Traction Awareness Through Haptic Feedback for the Teleoperation of UGVs*

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***Abstract*— Teleoperation of Unmanned Ground Vehicles (UGVs) is dependent on several factors as the human operator is physically detached from the UGV. This paper focuses on situations where a UGV designed for search and rescue loses traction, thus becoming unable to comply with the operator's commands. In such situations, the lack of Situation Awareness (SA) may lead to an incorrect and inefficient response to the current UGV state usually confusing and frustrating the human operator. The exclusive use of visual information to simultaneously perform the main task (e.g. search and rescue) and to be aware of possible impediments to UGV operation, such as loss of traction, becomes a very challenging task for a single human operator. We address the challenge of unburdening the visual channel by using other human senses to provide multi-modal feedback in UGV teleoperation. To achieve this goal we present a teleoperation architecture comprising (1) a laser-based traction detector module, to discriminate between traction losses (stuck and sliding) and (2) a haptic interface to convey the detected traction state to the human operator through different types of tactile stimuli provided by three haptic devices (E-Vita, Traction Cylinder and Vibrotactile Glove). We also report the experimental results of a user study to evaluate to what extent this new feedback modality improves the user SA regarding the UGV traction state. Statistically significant results were found supporting the hypothesis that two of the haptic devices improved the comprehension of the traction state of the UGV when comparing to exclusively visual modality.**

I. INTRODUCTION

Teleoperation of Unnamed Ground Vehicles (UGVs) allows the human operator to explore remote environments. However, the fact that the human operator is physically detached from the UGV raises several challenges. One particular challenge consists in providing an effective awareness of the robot situation, known as Situation Awareness. This paper focuses on the problem of dealing with situations where the UGV for search and rescue loses traction and is unable to comply with a human operator's commands. In these situations, awareness of traction loss is compromised by the physical detachment of the operator with respect to the UGV.

The concept of Situation Awareness (SA) was formally defined by Endsley [8] as a person's perception of the elements of the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future. This definition of SA, characterizes an understanding of the environment's state and its parameters, that can be divided into three levels of SA. Perception (Level 1 SA), is the first and lowest level of SA, in which a person is capable of perceiving the relevant information provided by the system. Comprehension (Level 2 SA), is the second and middle level of SA, in which a person is capable of understanding the perceived information and integrate it with the operation goals. Projection (Level 3 SA), is the last and top level of SA, in which a person is capable of predicting future events and system states, based on the previous comprehension of the system and its environment, allowing for timely and effective decision making [8].

In situations where the UGV loses traction, the lack of SA can lead to an incorrect and inefficient response to the current UGV state, usually confusing and frustrating the human operator [1]. In these circumstances, it is fundamental to have interfaces that can provide the relevant SA information when needed, without distracting the operator from its main task (e.g.search and rescue). Interfaces that exclusively use visual information can become challenging to human operators in situations where the robot is unable to comply with the given commands, such as loss of traction, as it requires the extraction of information based on subtle visual cues to estimate the current situation. Furthermore, only having a visual interface may hinder the perception of relevant information and clutter the image provided by the on-board cameras, which is needed to search for victims. One way of reducing the burden on the visual channel is to use other human senses and provide multi-modal feedback in UGV teleoperation. In this paper we use visual and tactile modalities.

A review of the literature reveals two mainly explored applications of haptics in teleoperation of mobile robots. Trajectory task following, explored by [2], [3], each provides force feedback regarding location and distance to the goal. Indication of the presence and proximity of surrounding obstacles, explored by [4], [5], providing force feedback for obstacle avoidance. Researchers have addressed the problem of traction loss in [6], although applied to autonomous operation, while the concept of friction rendering was explored using haptic devices such as E-Vita [7]. This paper combines all these concepts into a single teleoperation interface[1].

The traction detector module proposed here is based on the

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[1]Supplementary video is available in: https://youtu.be/szHA2nIhjAs

comparison of tracked wheel odometry with laser-based odometry. From this comparison, the traction state is estimated. For instance, if the robot is moving according to the tracks odometry but not according to the laser-based one, the robot is highly likely to be stuck. To convey the estimated traction state to the human operator we explored three types of tactile stimuli: (1) *friction*, using a rotating cylinder in contact with the operator's hand, (2) *vibration*, using a vibrotactile glove and (3) *texture*, using a texture rendering device.

The major contributions of this paper are two-fold. On the one hand, the integration of the haptic devices on the teleoperation system of RAPOSA-NG (Fig. 1), a tracked wheel search and rescue UGV prototype, which included the physical construction of the above mentioned friction and vibration devices, designed for non-expert system users. On the other hand, we contribute with a detailed user study to evaluate the three haptic devices, in comparison with the exclusive use of the visual channel, involving the teleoperation of RAPOSA-NG on locomotion challenging scenarios. The presented user study intends to answer two research questions: (*Q1*) "Does the addition of haptic feedback to the exclusively visual interface improve the user SA regarding the UGV traction state?" and (*Q2*) "Which of the presented haptic devices can best convey to the operator the traction state of RAPOSA-NG?".

As far as we know, this is the first paper that tackles traction loss in teleoperated UGVs, by providing tactile feedback to human operators and it is structured as follows: Section II explains the developed traction detection module, Section III describes the three haptic devices, Section IV reports the method employed during the user study, Section V presents the obtained results, Section VI presents the discussion, and Section VII presents our conclusions.

II. TRACTION DETECTION

Typical situations causing loss of traction are obstacles that either block the motion of the robot or raise the body of the robot in such a way the tracks lose contact with the ground. Another, less common, situation is the robot sliding down a smooth ramp.

The method we use to detect these situations is based on determining whether there is a mismatch between the expected motion, given tracked wheel odometry and the actual motion, given laser-based odometry. Whenever a significant mismatch is found (defined below), we estimate the traction situation of the robot, following the situation classification being shown in TABLE I.

Let the pose of the robot $\mathbf{Z}(t)$ be defined by three coordinates, two for position and one for orientation (we use boldface to denote vectors),

$$\mathbf{Z}(t) = \begin{bmatrix} x(t) & y(t) & \theta(t) \end{bmatrix}^\top = \begin{bmatrix} \mathbf{p}(t) & \theta(t) \end{bmatrix}^\top \quad (1)$$

The tracked wheel odometry is obtained directly from the ROS drivers of the robot, in the form of a coordinate transformation between two frames. The laser-based odometry

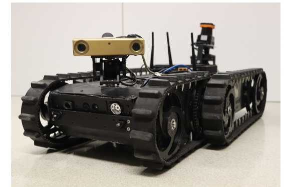


Fig. 1: RAPOSA-NG: the search and rescue UGV prototype used in the user study.

TABLE I: Classification of UGV traction states

Traction state	Tracks (odometry)	UGV (laser)	Traction Situation
Normal	Moving	Moving in the same direction	With
	Stopped	Stopped	With
Stuck	Moving	Stopped	Without
Sliding	Moving	Moving in a different direction	Without
	Stopped	Moving	Without

results from the integration of a scan matching algorithm, implemented by the *laser_scan_matcher* ROS package [10]. The mismatch detection between these two odometry measures is based on comparing the displacement according to each measure along a moving window of n samples. The window size n will influence the sensitivity to noise (greater n means smaller sensitivity) and the detection latency (smaller n means faster detection).

The filtering is done by comparing the measurements $\mathbf{Z}(t)$ at the start (t_{k-n}) and end (t_k) of the window, yielding the displacement $\Delta\theta(t_k)$ and $\Delta p(t_k)$ regarding orientation and position respectively. In what concerns orientation, the displacement $\Delta\theta(t_k)$ (2) can be obtained using the scalar difference of the orientation at t_{k-n} and t_k, modulo π.

$$\Delta\theta(t_k) = [\theta(t_k) - \theta(t_{k-n})], \theta(t) \in [-\pi, \pi] \quad (2)$$

To obtain the position displacement vector $\Delta\mathbf{p}(t_k)$ (3) with respect to a frame attached to $\mathbf{p}(t_{k-n})$, so that tracked wheel and laser based displacements can be compared, the following expression is used:

$$\Delta\mathbf{p}(t_k) = R^\top(\theta(t_{k-n}))[\mathbf{p}(t_k) - \mathbf{p}(t_{k-n})] \quad (3)$$

where $R(\theta)$ stands for the usual rotation matrix in $SO(2)$.

From the computed displacements $\Delta\theta(t_k)$ and $\Delta\mathbf{p}(t_k)$, the mismatch between the two odometry measures is quantified resorting to $\delta_p(t_k)$ (4) and $\delta_\theta(t_k)$ (5), concerning position and orientation respectively,

$$\delta_p(t_k) = \|\Delta\mathbf{p}_{tracks}(t_k) - \Delta\mathbf{p}_{laser}(t_k)\| \quad (4)$$

$$\delta_\theta(t_k) = \|\Delta\theta_{tracks}(t_k) - \Delta\theta_{laser}(t_k)\| \quad (5)$$

where the indices *tracks* and *laser* denote odometric measurements coming from the tracked wheel odometry and laser odometry.

Finally, the traction situation of the robot can be accessed using $\delta_p(t_k)$ and $\delta_\theta(t_k)$ and a corresponding decision threshold for both position and orientation. Whenever the obtained value is above the defined threshold it is considered that traction has been lost and the current traction state should be classified as “stuck” or “sliding”. Otherwise, it is considered that the robot has traction and the current traction state is classified as “normal”. To discern between “stuck” and “sliding” states, the earlier computed displacements (3) and (2) are compared. This comparison will allow to ascertain if either the tracks or the UGV is moving and classify the state as shown in TABLE I. From the verification of the comparison (6), regarding position, or the comparison (7), regarding orientation,

$$\|\Delta\mathbf{p}_{laser}(t_k)\| > \|\Delta\mathbf{p}_{tracks}(t_k)\| \tag{6}$$

$$\|\Delta\theta_{laser}(t_k)\| > \|\Delta\theta_{tracks}(t_k)\| \tag{7}$$

it can be inferred that the UGV is moving while the tracks are stopped, or moving significantly less (“sliding”). Otherwise the traction state is classified as “stuck” regarding orientation. Calculating α,

$$\alpha = \angle(\Delta p_{laser}(t_k), \Delta p_{tracks}(t_k)) \tag{8}$$

allows to investigate the possibility that both the tracks and the UGV are moving, however, in different directions. In that case, the value of α is greater than a small threshold value and the traction state is classified as “sliding”. Otherwise, the traction state is classified as “stuck” regarding position. Once the traction state as been detected and classified, it can be then conveyed to the human operator through tactile stimuli.

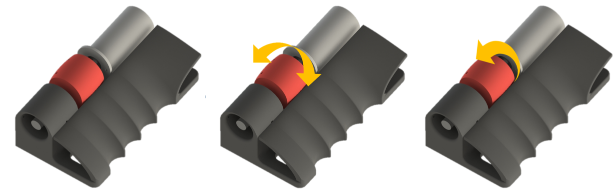
III. HAPTIC DEVICES

To convey the tactile component of the multi-modal feedback it was developed three haptic devices: Traction Cylinder (Fig. 2), Vibrotactile Glove (Fig. 3) and E-Vita (Fig. 4). Both the Traction Cylinder and Vibrotactile Glove were constructed and integrated by the authors, while E-Vita, solely the integration with RAPOSA-NG system was performed. The complete development of E-Vita was performed by the MINT research team.

A. Traction Cylinder

1) Device Description: The Traction Cylinder uses *friction*, provided by lateral skin stretch, as the tactile feedback modality. During its operation, a shear force is applied to the skin on the palm of the hand while the user is holding the device. The lateral skin stretch is accomplished resorting to a dynamic cylinder present on the device that rotates accordingly to the traction state of the UGV. It was desidned the CAD model of the device and, to the 3D printed structure, was added a bearing, a gear motor, a controller (Arduino Duemilanove Atmega328) and a driver. (MotoMama L298N)

2) Tactile Patterns: Three different tactile patterns were designed, as illustrated in Fig. 2. These patterns provide, on the palm of the hand, (1) no movement of the cylinder (Fig. 2a) to convey the “normal” state, that is, traction has not been lost and no attention from the user is required to this component of the system, (2) a stuckness sensation, using a back and forward motion of the cylinder (Fig. 2b) to convey the “stuck” state, and (3) a one direction continuous motion of the cylinder (Fig. 2c) to convey the “sliding” state.



(a) “Normal” state. (b) “Stuck” state. (c) “Sliding” state.

Fig. 2: Tactile patterns provided by the Traction Cylinder (yellow arrows: motion direction of the cylinder).

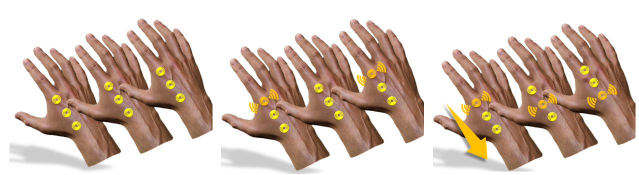
B. Vibrotactile Glove

1) Device Description: This device relies on *vibration* as the tactile feedback modality. This device consists of a glove, worn by the human operator, with three vibration motors (10mm diameter, 2.7mm thick). The amplitude of these motors was controlled resorting to an Arduino Mega 2560. The actuators were placed on the palm of the hand, along a single direction, in the area under the pinky finger. The actuation region was chosen to achieve a compromise between an high sensitivity hand area, while being as planar as possible.

2) Tactile Patterns: Three different tactile patterns were designed, as illustrated in Fig. 3. These patterns intend to provide, on the palm of the hand, (1) no vibration (Fig. 3a) to convey the “normal” state, (2) a stuckness sensation using one of actuators to provide an intermittent vibration (Fig. 3b) to convey the “stuck” state, and (3) a sliding sensation using the three actuators mimicking the tactile sensation of a directional movement along the hand (Fig. 3c) to convey the “sliding” state.

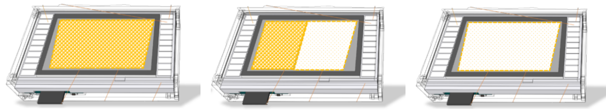
C. E-Vita

1) Device Description: E-Vita is a tactile tablet presented by Frédéric Giraud in [7] and its operation consists of modifying the perception of *texture* on the screen of the device. The rendered *texture* corresponds to the tactile feedback modality used to convey the traction state of the UGV. The integration of E-Vita on RAPOSA-NG’s system was performed using the ROS platform, where the communication with E-Vita was accomplished using a WebSocket communication protocol. An additional mechanism was developed with the purpose of translating the device side to side at a constant frequency while the participant maintains the finger motionless. This added mechanism was designed because



(a) “Normal” state. (b) “Stuck” state. (c) “Sliding” state.

Fig. 3: Tactile patterns provided by the Vibrotactile Glove (hands side by side represent the patterns along time).



(a) “Normal” state. (b) “Stuck” state. (c) “Sliding” state.

Fig. 4: Tactile patterns provided by E-Vita (yellow: rough texture, withe: smooth texture).

the perception of the different textures requires a sliding finger along the screen. However, moving the finger during teleoperation could represent a difficult task, as well as prone to forgetfulness.

2) Tactile Patterns: The three designed tactile patterns are illustrated in Fig. 4. The created patterns provide, on the tip of the finger, (1) a rough texture (Fig. 4a) to convey the “normal” state, (2) a stuckness sensation using a split screen with both rough and smooth textures (Fig. 4b) to convey the “stuck” state, and (3) a sliding sensation using a smooth texture (Fig. 4c) to convey the “sliding” state. The use of these intends to create a direct map between the existence of friction in the tip of the finger with the adhesive friction between the tracks and the floor (traction).

IV. METHOD

A. Participants

Thirty-two unpaid subjects (20 male, 12 female) aged between 18 and 27 years voluntarily participated in the user study where they were provided written consent. The participants had neither prior experience teleoperating RAPOSA-NG nor prior knowledge regarding the maps to be explored during the several trials. Twenty-six of the participants were right-handed and six were left-handed.

B. Apparatus

During the trials, the participant and the UGV were physically separated. The participant was sitting in the *Teleoperation Station* and the UGV placed in the *Navigation Scenarios*.

1) Teleoperation Station: During each of the different trials, the participants sat in front of the teleoperation interface, shown in Fig. 5, visualizing the image received from the on-board camera (Visual Feedback) while using a 3Dconnexion SpaceNavigator 6DoF joystick to control RAPOSA-NG and the three haptic devices to receive the tactile feedback regarding the traction state of the robot. The participants wore headphones for partial noise cancellation to ensure that the surrounding sounds would not interfere with the tests. All participants used the left hand to handle the joystick and control the UGV and the right hand to receive the tactile feedback through the haptic devices that were not visible during the trials. In standard systems (gamepad) the user controls the robot’s movement using the left hand (left joystick of the gamepad). As a design choice, this configuration was maintained.

2) Navigation Scenarios: While the participant sat in front of the Teleoperation Station the UGV was placed in

Fig. 5: Teleoperation Station: participant using the joystick and the Traction Cylinder while receiving visual feedback.

four different Maps: *M1*, *M2*, *M3* and *M4*. The created Maps intended to resemble a search and rescue environment and were explored by the participant while teleoperating RAPOSA-NG. Due to the existence of space limitations in the lab, it was only possible to create two asymmetric scenarios which were traversed in two different directions, providing a total of four different Maps. These Maps were built in such way that along the path the UGV would go through all of the possible traction states (“normal”, “stuck” and “sliding”). Ramps to make it slid and small blocks and narrow navigation spaces to make it stuck. Additionally, a member of the research team was present in the navigation scenarios to ensure the safety of the robot and that all participants experienced all possible traction states.

C. SA Assessment using SAGAT

The assessment of Situation Awareness (SA) was performed using the Situation Awareness Global Assessment Technique (SAGAT), a freeze on-line probe technique developed by Endsley [8], [9]. The administered SAGAT questionnaires[2] were designed to include queries regarding all levels of SA (perception, comprehension and projection). Users were instructed to perform the tasks as normally as possible, consider the SAGAT queries merely as secondary and make their best guess in case of uncertainty in the answer. A total of eleven randomly selected queries were administered at each interruption and classified as Correct or Incorrect. Special attention was taken during development and selection of the SAGAT queries not to focus excessively on the item of interest (traction state) and avoid shifting the attention of the participants to this factor and affect SA artificially. Furthermore, a previous investigation revealed that implementing changes to a part of the system may inadvertently affect SA on other issues [8]. Having a broader range of queries allows to investigate if adding this new component to the system could cause these changes.

D. Procedure

Written instructions regarding the apparatus and procedure of the user study were provided to the participants. After reading the provided instructions and signing the consent form, participants answered to a demographic questionnaire[2]. Each participant completed a training session where they got familiarized with the teleoperation interface, the robot operation and the haptic devices. The participants also received

[2]Questionnaires are available in the link: *https://goo.gl/rJbJKF*

instructions on how to answer each of the SAGAT queries. During this period the participants could see the robot and were free to control it while having access to the visual feedback from the on-board cameras and the different haptic devices. The participants were shown the different possible traction states of the robot, their implications for the robot's movement and possible actions that would allow the robot to overcome such states.

After the training period, each participant completed four trials: Exclusively Visual (*V*), Visual & Cylinder (*VC*), Visual & Vibrotactile Glove (*VB*) and Visual & E-Vita (*VE*) in one of the four trial orders: (*V*, *VC*, *VE*, *VB*); (*VC*, *VB*, *V*, *VE*); (*VB*, *VE*, *VC*, *V*); (*VE*, *V*, *VB*, *VC*). These possible orders where defined using a balanced latin square design with the intent of reducing the risk of carry-over effect between trials. At the beginning of the trials *VC*, *VB* and *VE* the participants had a brief training period to review the patterns of the haptic devices until they felt confident and ready to start. To start the trial, they would press the key "Enter", marked in red on the keyboard, prompting the image from the on-board camera on the screen and enabling the control the robot.

During all trials, the participants had to follow multiple red "X" placed on the walls and floor of the scenarios with the goal of finding the "stop" sign. After crossing the "stop" sign the trial would be terminated. Each trial was performed in a different map. Each trial had a maximum duration of eight minutes. During the trials, the teleoperation would be paused with a black screen and the participants were subject to the SAGAT questionnaires. Once the participants finished answering all SAGAT questions they could press "Enter" and resume the teleoperation of the robot. These interruptions would occur at random moments, a maximum of two times per trial.

After each trial, the participants answered two post-trial questionnaires: (1) NASA-TLX to evaluate workload and (2) a qualitative questionnaire[2] to assess overall perception of the traction states during that trial. After the trials *VC, VB* and *VE*, an extra set of questions were given to evaluate several metrics of the haptic devices. Following each trial, the participants would have a resting period (minimum two minutes) where they were free to move around the room until they felt relaxed and ready to start the next trial. Once all four Trials were complete, the participants were inquired regarding their preference and comments on the haptic devices.

E. Measures

The primary measure is SAGAT data. The secondary measures are the qualitative evaluation on the difficulty to perceive the traction states and the qualitative evaluation of several metrics of the haptic devices (discomfort, fatigue, distinguishability of the haptic patterns, usefulness, importance for the decision making and number of felt sensations). The tertiary measures are the NASA TLX questionnaire and the Video recordings of the participants during trials. Because the tasks were interrupted to answer the SAGAT questionnaires, task time could not be used as a measure of the study.

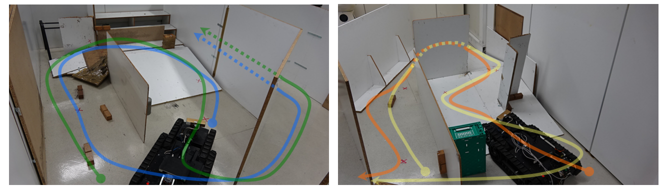


Fig. 6: Navigation Scenarios and Maps (blue: *M1*, green: *M2*, orange: *M3*, yellow: *M4*).

V. RESULTS

Interaction between Maps (M1, M2, M3, M4) and Devices (V, VC, VB, VE):

A two-way repeated measures ANOVA on $\%$ *of SAGAT Correct Answers* data with factors of *Maps*(4 levels) and *Devices*(4 levels) as within-subject variables was performed. No interaction between factors *Maps* and *Devices* was found in the two-way repeated measures ANOVA for $\%$ *of SAGAT Correct Answers*.

Interaction between SA Levels (Perception, Comprehension, Projection) and Devices (V, VC, VB, VE):

A two-way repeated measures ANOVA on $\%$ *of SAGAT Correct Answers* data with factors of *SA Levels* (3 levels) and *Devices* (4 levels) as within-subject variables. No interaction between factors *SA Levels* and *Devices* was found in the two-way repeated measures ANOVA for $\%$ *of SAGAT Correct Answers*. No statistically significant difference was found across the different levels of the factors *SA Levels* and *Devices*. All subsequent statistical analyses were performed on the factor *Devices* and performed with a confidence level of 95%.

SAGAT query-by-query Analysis:

For the SAGAT results of the query *"What is the state of the robot?"*, a Wilcoxon signed-ranks test showed that the *Devices VB* ($Z = -3.00$, exact $p = 0.002$, one-tailed) and *VC* ($Z = -2.00$, exact $p = 0.038$, one-tailed) were statistically significantly higher than only visual feedback, where higher represents a greater amount of correct answers. No statistically significant difference was found for the remaining queries of the SAGAT questionnaire.

Qualitative Post-Trial Questionnaires:

Difficulty to Understand the Traction States ("sliding" and "stuck"): A Friedman Test showed that there was a statistically significant difference in the difficulty to understand that the UGV was "stuck" or "sliding" depending on the used device: $\chi^2 = 21.773$, exact $p < 0.001$ regarding the "stuck" state and $\chi^2 = 11.429$, exact $p = 0.005$ regarding the "sliding" state. Post hoc analysis with Wilcoxon signed-rank tests was conducted with a Bonferroni correction applied, resulting in a significance level set at $p < 0.0083$ and the respective results are shown in TABLE II. This table should be read as follow: *Device X* is lower than *Device Y* (Z, exact p, one-tailed), in the difficulty to understand the *State*$_n$, where "lower than" means less difficulty to understand the *State*$_n$.

TABLE II: Results of the performed Post hoc analysis with Wilcoxon signed-rank tests regarding the Difficulty to Understand the traction states “stuck” and “sliding” during the trial.

State_n	Device X	Device Y	Z	exact p (one-tailed)
Stuck State	*VC*	*V*	-2.993	0.0008
	V	*VE*	-2.892	0.0002
	VC	*VE*	-3.866	< 0.0001
	VB	*VE*	-2.866	0.0016
Sliding State	*VC*	*VE*	-3.025	0.0006

Qualitative Metrics of the Haptic Devices:
A Friedman Test showed that there was a statistically significant difference in the qualitative evaluation of the several metrics[3] of the haptic devices presented in TABLE III depending on the device. These metrics include level of discomfort (1:no discomfort - 7:very discomforting), level of fatigue (1:no fatigue - 7:very fatiguing) and level of distinguishability (1:indistinguishable - 7:very clear).

Post hoc analysis with Wilcoxon signed-rank tests was conducted with a Bonferroni correction applied, resulting in a significance level set at $p < 0.0167$ and the results of this analysis are shown in TABLE IV. This table should be read as follow: *Device X* is higher than *Device Y* (Z, exact p, one-tailed), regarding $Metric_n$, where higher means greater $Metric_n$. E.g.: *VE* is higher than *VC* ($Z = -3.625$, exact $p < 0.001$, one-tailed) and *VE* is higher than *VB* ($Z = -3.430$, exact $p < 0.001$, one-tailed) regarding level of discomfort, where higher means greater discomfort.

VI. DISCUSSION

Interaction between Maps and Devices:

No interaction was found between the *Maps* and *Devices* factors, whereby it was verified that having only two scenarios, traversed in two different directions, did not influence the % *of SAGAT Correct Answers* and subsequent statistical analysis did not require taking into account the *Maps* factor.

SAGAT query-by-query Analysis:

When analyzing the % *of SAGAT Correct Answers*, on a query-by-query basis for the *Devices* factor, statistical evidence was found to support that the Traction Cylinder (*VC*) and Vibrotactile Glove (*VB*) improved the SA of the participants regarding comprehension of the UGV’s traction state when comparing to the exclusively visual modality (*V*). The obtained results show that the *friction* (*VC*) or *vibration* (*VB*) cues can be used to convey the traction state of the UGV can improve the SA of the participants regarding this item (first research question) and avoid overloading the visual channel to convey this new information. Regarding the second research question, no supported answer was obtained. Although it was found a statistically significant improvement of SA, regarding traction state, using the Traction Cylinder (*VC*) and the Vibrotactile Glove (*VB*) when comparing to E-Vita (*VE*), no statistically significant difference was found between *VC* and *VB*. It should be noted that these results

[3]Results of all metrics are available in link: https://goo.gl/t7eVGH

TABLE III: Friedman Test results for the several metrics of the haptic devices.

	χ^2	exact p
Level of discomfort	25.209	< 0.001
Level of fatigue	14.629	< 0.001
Level of distinguishability	48.136	< 0.001

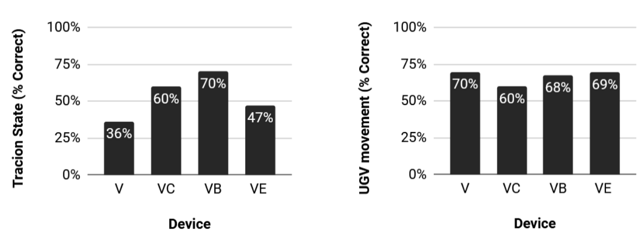
TABLE IV: Results of the post hoc analysis with Wilcoxon signed-rank tests for the several metrics of the haptic devices.

Metric_n	Device X	Device Y	Z	exact p (one-tailed)
Level of discomfort	*VE*	*VC*	-3.625	< 0.001
	VE	*VB*	-3.430	< 0.001
Level of fatigue	*VE*	*VC*	-2.852	0.002
	VE	*VB*	-3.832	0.000
Level of distinguishability	*VC*	*VB*	-2.812	0.002
	VC	*VE*	-4.740	< 0.001
	VB	*VE*	-4.562	< 0.001

show the viability of adding haptic feedback to the interface, as an alternative sensory modality and do not evidence that this modality can replace the same information to be provided visually, as that was not the intent of the study. Regarding E-Vita (*VE*), although there is evidence that it might improve the comprehension of the traction state of the UGV (Fig. 7a), it is not possible to make any statement supported by statistical significance.

It is interesting to notice that there was no statistically significant difference in the results across the Devices (*V, VC, VB, VE*) for the query *“Is there currently anything that might be preventing the robot desired movement?”*, shown in Fig. 7b. The obtained results show that participants are capable of comprehending the existence of an impediment to the UGV’s movement. However, only when using the Traction Cylinder (*VC*) or the Vibrotactile Glove (*VB*) a statistically significant improvement was obtained in the comprehension of the UGV’s traction state. These results address the previously presented issue of confusion and frustration during teleoperation due to loss of traction.

Regarding the SAGAT query *“What is the current traction situation of the robot?”*, there was no statistically significant difference across Devices and it was observed a disagreement with the given answers to the SAGAT query regarding the traction state. When inquired regarding traction state and traction situation at the same SAGAT interruption, 61.3% of the times, the participants that answered “stuck,” also



(a) “*What is the state of the robot?*” (*Normal*, *“stuck”*, *“sliding”* and *Don’t know*)

(b) “*Is there currently anything that might be preventing the robot desired movement?”* (*Yes*, *No* and *Don’t Know*)

Fig. 7: Results to two of the SAGAT Queries

answered “with traction”. This incoherence in the answers did not occur for the “sliding” state. These incoherences might have been caused by a lack of comprehension from the participants regarding the concept of traction and/or by a weak explanation of the concept during the training period.

Qualitative Post-Trial Questionnaire:

After each trial, participants were qualitatively inquired regarding their ability and difficulty to notice the “stuck” and “sliding” states. The “stuck” state was noticed by the participants 97% of the trials with the Devices (*V*) and (*VE*) and 100% of the trials with (*VC*) and (*VB*), while the “sliding” state was reported in the trials with the Devices (*V*) 50% of the trials, (*VC*) 81% of the trials, (*VB*) 69% of the trials and (*VE*) $59,4\%$ of the trials. This difference in reporting the “stuck” and “sliding” states might have occurred due to the fact that the “sliding” state was physically limited by the dimensions of the scenarios, making it a time-limited event, easier to overcome, and less frustrating and more likely to be forgotten by the end of the trial. Regarding the difficulty of traction state awareness, the participants described E-Vita (*VE*) as the Device with the greatest difficulty to grasp the “stuck” state. Participants also commented that the texture associated with the “stuck” state was very challenging to distinguish from the other provided textures.

Qualitative Metrics of the Haptic Devices:

Results showed that the Traction Cylinder (*VC*) was reported as the most distinguishable. Comparing these results to the ones obtained on a query-by-query basis, it is observable that there is a difference between the device with greater $\%$ *of SAGAT Correct Answers* (*VB*) and the qualitatively reported device with greater distinguishability (*VC*). Participants might have wrongly identified the patterns of the cylinder in cases where the the back and forward pattern occurred in a small period and only a single direction pattern was displayed, while vibrotactile patterns differentiate in terms of actuation point, frequency and, amplitude. The obtained experimental data also shows that E-Vita (*VE*) was the haptic device with greatest levels of discomfort, fatigue and lowest level of distinguishability. These results are in agreement with the obtained results from the SAGAT. Based on the comments made by the participants, these greater levels of discomfort and fatigue might have occurred due the fact the most frequent textures during the trials (normal and stuck) displayed high friction. Better distinguishability would require the redesign of the provided textures.

During the design of the study, several decisions were taken to minimize the bias. Yet, one should keep in mind the study limitations when interpreting the obtained results. It was not possible to guarantee that, in each trial, all participants experienced the same quantity of “stuck” and “sliding” occurrences. Yet, in each trial, all participants experienced every traction states at least once. Due to time constraints, it was not possible to perform a statistical analysis of the results obtained from the NASA-TLX questionnaire. Future analysis of the task load during the different trials should be performed. Finally, the influence of the demographic characteristics of the participants in the results should be investigated. In particular, the possible influence of the usage of the non-dominant hand.

VII. CONCLUSIONS

In this paper we presented a teleoperation architecture comprising a laser-based traction detector module and a haptic interface to convey the detected traction states to the human operator, through different types of tactile stimuli, provided by three haptic devices (E-Vita, Traction Cylinder and Vibrotactile Glove). We also performed a user study where it was found an improvement when using the Vibrotactile Glove (*VB*) and the Traction Cylinder (*VC*) regarding comprehension of the UGV’s traction state, with respect to the exclusively visual modality (*V*). This newly integrated feedback modality in the RAPOSA-NG system will avoid overloading the visual sensory channel as more feedback is added to the current interface.

Finally, this work contributes to the HRI research community by presenting a simple but robust approach to a real-world problem of robotics, the lack of traction awareness during the teleoperation of a UGV.

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