ENHANCED HAPTIC INTERFACE FOR ROVER TELEOPERATION

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ABSTRACT

A well know challenge in rover teleoperation is the lack of situational awareness of the operator. This often leads to an erroneous perception of the status of the rover and its surrounding environment and, consequently, lead to faulty decision making. We conceptualise a novel teleoperation method to drive a rover in the context of planetary exploration. The proposed teleoperation interface employs a force feedback device to control the navigation of a rover while providing haptic feedback to ensure the operator's appropriate situational awareness. In particular, we will design and iterate proprioceptive cues (e.g. to convey the rover's attitude) and vibratory cues (e.g. to convey traction losses of the rover's wheels) to enhance the situational awareness of the astronaut. Finally, the implemented rover control and feedback will be systematically evaluated and iterated through user studies using a real robot in an analog environment.

Key words: haptics, robotics, teleoperation, proprioception, vibration.

1. INTRODUCTION

Planetary missions often resort to teleoperated robotic systems with different levels of onboard autonomy. Robotic platforms on the surface of Mars, for example, require several autonomy components to ensure safety and task completion. Yet, unexpected events can occur (e.g. a rover's wheels getting stuck [1]) that these autonomy components fail to resolve [2]. Additionally, navigation on a planetary surface involves complex tasks and decision-making processes that current state of the art autonomy does not fully address. Such cases often require human intervention through direct teleoperation.

Furthermore, adding human cognitive skills to the control loop through direct teleoperation could provide more effective and valuable scientific data [3, 4]. For example, Fong [5] reported that scouting missions were more successful when operators could manually control a rover compared to autonomous navigation. Hence, a central challenge is understanding how humans and robots can work efficiently and effectively together to maximize performance, crew safety, scientific return, and mission success [4, 5].

To ensure appropriate decision making, the operator should have a comprehensive Situational Awareness (SA) regarding the robot state and its surrounding environment. SA is highly dependent on the teleoperation interface as this is the only connecting link to compensate for the physical detachment between operator and remote robot. Thus, investigating ergonomic and efficient teleoperation interfaces for robotic systems in the context of planetary exploration is crucial.

Conventional teleoperation interfaces often convey a vast amount of visual information to the operator. Such an approach may lead to an increase in the operator workload and difficulty acquiring the relevant information. One way to reduce the cognitive load on the human visual channel is by resorting to haptic feedback during teleoperation. Providing haptic cues during robot teleoperation can significantly improve the detection of faults [6], reduce task difficulty and create a greater sense of operator immersion in the remote environment [7]. In particular, unstructured environments with poor lighting conditions (e.g. Moon surface) can lead to navigation shortcomings such as traction losses and hazardous orientations that can be effectively conveyed, to the operator, through haptic feedback [8, 9].

2. RELATED WORK

Current planetary exploration still relies on ground control operations to assess situations and plan for the following actions [10]. However, future planetary exploration will allow for low latency telerobotics and incorporate human cognitive skills in the control of ground rovers, through direct teleoperation. The literature on this problem reveals two broad approaches for future planetary exploration that will enable low-latency telerobotics. One approach is having astronauts teleoperating the robot from a planetary base station [11, 12]. The other approach is having astronauts teleoperate the surface robot from an orbiting spacecraft [13].

In particular, ESA and NASA are currently working on complementary initiatives that aim to validate low latency technologies through a range of ground and flight experiments with humans and robots in the loop [14]. Multi-Purpose End-To-End Robotic Operations Network (METERON) [13] and Human Lunar Exploration Precursor Project (HLEPP) [15], from ESA, and Human Exploration Telerobotics (HET) [3] and Deep Space Gateway (DSG) [16, 4] from NASA, are currently undertaking enterprises that aim to validate crew-controlled communications, operations, and telerobotic technologies [14, 5]. Moreover, since the DSG will not be manned year-round, it will also serve as a communication relay between ground assets on the lunar farside and Earth command stations [17, 18]. These technologies will provide an opportunity for novel and more effective interaction methods between humans and robotic platforms for planetary exploration.

A series of experiments and validation of technologies for low latency telerobotics have been performed during the past few years on the International Space Station (ISS). These experiments investigated mainly two topics: (1) the use of force feedback devices for manipulation tasks and (2) supervisory control of ground robots. Yet, direct teleoperation of ground rovers has been mainly limited to the use of joysticks and dedicated Graphical User Interfaces (GUIs).

Experiments validating and studying force feedback devices include the Haptics-2 experiment [19], which showed the feasibility of performing haptic interactions between humans from space to the ground. Additionally, Artigas [20] used a novel 2-DOF robot controller, KONTUR-2 [21], to teleoperate a robot manipulator on the ground. And more recently, the ANALOG-1 experiment [22, 23] successfully used a 7-DOF haptic input device, sigma.7[1] from Force Dimension, to perform a manipulation task on the ground from the ISS. Because this device is still available on the ISS, there is an opportunity to advance the current state of the art by building on top of this validated technology and explore novel telerobotics strategies for future planetary exploration.

Moreover, further experiments on the ISS have shown that supervisory control is an efficient method for future crew-centered teleoperation. Schmaus [13, 24] presented the results of the METERON SUPVIS Justin space telerobotics experiment suite, where astronauts onboard the ISS commanded a dexterous humanoid service robot on Earth to execute complex surveillance, service, and repair tasks in a simulated Martian environment. Fong [4, 25] and Bualat [26, 27] also performed a set of experiments where astronauts teleoperated NASA's K10 rover on Earth. Here, the astronauts used supervisory control (command sequencing with interactive monitoring) and teleoperation (discrete commanding) to operate K10 in a lunar analog terrain.

The described experiments demonstrated that when using a supervisory control method, astronauts can maintain appropriate SA with a low effort and workload while ensuring overall mission success. Nevertheless, there are often events that current state of the art autonomy fails to solve and requires human intervention through direct teleoperation. Schreckenghost [2] showed that, during an autonomous recon mission, humans had to spend a significant amount of time handling anomalies that interrupted robot activity. On average, operators had to intervene every 24 minutes (minimum: 5.5 min, to maximum: 1 h) and each intervention was on average 5.6 minutes (minimum: 1.6 min to maximum: 17.9 min).

Future telerobotics systems should allow for direct teleoperation in such a way that crew members can perform low-level commands (e.g. wheel motion) while maintaining appropriate SA. When designing and implementing these direct teleoperation interfaces it is necessary to consider the context specific needs. For ground rovers in the context of planetary exploration, it is necessary to convey to the operator appropriate SA of the robot status and any possible mobility faults. The latter are often unexpected events that onboard current state of the art autonomy still fails to solve and require human cognitive and dexterous skills to solve [2].

Unexpected anomalies that might compromise the mobility of the rover in the context of planetary exploration include: limited perception of the remote environment (e.g. low lighting conditions), dangerous inclinations of the rover, wheel entrapment, progressive wheel sinkage, and hardware or cabling failures [1, 10, 28]. In particular, Rankin [1] reports that during the first seven years of its mission, Curiosity Rover encountered 11 drive faults due to excessive wheel slip. Thus, to ensure efficient decision making, the operator should have a comprehensive SA of the rover status and its interaction with the remote environment.

There are several applications on Earth (e.g. search and rescue [29]) that have successfully resorted to force feedback to devices to control a mobile robot and provide appropriate SA regarding collision avoidance [30, 31], delay perception [32], wireless signal strength [33], and goal following indications [29]. Yet, to the best of our knowledge, there is no approach in the literature exploring a force feedback device to control a ground robot while conveying haptic information regarding its attitude and traction.

Based on the presented literature review and known limitations of state of the art autonomy, we conceptualise a teleoperation interface to drive a ground rover using a force feedback device capable of emulating proprioceptive cues (e.g. to convey the rover's attitude) and vibratory cues (e.g. to convey traction losses of the rover's wheels) to enhance the situational awareness of the astronaut. The proposed work intends to advance the current

[1] https://www.forcedimension.com/products/sigma (acccessed May 2, 2022)

Figure 1. Setup for ANALOG-1 teleoperation experiment [23]: Mobile robot platform on ground with robot manipulators.

Figure 2. Setup for ANALOG-1 teleoperation experiment [23]: robot control terminal on board the ISS with laptop, joystick (bottom left) and sigma.7 device (bottom right).

state of the art by systematically developing and evaluating a teleoperation interface, as well as provide valuable insights for future development of teleoperation interfaces for planetary exploration.

3. PROPOSED TELEOPERATION CONCEPT

3.1. Haptic Control of the Rover

The 7-DOF haptic input device sigma.7 from Force Dimension (see Fig. 3) has been used to control a robotic manipulator on ground from the ISS with force feedback, in the ANALOG-1 experiment [22, 23]. In this experiment, the manipulator was mounted on a mobile platform (rover), which could be controlled in Ackermann steering or make spot-turns. With these steering possibilities, the rover can achieve a greater variety of motions compared to a traditional differential drive approach. During the ANALOG-1 experiment, the astronaut controlled the rover's movement with a 3-axis joystick without force feedback. Thus, all telemetry information was conveyed to the operator through the visual interface. The setup of the experiment can be seen in Fig. 1 and 2.

We build upon this setup, to enhance the operator's situational awareness and avoid overloading the visual interface. Thus, the sigma.7 could be used to navigate the rover and receive haptic feedback. Yet, due to the limited available actuation area of the sigma.7, it should have a spring-like behaviour, similarly to mainstream joysticks. With this approach, sigma.7 responds to human actuation by trying to return to a neutral position.

When developing new control methods, the mapping between human actuation and robot motion should be carefully designed and iterated. Empirical observation shows that operators often become frustrated when they perceive their mental mapping between the joystick actuation and the robot movement as incorrect, and they need to readjust their mental models. For the proposed haptic teleoperation interface, the initial design of the haptic control will involve a direct mapping between the motion of the sigma.7 and the rover in the different degrees of freedom. Yet, given the 7-DOF of the sigma.7, there is some freedom for experimenting with various mappings between human actuation and rover's motion. Therefore, the testing and iteration process will be crucial to determine the most intuitive and efficient control method.

3.2. Haptic Feedback: Attitude and Traction

Force feedback devices in teleoperation mainly focus on providing contact forces for manipulation tasks. Yet, previous results by some of the authors have shown that providing proprioceptive cues to convey the rover's attitude [9] and vibratory cues to convey its traction state [8] can significantly improve the SA of the operator.

Corujeira et al. [9] proposed a novel attitude haptic feedback device that provides information about the roll and pitch of a ground robot, through the use of upper limb proprioception. By holding this device with the hand (see Fig. 4), the operator can feel the pitch and roll of the rover on the remote environment. Luz et al. [8] presented a wearable device to generate different vibration patterns depending on the traction state (nominal, stuck

Figure 3. Operator holding the 7-DOF haptic input device sigma.7 from Force Dimension[1].

Figure 4. Setup for MEROP experiment during AMADEE-20 Mars Analog Mission [34]: analog astronaut teloperating a ground rover outside of the habitat with a joystick (right hand), attitude device [9] (left hand), and traction glove [8] (right hand).

and sliding) of the ground robot. The operator can wear the device (glove in Fig. 4) and feel the vibration patterns on the palm of the hand when the robot loses traction. Both haptic devices were successfully integrated into a multimodal teleoperation interface as part of the MEROP experiment (see Fig. 4), during the AMADEE-20 Mars Analog Mission [34].

The proposed haptic interface will resort to sigma.7 to emulate proprioceptive and vibratory cues during the rover's navigation. The operators will perceive the haptic feedback as they are sending locomotion commands to the rover with the sigma.7. Different haptic patterns will be explored and iterated to convey the rover status. For example, employing a vibration pattern with sigma.7 when the rover loses traction or rotating the manipulator held by the astronaut as the rover is reaching a precarious orientation. With the proposed haptic feedback, the operator can be aware of when the rover is reaching hazardous states and adjust the locomotion controls accordingly.

3.3. System Architecture

Fig. 5 shows the system architecture for the proposed teleoperation interface. From the remote environment, the Rover broadcasts the image from the onboard cameras and telemetry data. The camera's image stream is displayed on the Visual Interface, while the telemetry data is processed (Telemetry Processing) to obtain relevant information regarding the rover status (e.g. traction and attitude). From the telemetry data, IMU (inertial measurement unit) data is used to obtain the attitude of the rover,, while the traction uses two independent sources of position estimation (e.g. wheel odometry, visual odometry). With the rover status information, the Haptic Rendering module estimates the necessary force and torque to emulate the proprioceptive and vibration cues (described in Section 3.2) that are conveyed to the operator. While

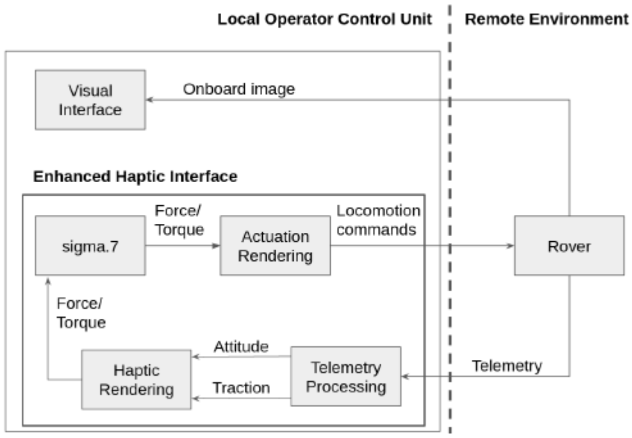

Figure 5. System architecture for the proposed teleoperation interface.

holding sigma.7, the operator can feel the haptic feedback and apply a force to drive the rover. The force applied is used by the Actuation Rendering module to map between human actuation and rover locomotion commands (described in Section 3.1). Finally, the locomotion commands are sent to the rover, closing the control loop.

One of the main contributions of the proposed teleoperation interface to the current state of the art is the systematic development of the two modules Haptic Rendering and Actuation Rendering. Systematically studying the appropriate and efficient feedback and actuation methods will provide valuable data for future planetary exploration.

3.4. Evaluation

The proposed haptic interface will be incrementally and systematically evaluated. First, the haptic and non-haptic controls will be compared through a series of pilot tests where the rover is not in line-of-sight of the operator. The results from these pilot tests will provide early insights that will be critical to identifying and iterating any shortcomings of the initial design. Second, once the attitude and traction feedback is integrated with the validated control method, additional pilot tests will be required to ensure the effectiveness and ease of use of the haptic feedback. Third, a final systematic user study will evaluate the integrated haptic interface in analog scenarios. By conducting a thorough user study in realistic scenarios, we expect to identify aspects of haptic feedback which measurably improve performance for an astronaut teleoperating a rover.

4. CONCLUSIONS

In this paper, we proposed an enhanced haptic interface for direct teleoperation of a ground rover in the context of planetary exploration. The conceptualised approach resorts to 7-DOF haptic input device sigma.7 (currently installed in the ISS) to control a rover while receiving haptic feedback. First, the sigma.7 will be used to iterate and determine the most intuitive and efficient control method. This process will have to be carefully developed to ensure that the implemented control method can be easily learned and used by the operators without causing additional workload or frustration to the teleoperation process. Second, the sigma.7 device will be used to iteratively design the proprioceptive and vibratory cues that can effectively convey the status of the rover (e.g. traction and attitude) to the astronaut. Thus, ensuring a comprehensive situational awareness and adequate decision making of the astronauts during teleoperation. Third, we presented the system architecture that will integrate the proposed control and feedback methods with a ground rover to achieve a novel haptic teleoperation interface. Finally, we presented the planned evaluation methodology that will allows us to systematically test and iterate ergonomic and efficient control and feedback methods for the direct teleoperation of a rover in the context of planetary exploration. Through the series of proposed user studies in analog scenarios, we expect to quantify and identify aspects of haptic feedback that enhance the performance of an astronaut during teleoperation and increase the likelihood of task success.

Future work will include the implementation and evaluation of the conceptualised teleoperation architecture, as well as the report of the results and lessons learned from the systematic user studies. The insights from this project will be crucial for the development of haptic interfaces to intuitively control robotic assets on planetary surfaces for exploration, development and ISRU (In-Situ Resource Utilization).

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