Feeling the Slope? Teleoperation of a mobile robot using a 7DOF haptic device with attitude feedback

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***Abstract*— A well-known challenge in rover teleoperation is the operator's lack of situational awareness (SA). This often leads to an inaccurate perception of the rover's status and surroundings and, consequently, to faulty decision-making by the operator. We present a novel teleoperation interface to control the locomotion of a ground rover with a 7DOF force feedback device (sigma.7), while providing haptic feedback to ensure appropriate SA. In particular, the device provides proprioceptive cues to convey the rover's attitude. This can be particularly useful for environments with insufficient visual cues to estimate attitude (e.g., a cave). In systematic experimental trials controlling a robot in an outdoor environment, we evaluated the validity of employing sigma.7 as an alternative to a standard joystick. We tested the use of attitude as an aid to situational awareness. We found no significant detriment in manoeuvrability compared to a conventional joystick, thus validating the sigma.7 as an effective control device. Regarding SA, results showed no statistical difference between the visual and haptic cues for attitude feedback, thus validating the haptic method as an effective alternative to offloading the visual channel by conveying attitude information through the haptic channel instead of visual cues. Finally, qualitative observations of the participant's behaviour during the experiments showed that operators with haptic feedback were comprehensively aware of the rover's status.**

I. Introduction

Locomotion in unstructured environments with limited visibility (e.g., Moon surface or caves on Mars) 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, enabled by low-latency telerobotics. For remotely operated rovers, it is essential to convey appropriate Situational Awareness (SA) to the operator regarding the robot's status and any possible mobility faults. The latter are often unexpected events that onboard state-of-the-art autonomy still fails to solve and requires human cognitive and dexterous skills, through direct teleoperation [1]. Validation of low latency operations provides an opportunity for novel and more effective interaction methods between humans and robotic platforms in future planetary operations that acquire valuable scientific data [2]. For example, Fong [3] reported that scouting missions were more successful when operators

* This work involved human subjects in its research. All ethical and experimental procedures and protocols were performed following the guidelines of the Ethics Committee of Instituto Superior Técnico (CE-IST).

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Fig. 1: Interact rover: four-wheel-steering mobile platform [4].

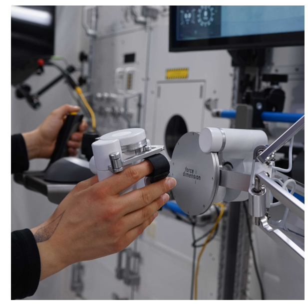

Fig. 2: Operator holding sigma.7 device while it displays the rover's pitch.

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 overall mission success.

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 [4] and (2) supervisory control of ground robots [5]. Yet, direct teleoperation of ground rovers locomotion has been mainly limited to the use of joysticks and dedicated Graphical User Interfaces (GUIs). We propose a novel teleoperation approach to control the locomotion of a ground rover (see Fig. 1) with 7DOF force feedback device (sigma.7, Fig. 2) that provides attitude feedback to ensure appropriate operator's SA.

To ensure adequate decision-making, the operator should have a comprehensive SA regarding the robot's state and surrounding environment. SA is highly dependent on the teleoperation interface as this is the only connecting link to compensate for the physical detachment between the operator and the remote robot. Field experiments have shown that operators often struggle to acquire and maintain adequate SA during teleoperation [6]. This can often lead to disorientation and cognitive mistakes (e.g., decision-making), and negatively impact overall performance during field missions [7]. Therefore, investigating efficient teleoperation interfaces for robotic systems is crucial to ensure overall task success.

Conventional teleoperation interfaces often convey a vast amount of visual information to the operator. Such an approach can lead to an increase in the operator workload and difficulty acquiring the relevant information. One way to

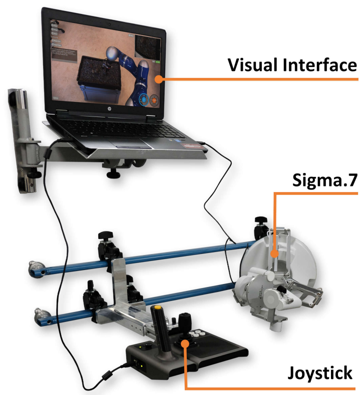

Fig. 3: Setup for ANALOG-1 teleoperation experiment [4].

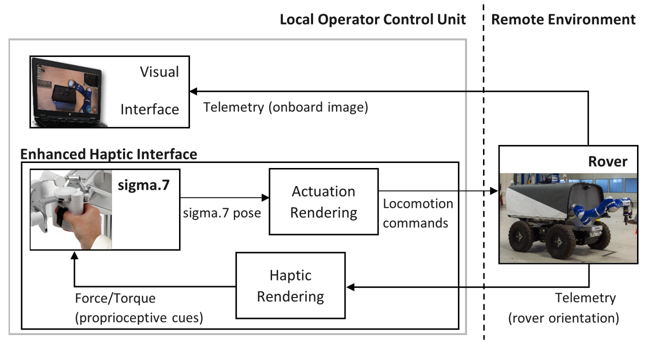

Fig. 4: System architecture and its main components: *"haptic rendering"*, *"sigma.7"*, and *"actuation rendering"*.

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 [8], reduce task difficulty and create a greater sense of operator immersion [9]. Finally, unstructured environments with poor lighting conditions (e.g. Moon surface) can lead to navigation shortcomings such as hazardous orientations that can be effectively conveyed through haptic feedback [10]. Corujeira [10] presented a handheld passive haptic device to provide proprioceptive cues regarding the attitude of a remotely operated rover. Results of the systematic user study revealed that participants successfully perceived the attitude states (stable, unstable and critical) and direction of rotation. However, this device only conveys feedback and did not allow to the control of the robot. In this paper, we propose a novel teleoperation system that uses a 7DOF force feedback haptic device that allows the operator to control the locomotion of a mobile rover while receiving haptic attitude feedback.

This work's contributions are three-fold. First, the teleoperation system implements a joystick-like behaviour in a 7DOF device (sigma.7) to control the locomotion of a ground rover. Second, the teleoperation system integrates proprioceptive cues to convey the rover's attitude (pitch and roll) using a bilateral force feedback haptic device commonly used for manipulation tasks [11]. The current literature on robot locomotion mainly employs force feedback devices to convey information regarding collision avoidance [12], wireless signal strength [13], or goal-following indications [13]. However, current literature does not study a force feedback device to drive a ground robot while conveying haptic information regarding its attitude. Third, we present the experimental results of two systematic evaluations to validate the proposed teleoperation system.

II. Teleoperation System: Design and Implementation

We present a teleoperation system to control the rover's locomotion and provide multimodal feedback (visual and haptic). The Interact rover (Fig. 1) has a four-wheel-steering platform, allowing to achieve double Ackerman steering and spot-turning. On the operator side, the sigma.7 device, a 7DOF bilateral force feedback device, provides locomotion capabilities and haptic feedback (pitch and roll). Fig. 4 shows the implemented system architecture. Here, the rover and operator control unit communication was achieved using the Data Distribution Service (DDS™) standard and RTI Connext® software as an implementation of this standard. Finally, the functional blocks for *actuation rendering* (Section II-A), *haptic rendering* (Section II-B), and *sigma.7* resorted to MATLAB Simulink®.

A. Haptic Control

1) Virtual Joystick Design: The implemented teleoperation system emulates the behaviour of a conventional joystick by implementing the dynamics of a spring-mass-damper system. With this approach, the operator can push the sigma.7 forward, backwards, sideways, and turn the wrist to achieve all the navigation motions available for the Interact rover (Ackerman and spot-turn motions), similarly to a conventional joystick.

The integration of the sigma.7 device into the teleoperation control was performed with a Simulink block that wraps functionalities of the Force Dimension SDK[1]. With this block (see Fig. 5), the sigma.7 receives a force command, $F(t)$, that specifies the force and torque to be applied to each of the 7 axes (6 axes in the Cartesian space, plus the gripper axis):

$$F(t) = \begin{bmatrix} F_x & F_y & F_z & F_\alpha & F_\beta & F_\gamma & F_\lambda \end{bmatrix}^\top \quad (1)$$

and provides state information $p(t)$ and $v(t)$ about the current pose and velocity:

$$p(t) = \begin{bmatrix} p_x & p_y & p_z & p_\alpha & p_\beta & p_\gamma & p_\lambda \end{bmatrix}^\top \quad (2)$$

$$v(t) = \begin{bmatrix} v_x & v_y & v_z & v_\alpha & v_\beta & v_\gamma & v_\lambda \end{bmatrix}^\top \quad (3)$$

where p_α, p_β, and p_γ are the sigma.7's roll, pitch, and yaw, and p_λ is the gripper opening. By extension, $v(t)$ refers to the velocity in those same axes. With these inputs (force) and outputs (pose and velocity), we implemented a position control algorithm based on a spring-mass-damper model:

$$F(t) = r(t)\ \left(K_S\ (p_d - p(t)) + K_D\ v(t)\right) - A(t) \quad (4)$$

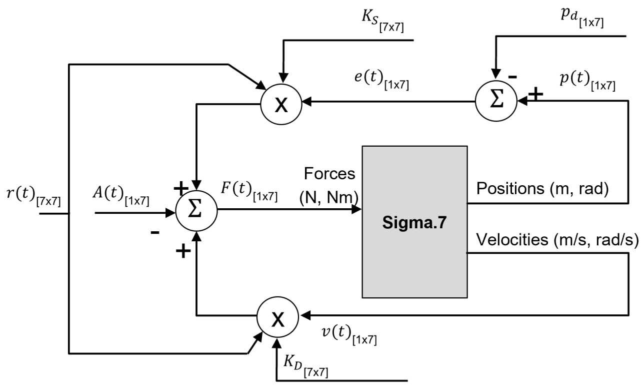

Fig. 5: Control loop implemented to control sigma.7 (see Section II-A for the notation used).

Here, p_d is the desired sigma.7 pose, K_S and K_D are diagonal matrices with the spring and damping coefficients for each of the axes, $r(p)$ is a pose-dependent resistance factor, and $A(p)$ is the component that ensures continuity of the applied forces along the sigma.7 workspace.

By implementing the spring behavior on the sigma.7, the operator can feel the center position (Eq. 5) of the actuation area ($W1$ shown in Fig. 6). To accommodate the natural resting position of the human wrist, the center position of the sigma.7 includes a rotation offset (γ_0) around the z-axis. This offset results in a center position, for the control loop:

$$p_d = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & \gamma_0 & 0 \end{bmatrix}^\top \tag{5}$$

Regarding the definition of the spring (K_S) and damping (K_D) coefficients, these were experimentally determined and tuned to achieve the following goals:

1) Clearly indicating the center position of the sigma.7 while avoiding fatigue during long operations. For this reason, the axes used for the input of the rover's movement (x, y, and γ, described in Section II-A.2) had low stiffness coefficients (K_S), to avoid fatigue, but high enough to allow the operator clearly feel the center position. The remaining axes had a significantly higher stiffness to indicate that movement in that axis will not generate rover movement.
2) The system supports the weight of the operators' hand (avoid operation fatigue) and emulates the feeling of actuation in a 2D plane (Fig. 6). To achieve this goal, the system had a high stiffness coefficient on the z-axis (K_S^z), such that the operator could comfortably rest their hand while holding the sigma.7, without causing vertical movement of the sigma.7.
3) The system is critically damped (smoothly tends to the center position without oscillations). To achieve this goal, we experimentally determined the natural frequencies of each axii, given the pre-determined spring coefficients. Using these values, we estimated and tune the respective critical damping coefficients.

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

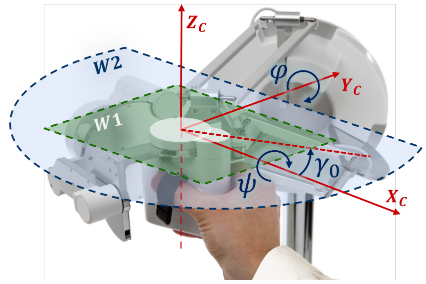

Fig. 6: Sigma workspace ($W1$: actuation area, $W2$: saturation area), Cartesian frame (X_C, Y_C, Z_C), wrist offset (γ_0), and haptic feedback (ψ: roll, $\varphi(t)$: pitch).

Given the experimentally coefficients, we additionally defined two areas within the available workspace of the sigma.7. First, the actuation area $W1$ (see Fig. 6), a symmetrical space where displacements of the sigma.7, relative to p_d, generates an increase of rover's speed. Second, the saturation area $W2$, where the maximum speed of the rover has been reached, and the displacement of sigma.7 does not increase the speed of the rover. In conventional joysticks, the saturation of speed is clearly provided to the operator by the physical limits of the hardware. However, with presented implementation on sigma.7, it was necessary to design a feedback method to convey to operator the limits of the actuation area. To achieve this goal, we defined $r(p)$, a pose-dependent resistance factor:

$$r(p) = \begin{cases} r_1 = 1, & p < p^{\max} \ (W1) \\ r_2 = 1.5, & p \geq p^{\max} \ (W2) \end{cases} \tag{6}$$

With this approach, the operator feels a significantly higher resistance in $W2$ (emulation of physical limits of the conventional joystick), while maintaining the system critically damped (higher spring coefficients require higher damping coefficients). The force profile within the workspace can be visualized in Fig. 7 (example for the x-axis). With this profile, the operator feels a constant increase in the applied force as the sigma.7 moves from the center until the border of the actuation area ($W1$). Once the sigma.7 reaches the saturation area ($W2$), the operator feels a increase in resistance, indicating maximum speed of the rover.

Moreover, to ensure the continuity of the applied forces at the edge of the two areas ($W1$ and $W2$), a last element was included in the control loop, $A(p)$:

$$A(p) = \begin{cases} 0, & p < p^{\max} \ (W1) \\ (r_1 \ K_S - r_2 \ K_S) \frac{p}{|p|} p^{\max}, & p \geq p^{\max} \ (W2) \end{cases} \tag{7}$$

where $p_{\max}$ defines the boundary between the areas $W1$ and $W2$, and r_1 and r_2 are the resistance coefficients of the respective areas.

2) Actuation Rendering: To control the rover, the actuation rendering modules outputs a locomotion command ($\dot{q}$) that contains the desired linear (v_x and v_y) and angular velocity (w_θ) components:

$$\dot{q} = \begin{bmatrix} v_x & v_y & w_\theta \end{bmatrix} \tag{8}$$

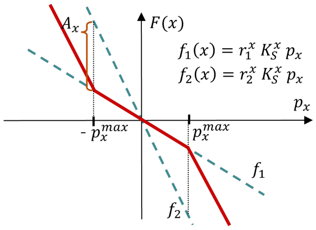

Fig. 7: Implemented force profile (full red line, Eq. 4).

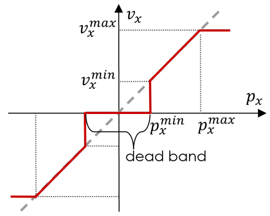

Fig. 8: Actuation rendering (mapping p_x and v_x, Eq. 9).

Given the implemented behavior of the sigma controller (Section II-A.1) and the defined actuation area $W1$, the input to the rover ($\dot{q}$) is computed proportionally to the displacement of the sigma.7 controller from the center position (p_d). The x-axis maps into linear speed, while the y and γ map into rotational component of the $\dot{q}$ command:

$$\begin{aligned} v_x &= \frac{p_x}{p_x^{\max}} \; v_x^{\max} \\ w_\theta &= \left(\frac{p_y}{p_y^{\max}} + \frac{p_\gamma}{p_\gamma^{\max}} \right) \; w_\theta^{\max} \end{aligned} \tag{9}$$

Here, for the angular component of the $\dot{q}$ we combined the values coming from the y and γ axes of the sigma.7. This allows the operator to decide if (s)he prefers to twist the wrist (γ) or move the hand sideways (y) to rotate the rover. Finally, the $\dot{q}$ outputted by the *actuation rendering* module (Fig. 4) filters the values (see Fig. 8) to achieve two goals. First, saturation of the velocity values based on the rover's maximum velocities: $v_x^{\max}$ and $w_\theta^{\max}$. Second, creation of a deadband region where the $\dot{q}$ command is zero. The definition of this region was experimentally determined such that only significant motions of the sigma.7 maps into rover motion.

B. Haptic Rendering: Attitude Feedback

To provide situational awareness regarding the attitude of the rover, the sigma.7 tilts in such a way that it reproduces the current attitude of the rover (roll and pitch), see Fig. 6. This type of feedback explores the proprioceptive abilities of the operator to recognize, in an intuitive way, the current attitude of the rover. Such haptic cues are closer to the way the attitude would be naturally perceived if the operator was inside the rover, compared to conventional visual attitude displays. Thus, we present the *haptic rendering* module (Fig. 4), were the haptic cues are modulated by changing the desired pose (p_d) of the sigma.7 in the control loop (Eq. 4) to integrate the rover's attitude:

$$p_d(t) = \begin{bmatrix} 0 & 0 & 0 & \psi(t) & \varphi(t) & \gamma_0 & 0 \end{bmatrix}^\top \tag{10}$$

where ψ and φ represent the roll and pitch, respectively.

III. System Evaluation

A. User Studies Design

1) Control Validation Study: To validate the sigma as an effective control device, we employed a within-subject design (maximize number of samples) where each participant performed the two experimental conditions:

- **Sigma Control (SC):** locomotion of the rover is achieved using the sigma.7 (without attitude feedback).
- **Joystick Control (JC):** locomotion of the rover is achieved using a conventional joystick (see Fig. 3).

The order in which the participants performed the experimental conditions was permuted to minimize the carryover effects inherent to a within-subject design. Half of the participants started the study with SC, and the other half with JC. By comparing these experimental conditions, we aimed to answer the following research question:

- ***RQ1***: *"Is the ability of the operator to manoeuvre the rover impacted by the control device (JC, SC)?"*

2) Attitude Feedback Validation Study: To validate the sigma.7 as an effective feedback method, we employed a between-subject design. There were two points supporting this decision: (1) there was limited space available to create multiple rich exploration areas (variance in attitude), and (2) a between-subject design ensured that all participants experienced the same environmental conditions (changes in rover attitude). Finally, each participants controlled the locomotion of the rover with the sigma.7 device and received attitude feedback through visual or haptic cues, depending on the experimental condition:

- **Visual Feedback (VF):** Attitude was provided with visual cues. The visual interface displayed a standard artificial horizon to represent the attitude.
- **Haptic Feedback (HF):** Attitude was provided with haptic cues on the sigma.7 (proprioceptive cues described in section II-B).

With these two experimental conditions, we aimed to answer the following research questions:

- ***RQ2***: *"Is the operators' ability to perceive changes in attitude impacted by the feedback modality (VF, HF)?"*
- ***RQ3***: *"Is the operators' ability to accurately characterize changes in attitude impacted by the feedback modality (VF, HF)?"*

B. Experimental Apparatus

1) Teleoperation Station: During the user study, the participants stood in front of a desk with the visual interface displaying telemetry from the rover and the two control devices: joystick and sigma.7 (see Fig. 9). Additionally, the teleoperation station included a video camera to record the interaction of the participants with the devices and verbal reporting made during the experiments.

2) Remote Environment: The remote environment, where the robot navigated during the experimental trials was an outdoor area with two sections with marked trajectories: (1) a section with even terrain for the control study; and (2) a region with uneven terrain (significant changes of inclination) for the feedback study. These trajectories were iterated during a series of pilot tests.

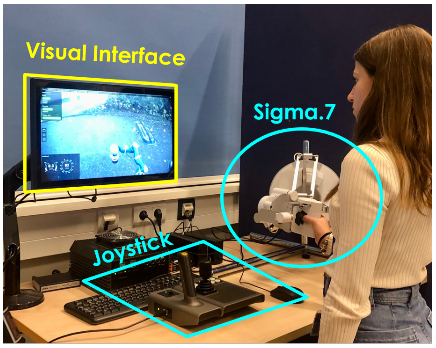

Fig. 9: Apparatus: Teleoperation Station with the visual interface, sigma.7 and joystick.

For the control study, the trajectory ensured different manoeuvres, i.e., straight lines, spot-turns, and curves with various radii. Due to weather conditions the trajectory marked on the floor varied slightly from day-to-day. Nevertheless, all control trajectories had the same maneuvering characteristics. This practical limitation was taken into account during processing and analysis of the experimental metrics. The length and complexity of the trajectory were iterated upon to ensure that all participants drove the rover for a minimum of 5 minutes. For the attitude study, the marked trajectory ensured various changes in pitch and roll. For this, the trajectory included the rover climbing up and down a curb, moving over an inclined ramp, going over a speed bump, and traversing a section with one or two left wheels on the curb.

C. Procedure

Before executing the experimental trials of the user study, all participants read the respective description and instructions. After reading these, participants signed a consent form which allowed the recording and publishing of the experimental data, including imagery and sound. For participants that did not consent to having their image recorded, the position of the video camera was altered to record only the devices, the visual interface, and audio of their verbal reporting. A training session preceded all experimental conditions. During the training sessions, the participants learned how to control the rover with the different control devices (sigma.7 and joystick) and interpret the information on the visual interface (including the artificial horizon). The trials would only start once the experimenter confirmed that the participant was able to perform all necessary maneuvers with the robot and report attitude information. For both studies, participants were instructed to follow the marked trajectory.

D. Experimental Task

1) Control Study: The control study focused on the operator's ability to execute specific manoeuvres. Thus, we designed an experimental task that focused on executing a pre-defined trajectory with various manoeuvres achievable by the locomotion capabilities of the rover (Ackerman and spot-turn steering). Moreover, the trajectory was designed to be executed starting at either end. Thus, the direction of the trajectory was also included in the condition permutations.

2) Attitude Study: For the attitude study, we designed a task that ensured changes in pitch and roll that would be replicable for all participants. Thus, we marked trajectory in a terrain with elevation changes to ensure that all participants experienced the same changes in attitude. For the created trajectory, there were a total of eighteen (18) interest points of relevant attitude changes the participants needed to verbally report. Before the experimental tasks, participants were given words they could use to describe the attitude ("up", "down", "left", "right", and "horizontal") to facilitate the reporting and decrease the mental workload associated with the double task (driving the rover and reporting attitude). However, they were additionally instructed to use whatever words or descriptions they felt were adequate and better matched their mental model of the current status of the rover.

E. Experimental Metrics

1) Control Validation: A search through the current state of the art did not reveal metrics to quantify manoeuvrability (*RQ1*). Thus, we devised a series of indirect measures to infer manoeuvrability. Higher capability for manoeuvrability meant that participants can execute the manoeuvres required by the pre-defined trajectory. Thus, we measured how closely participants followed the marked trajectory, resulting in three experimental metrics. First, Mean Square Error (*MSE*) along the complete trajectory, to quantify the average error (Euclidean distance) of the rover's position along the trajectory, compared to the expected trajectory. Second, Maximum Squared Error (*ME*) along the trajectory, to quantify the maximum error of the rover position during the task. Third, Normalized Warp Path Distance (*WPD*) [14], to quantify the similarity between the executed and expected trajectories.

Here we assume that lower values of all metrics imply greater manoeuvrability. The experimental metrics were calculated by comparing the trajectory recorded during the task execution by the participants with a pre-recorded trajectory (expected trajectory). The rover's position was measured using a GPS (Global Position System) capable of (RTK Real-Time Kinematics) with an average 1-8 centimetres accuracy. Finally, all recorded trajectories were re-sampled to equally spaced points, and the points on the executed and expected trajectories were matched using DTW algorithm [14].

2) Attitude Feedback Validation: The perception (*RQ2*) and characterization (*RQ3*) of attitude changes were measured based on the utterances of perceived attitude change by the participants during verbal reporting. Here we consider that more accurate reporting implies a more effective feedback modality (visual and haptic). Thus, to answer *RQ2* and *RQ3*, respectively, we defined two experimental metrics. First, *attitude perception* (*AP*) that was obtained by verifying if the attitude change at each interest point had a corresponding utterance from the participant. Here, the reports were classified as *aware* and lack of report as *unaware*. Second, *attitude characterization* (*AC*), obtained by verifying each reported attitude matched the actual attitude of the rover. Reports were classified as *correct*, or *incorrect*, and lack of report as *unaware*.

TABLE I: Descriptive statistics (*M*, *SD*) and statistical analysis (paired-samples t-test) of the metrics for the control study.

	SC	*JC*	Paired-samples t-test
MSE	$M = 0.130$ m, $SD = 0.068$	$M = 0.136$ m, $SD = 0.058$	$t(16) = 0.396, p = 0.70$
ME	$M = 1.115$ m, $SD = 0.271$	$M = 1.258$ m, $SD = 0.289$	$t(16) = 1.926, p = 0.07$
WPD	$M = 0.277$, $SD = 0.074$	$M = 0.281$, $SD = 0.071$	$t(16) = 0.174, p = 0.86$

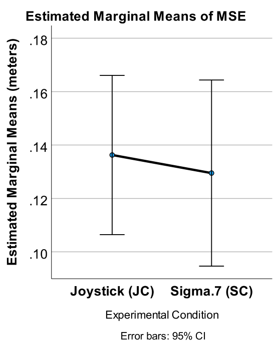

Fig. 10: Mean Square Error (*MSE*) ($p = 0.698$).

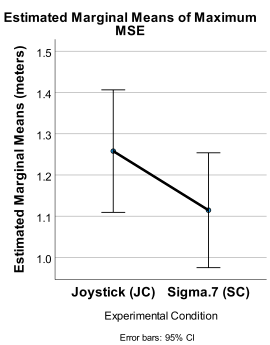

Fig. 11: Maximum Squared Error (*ME*) ($p = 0.072$).

TABLE II: Descriptive statistics (*MR*: mean rank) and statistical analysis (Kruskal-Wallis H test) of the attitude study.

	HF	*VF*	Kruskal-Wallis H test
AP	$MR = 479.38$	$MR = 494.6$	$X^2(1) = 1.382$, $p = 0.24$
AC	$MR = 482.62$	$MR = 488.38$	$X^2(1) = 0.122$, $p = 0.73$

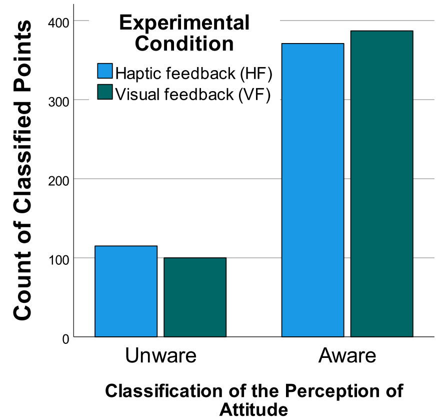

Fig. 12: Attitude (pitch and roll) characterization (*AC*), $X^2(1) = 0.122$, $p = 0.727$ ($N = 971$ classified points).

IV. Results and Discussion

A. Control Validation Study (SC vs JC)

We performed the Shapiro-Wilk test on the metrics *MSE*, *ME*, and *WPD*, and all confirmed normality (p-value > 0.05). The population for this study had a total of twenty-two (22) participants aged between 21 and 30 (average age 25). Eight were female, and fourteen were male. We excluded the data from five participants from the analysis due to incomplete or inaccurate recorded data, mainly due to substandard localization data, and recording issues. As such, the analysis was performed on the data of 17 participants. Accordingly, Table I and Figs. 10 and 11 show the results of the statistical analysis (paired-samples t-test). These results reveal no statistical difference between using the joystick (JC) and the sigma.7 (SC). However, for the *ME* metric, there was a statistical tendency ($p = 0.072$) for higher *ME* in JC condition, compared to SC. From the presented results we can conclude that there was no significant detriment to the operators' ability to manoeuvre the rover when using sigma.7 compared to the joystick (*RQ1*). Thus, validating the novel interaction method (sigma.7) as an effective control strategy for the locomotion of remotely operated rovers. Finally, since the proposed system (section II-A) was an initial prototype, beyond quantifying rover maneuvrability, we sought to find the system's shortcomings and common interaction behaviours. Next iterations of the control method will integrate the lessons learned during the control study:

- Participants were fast to understand the control method with sigma.7. Most participants could understand how to use the device to control the rover, even before receiving instructions from the experimenter.
- Having two interaction methods to rotate the rover (side motion and wrist rotation) occasionally caused unwanted rotation motions. Participants often pulled the device left (closer to their body and visual interface, see Fig.9) 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 motion. Future system iterations will investigate effective methods to convey the deadband area to the operator and user preference on wrist versus sideways motions to rotate the rover. Qualitative observations during the studies revealed that this preference often depended on the participant pre-existing mental model and would occasionally change during training periods.
- Twisting the wrist was reported as an intuitive method to rotate the rover. However, it appeared to be an issue for some participants, as they would try to twist the sigma.7 beyond the actuation area to increase the robot's rotation speed. Thus, they often twisted their wrist to positions with higher resistance, leading to discomfort.

B. Attitude Feedback Validation Study

Since the *AP* and *AC* data is non-parametric, we performed a Kruskal-Wallis H test for these metrics. The results of this analysis are summarized in Table II and Fig. 12. Due to the different design of user study, a group of fifty-two (52) participants aged between 21 and 35 (average age 27), participated in the attitude trials. Regarding gender, 19 participants were female, and 33 were male. We excluded from the analysis the data from six participants due to inaccurate reporting and recording issues. As such, the analysis was performed on the data of 46 participants (23 participants per condition). The results of the statistical analysis show no significant difference for both metrics when comparing HF and VF conditions and support the answers to our second and third research questions: the ability of the operator to perceive (*RQ2*) and characterize (*RQ3*) changes in attitude is not impacted by the feedback modality (*VF*, *HF*). These results show that haptic feedback can be an effective way of reducing the cognitive load on the human visual channel by resorting to haptic feedback during teleoperation. Here, participants with the haptic feedback were able to correctly perceive and characterize attitude similarly to participants that were reading the values from the visual indicator. However, participants from the haptic group had the advantage of focusing their visual focus on the image stream, unlike the visual group. For example, one participant in the visual feedback group reported that he/she mainly focused on the visual indicator of attitude and was driving the rover with his/her peripheral vision (unwanted behaviour).

Moreover, when using visual feedback, several participants often reported the wrong attitude and needed to correct themselves, indicating a higher mental workload during the experimental task. When using haptic feedback, participants often reported which of the four wheels was on the curb, indicating comprehensive knowledge of the rover's attitude. This type of attitude description indicates sensory immersion that the visual group did not demonstrate. The different type of reporting between the two groups provides a systematic indication that the haptic modality has the potential to convey the robot's status in a more intuitive manner. This sense of immersion will likely lead to enhanced SA and, consequently, more effective decision-making during teleoperation during more complex tasks that require different goals integration in the robot operation.

Additionally, the SA probing technique (verbal report of attitude) potentially impacted the experimental metrics, as it required the participants to pay attention to a single element of the system. We expect that in more complex tasks with a different probing technique (e.g., SAGAT), the feedback modality significantly impacts the operator's SA, as the visual focus of the operator needs to be distributed through various elements of the GUI. Finally, attitude changes within the designed trajectory were mainly in the pitch axis (realistic environment). Thus, the conclusions from the reported results should be contextualized within these limitations of the study.

V. Conclusions

In this paper, we presented the design and systematically evaluated a new interaction for haptic driving of a remotely operated rover using a 7DOF force feedback device. Moreover, the proposed teleoperation system conveyed haptic cues to the operator regarding the rover's attitude. Two systematic user studies validated the system. Results from the first study showed no detriment in manoeuvrability compared to a standard joystick, thus validating sigma.7 as an effective control method. The second study showed no statistically significant difference in perceived and characterized attitude reporting, when comparing visual and haptic cures. These results, validated the proprioceptive attitude (pitch and roll) cues as an effective alternative to the visual indicator. Moreover, this alternative can offload the visual channel by conveying attitude information through the haptic channel.

The proposed system and the findings of the systematic studies can likely be extended to other teleoperated mobile robots in unstructured environments (e.g., search and rescue scenarios) or with low visibility conditions (e.g., underwater vehicles). In such cases, the proposed haptic driving can be adapted to teleoperate robots with different DOF of mobility (e.g., aerial vehicles) and display relevant haptic feedback.

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