” button, and (3) the sigma.7 device, a 7-DoF bilateral haptic device (6-DoF in the cartesian space and 1-DoF for the gripper). On the remote side, the Interact rover, shown in Fig. 2 (four-wheel-steering platform), has a robotic arm that the astronaut can remotely operate (e.g., rock picking or remote sensor handling).

2.3. Haptic Manipulation

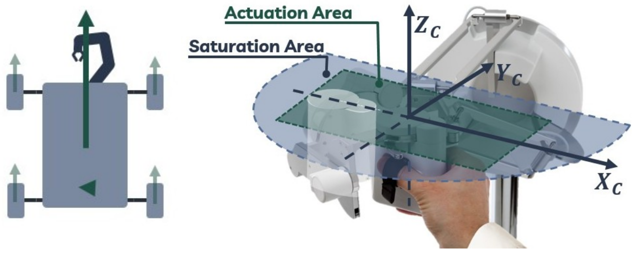
With the “Haptic Manipulation” component, the astronaut uses the sigma.7 to control the remote robotic arm to perform manipulation tasks, such as collecting rock samples. During these interactions, the astronaut can feel, on the sigma.7 device, the contact forces between the remote arm and its surrounding environment. The formal description of this implementation can be found in [9]. The implemented approach ensures a safe, stable, and transparent space teleoperation and results of the 6-DoF closed-loop telemanipulation with force feedback from a spacecraft to the ground [9, 10].

This implementation was demonstrated and evaluated during the ANALOG-1 experiments [9, 10]. These showcased the feasibility of a complete space exploration scenario via haptic telemanipulation under spaceflight conditions. Results showed the benefits of this control method for safe and accurate interactions and haptic feedback in general. Moreover, the subjective ratings of the astronaut indicate a low overall workload and that the control is intuitive and provides a sufficiently natural feeling of interaction.

2.4. Haptic Driving

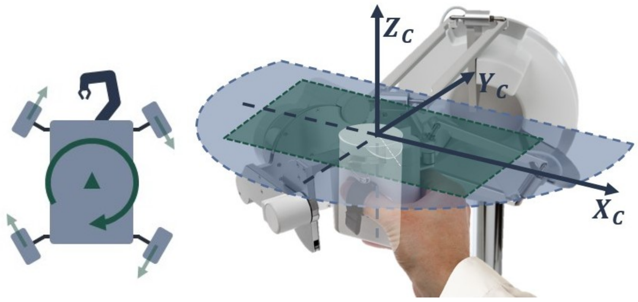
The “Haptic Driving” component, implemented on the sigma.7, provides a driving functionality by implementing a spring behavior similar to conventional joysticks. Furthermore, this component integrates relevant feedback during driving tasks in the haptic device. This is, the operator can move the sigma.7 within a horizontal plane from its centre position to move the rover (see Fig. 8), and when released, the device returns to its central position, and the rover stops. The implemented spring-mass-damper system in the sigma.7 is formally described in [15]. With this approach, the operator can push the sigma.7 forward, backwards, sideways, and rotate the wrist to achieve all the navigation motions available for the Interact rover: Ackerman and spot-turn motions (see Fig. 8 and 7). Additionally, the operator can feel the spatial orientation of the rover and its traction in the device, described in sections 2.4.1 and 2.4.2, respectively.

The driving functionality of the “Haptic Driving” module was systematically evaluated through a series of ground tests [15]. This evaluation validated sigma.7 as an effective control device with no detriment to the rover’s manoeuvrability compared to a conventional joystick.



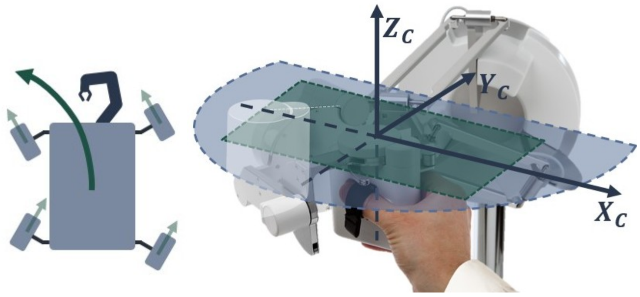
(a) Rover motion (b) Sigma.7 motion.

Figure 6: Forward motion with sigma.7 and actuation and saturation areas [15].



(a) Rover motion (b) Sigma.7 motion.

Figure 7: Spot-turn steering with sigma.7.



(a) Rover motion (b) Sigma.7 motion.

Figure 8: Double ackerman steering with sigma.7.

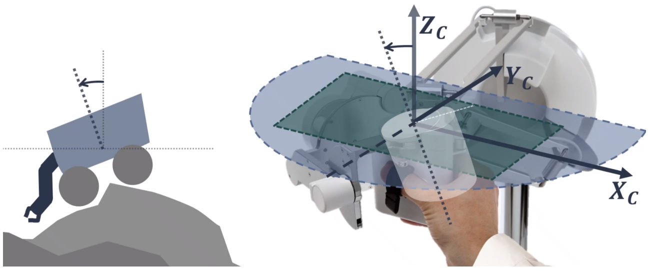


Figure 9: Illustration of the rover's inclination display with sigma.7 (pitch component).

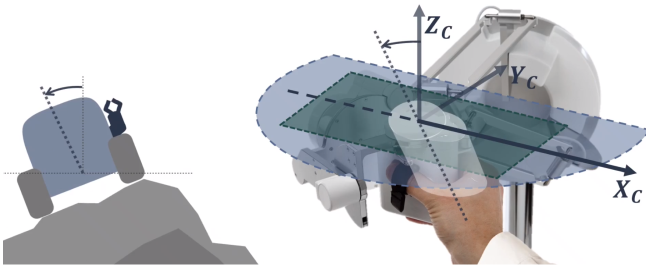


Figure 10: Illustration of the rover's inclination display with sigma.7 (roll component).

2.4.1. Attitude Feedback

To the driving functionality implemented with sigma.7, we added proprioceptive cues such that the operator can feel the rover's attitude (pitch and roll) on her/his hand (see Fig. 9 and 10). During driving tasks in unstructured environments, visual cues are often insufficient to provide adequate SA to the operator, and haptic cues have been shown to be an effective feedback method to address this shortcoming [18]. The implemented attitude feedback presents an alternative to the standard visual attitude indicator and conveys the rover's attitude more intuitively.

To provide situational awareness regarding the rover's attitude, the sigma.7 tilts to reproduce the rover's current roll (Fig. 10) and pitch (Fig. 9). This is achieved by dynamically modifying the orientation (pitch and roll) of the sigma.7 handle during the driving tasks.

A systematic evaluation validated the attitude feedback with the sigma.7 as an effective method to offload the attitude information from the GUI [15]. When using haptic feedback, users often reported which of the four wheels was on the curb, indicating a comprehensive knowledge of the rover's attitude.

2.4.2. Traction Feedback

After validating the haptic driving (motion commands with attitude feedback), we explored the integration of vibration cues in the system to convey the rover's traction losses. This presents a novel approach as, typically, one haptic device only conveys one type of haptic stimuli. With this approach, we intend to create a more immersive experience during the rover teleoperation in a way that the operator perceives the remote rover and its environment in a more natural way, compared to the use of various visual indicators in the GUI.

However, integrating multiple feedback stimuli into a single device must be carefully designed to ensure a clear distinction between them and avoid overloading the user with too much information through the haptic sense. Here, we follow a user-centred approach, where we designed the vibration feedback and performed performed preliminary tests with several novice users (Section 3).

Our preliminary design of the traction feedback on the sigma.7 device builds upon our previous work regarding traction detection and vibration feedback with a costume-made wearable traction glove [19]. Here, we systematically verified that vibration cues significantly improved the SA of the operator. Thus, the first step to integrate these cues in the "haptic driving" module of the system architecture was to render vibration cues with the force feedback device.

Given the implemented spring-damper model on the sigma.7 with a goal position in the centre of the cartesian space of the device, the vibration cues are rendered by adding a high-frequency variation in the z-axis. The design choice of having a directional vibration in the z-axis was motivated by two main factors. First, the vibration feedback is decoupled from the DoFs used as an input source for the rover's control (x and y axis). Second, the feedback tries to replicate the sensation the op-

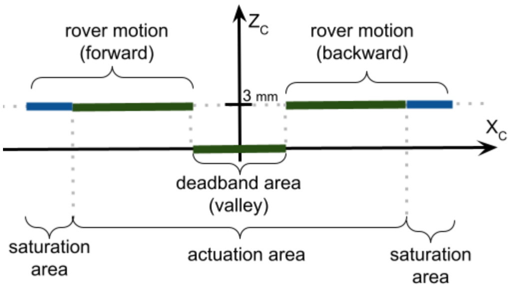


Figure 11: Illustration of the designed deadband feedback: vertical position of sigma.7 is higher outside the deadband area (example for the x-axis, X_C).

erator would feel if (s)he was onboard the rover when it got stuck, i.e., vertical trembling.

After an iteration process, we implemented a vibration with a frequency of $20Hz$ and an amplitude of $1mm$. On the one hand, the high frequency provided a clear vibration stimulus while holding the sigma.7. On the other hand, the small amplitude of vibration avoided an apparent instability of the device. In force feedback devices, high amplitude vibrations are often associated with system instability and cause operator nervousness.

2.4.3. Deadband Feedback

Finally, during the implementation of the "haptic driving" module, it was necessary to implement a deadband region where the velocity command sent to the rover is zero [15]. The definition of this region was experimentally determined such that only significant motions of the sigma.7 map onto rover motion. However, during the systematic evaluation of the module, participants often pulled the device left (closer to their body and visual interface; see Fig. 13) without noticing they were outside the defined deadband. This led to a rotation component in the robot's trajectory that needed compensation (small wrist rotations) to maintain the intended rover motion.

To address this issue, we integrate a new haptic feedback modality to the driving module such that the operator can feel when the sigma handle is outside of the defined deadband. We designed the deadband area to feel like a valley (see Fig. 11), and only when the sigma.7 reaches a higher step (3 mm) does it cause a rover motion.

3. PRELIMINARY USER TEST

3.1. User Test Setup

An initial evaluation of the integrated system was conducted to obtain feedback about the usability of the integrated system and the new feedback modalities (traction and deadband). In a semi-public setting (people with access to ESTEC campus), we performed an informal demonstration where inexperienced users interacted with the teleoperation system. Given the informal setting of the demonstration, users were not asked for any demographic information. Therefore, we cannot characterize the testing population quantitatively, yet we can report that approximately 20 young adults participated in this preliminary user test.

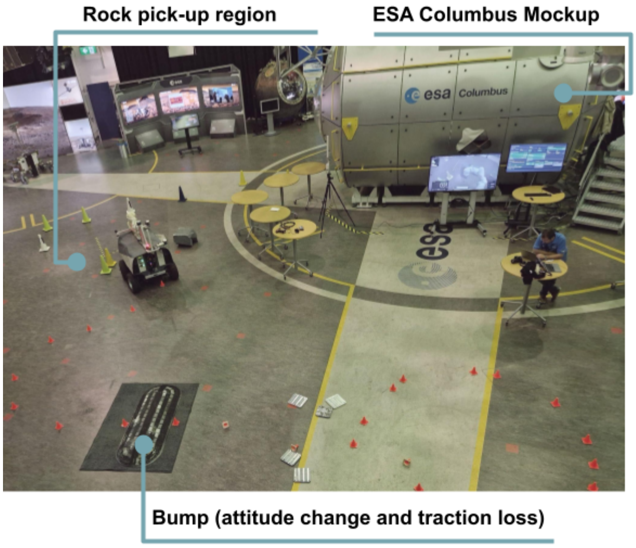


Figure 12: Overview of the testing scenario: predefined path, bump and rock samples for collection.

The teleoperation setup presented in this paper was deployed inside the ESA Columbus Mockup (see Fig. 1), located at ESTEC Erasmus High Bay, in the Netherlands. This presented the users with a visually realistic environment (the inside of the ISS). The Interact rover was placed on an open area (see Fig. 2) with a pre-defined path (orange markers in Fig. 12) that ensured different steering capabilities of the rover, changes in attitude (road bump) and a rock picking task. Such scenario presented a challenge that involved both driving and manipulation with the sigma.7.

Each user received a demonstration on how to interact with the system, including how to: (1) switch between the operation modes, (2) move the sigma.7 to drive the rover, and (3) move the sigma.7 to control the robotic arm. Then, they were instructed to follow the path marked on the floor until they reach a region with rocks, where they should pick up one and store it on the sample tray of the rover. Given the testing scenario (flat floor with high traction) traction losses were not very common. Thus, to feel the traction feedback, users received the suggestion to do a spot-turn with the rover while this one was on top of the road bump. This motion increased the chances of the users feeling the traction loss feedback (vibration).

3.2. Preliminary Results and Discussion

Following a user-centred approach, this preliminary user test sought to involve inexperienced users to understand

Figure 13: Operator controlling the rover with sigma.7 during the preliminary user test.

if the feedback modalities are effective and identify the system's shortcomings. Qualitative observation showed that users quickly learned to interact with the teleoperation system, switch operation modes, and control the remote rover and robotic arm with the sigma.7 device. All participants successfully completed the given task. Users often reported that the haptic feedback modalities were clear and intuitive and provided a good awareness of the rover's state.

Regarding the system shortcomings, we observed some patterns in user behaviour and interactions that should be taken into consideration in subsequent system iterations:

- When users switched to the camera control to adjust the camera perspective ("view" option in the interface control panel; Fig.4), they expected that the sigma.7 device would also allow them to control the camera view. They were confused until they remembered that they needed to switch to the joystick.
- Occasionally, people misinterpreted the deadband feedback as a traction loss. It most likely happened because both the traction and deadband feedback caused a vertical motion of sigma.7. Consequently, we infer that the implemented deadband valley might not be appropriate to convey deadband awareness in the system with traction cues clearly and should undergo a redesign process.

4. CONCLUSIONS

In this paper, we presented a multimodal teleoperation concept that integrated of a novel module for haptic driving (robot steering with attitude and traction feedback) into the teleoperation system used during ANALOG-1 experiments on the ISS. With the new haptic driving component the operator can use a 7-DoF force feedback device to steer a remote rover while, at the same time, receiving haptic feedback regarding the rover status. The haptic feedback during driving tasks included: attitude of the rover (pitch and roll) and traction losses. These were conveyed to the operator using two distinct haptic stimuli: proprioceptive cues to convey attitude, and vibration cues to convey traction losses.

Additionally, we presented the system architecture that allows the operator to easily switch between different operation modes designed for the sigma.7 device: haptic driving and manipulation. Finally, we performed a preliminary user test to assess the usability of the integrated system. During these tests, users were quick to learn how to interact with the teleoperation system, successfully completed a driving and manipulation task with the sigma.7, and described the haptic feedback modalities as clear and intuitive. Observed shortcomings of the system included momentary confusion of the operators when they needed to use a conventional joystick to move the onboard camera and interpretation of the deadband of the steering input device (sigma.7). This user feedback will be taken into consideration in future iterations of the multimodal teleoperation system.

ACKNOWLEDGMENTS

This work was supported by Fundação para a Ciência e Tecnologia (FCT, Portugal), through PhD Grant PD/BD/150634/2020, FCT Projects UIDB/50009/2020, UIDB/04466/2020 and UIDP/04466/2020, "Aero.Next Portugal" project, and was part of the ESA TDE (Technology Development Element) 4000136200/0/0/0 WP2021.

REFERENCES

[1] Schreckenghost, Debra, et al. "Measuring robot performance in real-time for nasa robotic reconnaissance operations." In Proceedings of the 9th Workshop on Performance Metrics for Intelligent Systems, 2009.

[2] Burns, Jack O., et al. "Science on the lunar surface facilitated by low latency telerobotics from a Lunar Orbital Platform-Gateway." Acta Astronautica 154 (2019): 195-203.

[3] Bualat, Maria, et al. "Results from testing crew-controlled surface telerobotics on the International Space Station." iSAIRAS-International Symposium on Artificial Intelligence, Robotics and Automation in Space. No. ARC-E-DAA-TN14584. 2014.

[4] Birkenkampf, Peter, Daniel Leidner, and Christoph Borst. "A knowledge-driven shared autonomy human-robot interface for tablet computers." 2014 IEEE-RAS International Conference on Humanoid Robots. IEEE, 2014.

[5] Lii, Neal Y., et al. "Command robots from orbit with supervised autonomy: An introduction to the meteron supvis-justin experiment." Proceedings of the Tenth Annual ACM/IEEE International Conference on Human-Robot Interaction Extended Abstracts. 2015.

[6] Rankin, Arturo, et al. “Driving curiosity: Mars rover mobility trends during the first seven years.” 2020 IEEE Aerospace Conference, 2020.

[7] Luz, Rute, José Luís Silva, and Rodrigo Ventura. ”Enhanced teleoperation interfaces for multi-second latency conditions: System design and evaluation.” IEEE Access 11 (2023): 10935-10953.

[8] Schmaus, Peter, et al. ”Continued advances in supervised autonomy user interface design for meteron supvis justin.” 2019 IEEE Aerospace Conference. IEEE, 2019.

[9] Panzirsch, Michael, et al. ”Exploring planet geology through force-feedback telemanipulation from orbit.” Science Robotics, 2022.

[10] Krueger, Thomas, et al. “Designing and Testing a Robotic Avatar for Space-to-Ground Teleoperation: the Developers’ Insights.” 71st International Astronautical Congress. 2020.

[11] Wedler, Armin, et al. ”Finally! insights into the arches lunar planetary exploration analogue campaign on etna in summer 2022.” 73rd International Astronautical Congress, IAC 2022. 2022.

[12] Lii, Neal Yi-Sheng, et al. ”Introduction to Surface Avatar: the First Heterogeneous Robotic Team to be Commanded with Scalable Autonomy from the ISS.” Proceedings of the International Astronautical Congress, IAC. International Astronautical Federation, IAF, 2022.

[13] Wormnes, Kjetil, et al. ”ANALOG-1 ISS–The first part of an analogue mission to guide ESA’s robotic moon exploration efforts.” Open Astronomy 31.1 (2022): 5-14.

[14] Fong, Terrence, et al. “The Human Exploration Telerobotics project: objectives, approach, and testing.” 2012 IEEE Aerospace Conference, 2012.

[15] Luz, Rute, et al. “Feeling the Slope? Teleoperation of a mobile robot using a 7DOF haptic device with attitude feedback” 32nd IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN), 2023 [in press]

[16] Huang, Ya, et al. ”Recent advances in multi-mode haptic feedback technologies towards wearable interfaces.” Materials Today Physics 22 (2022): 100602.

[17] Keef, Colin V., et al. ”Virtual texture generated using elastomeric conductive block copolymer in a wireless multimodal haptic glove.” Advanced Intelligent Systems 2.4 (2020): 2000018.

[18] Corujeira, J., José Luís Silva, and Rodrigo Ventura. ”Attitude perception of an unmanned ground vehicle using an attitude haptic feedback device.” 2018 27th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN). IEEE, 2018.

[19] Luz, Rute, et al. ”Traction awareness through haptic feedback for the teleoperation of UGVs.” 2018 27th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN). IEEE, 2018.