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On the Use of Haptic Tablets for UGV Teleoperation in Unstructured Environments: System Design and Evaluation

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ABSTRACT Teleoperation of unmanned ground vehicles (UGVs), particularly for inspection of unstructured and unfamiliar environments still raises important challenges from the point of view of the operator interface. One of these challenges is caused by the fact that all information available to the operator is presented to the operator through a computer interface, providing only a partial view of the robot situation. The majority of existing interfaces provides information using visual, and, less frequently, sound channels. The lack of situation awareness (SA), caused by this partial view, may lead to an incorrect and inefficient response to the current UGV state, usually confusing and frustrating the human operator. For instance, the UGV may become stuck in debris while the operator struggles to move the robot, not understanding the cause of the UGV lack of motion. We address this problem by studying the use of haptic feedback to improve operator SA. More precisely, improving SA with respect to the traction state of the UGV, using a haptic tablet for both commanding the robot and conveying traction state to the user by haptic feedback. We report 1) a teleoperating interface, integrating a haptic tablet with an existing UGV teleoperation interface and 2) the experimental results of a user study designed to evaluate the advantage of this interface in the teleoperation of a UGV, in a search and rescue scenario. Statistically significant results were found supporting the hypothesis that using the haptic tablet elicits a reduction in the time that the UGV spends in states without traction.

INDEX TERMS Haptic interfaces, human–robot interaction, rescue robots, situation awareness, tactile tablet, telerobotics.

I. INTRODUCTION

Teleoperation can be seen as an extension of a person's sensing, decision making, and manipulation capability in a remote location [1]. Resorting to teleoperation of Unmanned Ground Vehicles (UGVs), humans are able to explore and act on remote, possibly inaccessible, possibly hazardous environments. Thus, UGV teleoperation is particularly advantageous in applications such as Urban Search and Rescue (USAR) [2], [3], [4], Explosive Ordnance Disposal [5], and Hazardous Material Handling [6], to name a few examples. However, when a mobile robot operates in a unstructured or highly dynamic situation, it may be difficult for the operator to accurately perceive the remote environment and make timely and effective control decisions [7]. Thus, the physical separation between the human operator and mobile robot during UGV teleoperation raises several challenges [8]. One particular challenge consists in providing an effective awareness of the robot situation, known as Situation Awareness (SA).

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The concept of SA was formally defined by Endsley [9] 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: (1) Perception is the lowest level of SA in which a person is capable of perceiving the relevant information provided by the system, (2) Comprehension is the middle level of SA in which a person is capable of understanding the meaning of the perceived information and integrate it with the operation goals, and (3) Projection is the 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. This projection of events and states will allow timely and effective decision making [9].

Despite the importance of SA during the teleoperation of UGVs, experience has shown that operators typically do not demonstrate sufficient awareness of the status and surroundings of the robot [10]. For example, in the case of the World Trade Center [3], [11], operators had difficulty building and maintaining the lowest levels of SA, and needed to compensate for lack of awareness by communicating with a partner. In UGV teleoperation, this lack of SA can lead to disorientation and cognitive mistakes (e.g., in decision making), which negatively impact overall performance during field missions [12].

This paper focuses on situations where a UGV loses traction, thus not behaving as the human operator expects given his/her commands. This traction loss usually occurs due to the irregularity of the terrain and unpredictability of the obstacles of the remote environment. Previous research reports occurrences of mobile robots becoming stuck during USAR operations and, due to the limited view of the on-board cameras, the operator was not able to diagnose the problem [3]. Scholtz [2] also reports many instances of robots getting stuck or entangled with obstacles, while the operators lacked sufficient SA to understand the cause of the entanglement. Operators inferred that something was wrong whenever the image received from the on-board cameras does not change, even though they are commanding the robot to move. In such situations, the lack of SA can lead to an incorrect and inefficient response to the current UGV state, usually confusing and frustrating the human operator [2]. Therefore, it becomes essential to have teleoperation interfaces that can provide adequate SA.

Due to the physical detachment between UGV and human operator, teleoperation interfaces are a crucial element to convey the information regarding the status of the robot and the remote environment [10], [13], [14]. Hence, it may become necessary for these interfaces to present a great quantity of information. However, the vast quantity of information should not clutter the visual feedback provided by the on-board cameras, needed for the main task, or hinder the search for the needed information. One way of reducing the burden on the visual channel is resorting to other human senses and provide multi-modal feedback in UGV teleoperation. In this paper, we explore visual and tactile modalities.

A review of the literature shows that enhancing the feedback provided to the human operator, during teleoperation, plays an important role in decreasing task difficulty and creating a greater sense of operator immersion in the remote environment [14], [2]. In particular, using haptic displays to supplement the visual channel without taxing the visual interface, can significantly improve the detection of faults, and serve as an effective cueing mechanism [15]. In teleoperation, haptic displays have been widely employed in two main applications: (1) to provide information concerning the location of the UGV and distance to the goal [16], [17], and (2) to provide warning cues regarding the presence and proximity of surrounding obstacles [18]. Previous applications resorted to haptic cues such as vibration [19], force [20], [21], electro-tactile [22] feedback, and a combination of kinesthetic, tactile, and vibratory cues [23]. Haptic feedback provides the operator with more comprehensive knowledge and enhances the sense of being present in the remote environment, thereby improving the ability to perform complex tasks [2].

Our approach focuses on exploiting E-Vita [24] (see Fig. 1), a haptic tablet, to control RAPOSA-NG [4] (see Fig. 2), a UGV, and provide haptic feedback regarding its current state. In particular, E-Vita aims to enhance the SA of the human operator in situations where a UGV loses traction, by providing friction feedback on the screen of the device.

The major contributions of this paper are two-fold. On the one hand, the integration of the haptic tablet in the teleoperation architecture of a UGV, designed for non-expert system users. On the other hand, we contribute with a detailed user

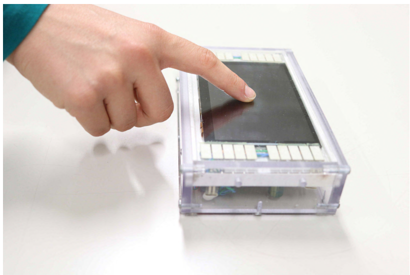


FIGURE 1. E-Vita, a haptic tablet capable of modifying the perception of texture on the screen of the device.

FIGURE 2. RAPOSA-NG, a tracked wheel search and rescue UGV prototype.

study to evaluate the advantages of the haptic tablet in UGV teleoperation. This evaluation was performed in comparison to a conventional interface (we used a gamepad) and involved the teleoperation of a UGV on locomotion challenging scenarios.

Comprehensive work was developed integrating haptic feedback in teleoperation interfaces and demonstrate its advantages in improving SA of the human operator. However, in what concerns the use of touch devices, a review of the literature shows that participants frequently need to pay attention to the touch controls because they lack the haptic cues to aid their performance. The novelty of our approach consists in the addition of haptic cues to the use of touch interfaces for the teleoperation of UGVs. As far as we know, this is the first paper that uses a haptic tablet to teleoperate a UGV and provide tactile feedback to the human operator.

This paper is structured as follows: Section II presents a brief review of related work concerning current applications of tactile tablets and the use of touch interfaces in UGV teleoperation, Section III presents the teleoperation architecture and the design of its different modules, Section IV reports the method employed during the user study, Section V presents the obtained results and discussion, and Section VI presents our conclusions.

II. RELATED WORK

When designing interfaces, the designer must carefully choose control methods that give clear affordances and appropriate feedback to the user [13]. In UGV teleoperation, a review of the literature reveals diverse approaches concerning input modalities. Some of these approaches include the use of joystick and button based gamepads [3], mouse and keyboard [13], steering wheels [21], gestures based controls [26], haptic controllers [27], and touch devices [13], [28], [30]. Nevertheless, the gamepad is still one of the most mainstream input modalities in UGV teleoperation [2], [7], [29] because it is portable, durable and ergonomically designed [30]. For that reason, the current research, when presenting novel input modalities, utilizes the gamepad as a baseline comparison [13], [28], [30].

With the widespread usage of touch devices (e.g. smartphones and tablets), the applications of this technology in UGV teleoperation naturally arises. With a touch device, there is greater freedom in control definition when comparing to a joystick-based gamepad. A joystick can restrict the user to a relatively small set of interaction possibilities while a touch device allows for numerous interaction methods using a large set of gestures on a 2D plane [13]. However, the flexibility of the interface also presents a problem for the designer, who must carefully choose control methods that give clear affordances and appropriate feedback to the user. Additionally, touch devices allow for control using only one hand. This is particularly useful in field missions, where the operator must put down the controller to respond to the radio query [30].

Keyes [13] and Pettitt [30] have previously reported on the use of touch interfaces for the teleoperation of a UGV. Keyes [13] investigated the impact of a multi-touch interaction device on robot control. The developed work intended to allow users to more directly interact with the robot and affect its behavior. Results showed that performance was not degraded by the act of porting the previously developed interface to a touch table and that further optimization could be performed, regarding the design of multi-touch interaction. Pettitt [30] performed an evaluation of controller options by comparing a gamepad with a tablet computer for UGV teleoperation. There was no significant difference in terms of driving errors between the controller conditions. Even though operators expressed an overall preference for the gamepad, with this controller, they were unable to make the robot perform small and precise movements. However, in both studies, participants had to visually pay attention to where the virtual joystick was placed relative to the direction they wanted the robot to move because they lacked haptic cues. Our paper presents a potential solution to this deficiency by utilizing a touch device capable of providing haptic feedback to the human operator.

Haptic interactive systems have known, in the recent years, a strong scientific and technological activity. Technologies emerge, that allows to co-locate tactile and visual information. Vibrotactile systems [24] offer a rich feedback, for which the question to target most relevant application remains an open question. Some practical interest for interaction have previously been demonstrated [31] and a lot of improvements are currently being achieved on such technology [32], [33]. In the present work we explore the practical gain in using such interface for teleoperation of a UGV.

III. APPROACH

In this paper, we present a functional teleoperation architecture that incorporates: (1) a tracked wheel UGV with given wheel odometry and a laser rangefinder, (2) a laser-based traction detector module, to discriminate between traction losses (stuck and sliding) and (3) a haptic tablet to control the UGV and convey the detected traction state to the human operator through different tactile stimuli. As a case study, RAPOSA-NG, a search and rescue UGV, was used. Notwithstanding, the extent of the presented work goes beyond USAR operations and can be employed in various UGV teleoperation applications.

In this Section, a brief introduction regarding the interface used in the particular case of RAPOSA-NG and the traction detection module is performed. Furthermore, we explain, in detail, the system of the haptic tablet and its integration in the UGV teleoperation interface.

A. RAPOSA-NG, A SEARCH AND RESCUE UGV

RAPOSA-NG (See Fig. 2) is a tracked wheel search and rescue UGV prototype designed to perform structural inspection of an endangered area and teleoperated detection victims [4], [12]. The sensors on-board the UGV provide information

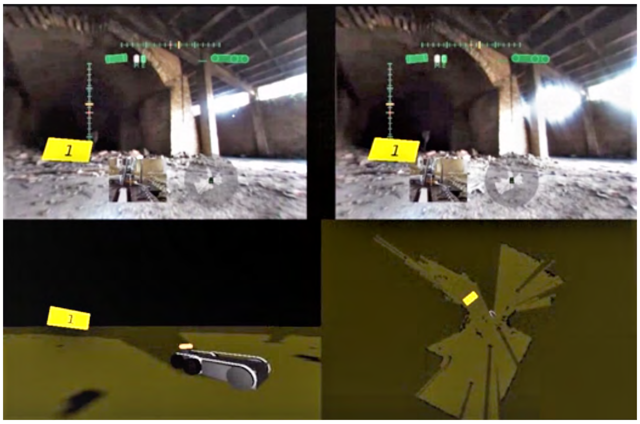


FIGURE 3. Screenshot of the GUI of the teleoperation console including an interactive 3D virtual mode (top), and a real-time 2D map (bottom). The 3D virtual mode includes stereo and rearview images from the on-board cameras, robot status, and map.

regarding the robot status, including robot attitude, battery level, and robot position in the mapped area. This information is then provided to the user through the teleoperation interface to enhance its SA.

1) THE VISUAL INTERFACE

The image provided by the on-board cameras and the status of the robot are conveyed to the user using a visual augmented reality Graphical User Interface (GUI), shown in Fig. 3. The visual interface was designed to provide immersive navigation that resorts to augmented reality to mark points of interest in the explored area (yellow markers shown in Fig. 3. The features of this visual interface were developed to enhance the SA of the operator. However, this interface still required the users to estimate the current traction state of the UGV based on subtle visual cues. In cases of traction loss, the user needed to integrate the motion of the image, to know the real movement of the UGV, with the visual indicators regarding the movement of the tracks. Still, in cases where the UGV was unable to comply with the given commands, due to traction loss, the situation was frequently mistaken for a communication or hardware problem. Therefore, we developed a traction detection module to discriminate between traction losses (stuck and sliding) and enhance SA of the user regarding the traction of the UGV.

2) THE PREVIOUS CONTROL METHOD: GAMEPAD

RAPOSA-NG is a tracked wheel robot with two pairs of tracked wheels, with one pair on each side and coupled between two different bodies: a base body and a frontal body. The robot motors are controlled by the human operator using a gamepad (Rumblepad$^{\text{TM}}$2 from Logitech). The velocity of each pair of tracks can be controlled to move the robot with 2 degrees of freedom, and the angle of the frontal body can be modified to overcome obstacles and stairs while traversing unstructured environments. The operator can also control the camera orientation; however, this feature was not used in the study (the camera orientation was held fixed).

TABLE 1. Classification of UGV traction states based on the comparison between expected motion (Tracks) and the actual motion (UGV) of the robot.

Traction State	Tracks	UGV
Normal	Stopped	Stopped
	Moving	Moving in the same direction
Stuck	Moving	Stopped
Sliding	Moving	Moving in a different direction
	Stopped	Moving

3) TRACTION DETECTION MODULE

Typical situations causing loss of traction are obstacles that either block the motion of the robot or lift 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.

To improve the SA of the human operator, regarding the traction state of the robot, haptic feedback is provided to the operator during teleoperation. This feedback is based on the output of a traction state classification module described with detail in [8]. This method is based on determining whether there is a mismatch between the expected motion, given by tracked wheel odometry, and the actual motion, given by laser-based odometry. From this comparison, the traction state is estimated. This module discriminates between three possible traction states: *normal*, *stuck*, and *sliding*, as summarized in TABLE 1. For instance, if the robot is moving according to the tracks odometry but not according to the laser-based one, the estimated robot state should be *stuck*.

Once the traction state has been estimated, it can be conveyed to the human operator through different tactile stimuli. Previous research [8] shows that the use of haptic feedback can improve the comprehension of the traction state of the UGV when comparing to exclusively visual modality. These results were obtained when we conveyed the traction state of the UGV trough *vibration*, using a vibrotactile glove, and through *friction*, using a rotating cylinder in contact with the operator's hand.

In the previous integration of E-Vita into the teleoperation architecture of RAPOSA-NG, the human operator could only receive feedback and was not able to control the motion of the robot. In this paper, we present our strategy toward enhancing the interaction with E-Vita by utilizing it as a bilateral device. This way, the human operator, in addition to receiving haptic feedback, can also use E-Vita to provide motion commands, as described in Section III-B. This new iteration of the haptic tablet in UGV teleoperation was a product of the lessons learned in the previous study [8] and the limitations presented by the state of the art.

B. E-VITA, THE TACTILE TABLET

1) SYSTEM DESCRIPTION AND INTEGRATION

E-vita is a multimodal haptic system, that is able to create a tactile stimulation to user's fingertip when it is sliding

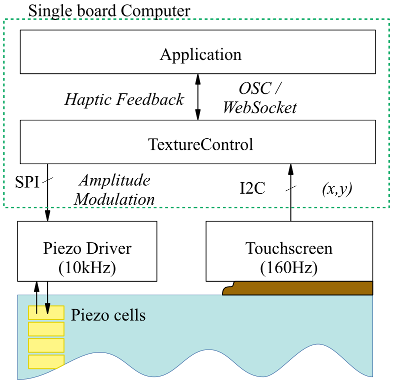


FIGURE 4. Representation of the framework (TextureControl) that ensures high fidelity haptic rendering with a low bandwidth touch sensor.

along the device [24], [25]. For that purpose, a glass plate is actuated by two layers of 10 piezoelectric actuators each, at an ultrasonic frequency (66kHz), and low vibration amplitude (around 1μm peak to peak). This vibration is not directly perceived by the user, but it has an effect on the tribological contact conditions between its fingertip and the glass plate: friction is reduced when vibration occurs, a phenomenon called ‘‘active lubrication’’. A projected capacitive touch sensor, placed between an LCD display and the glass plate can precisely measure finger’s position at a frame rate of 160Hz and a resolution of $125\mu m$. By modulating the vibration amplitude as a function of the position, it is possible to create several stimuli, like gratings, for instance, [34].

The visual feedback, provided by the LCD display, and the tactile feedback, produced by the glass plate, is managed by a single board computer (bananapi from bpi-China, running Linux). To produce a high fidelity tactile feedback, it is necessary to ensure a high sampling rate for the vibration modulation (around 2kHz), so as for the finger’s position measurement. Due to the low frame rate of the touchscreen, a specific framework has been developed. This framework consists of a haptic thread named TextureControl (see Fig. 4). The position of the finger is obtained directly from the capacitive touch sensor, which calculates the vibration amplitude modulation based on a *velocity algorithm* [24]. Then, the main application, running at a slower rate and managing the visual feedback, gets the finger’s position from an Open Sound Communication (OSC) software link, provided by the haptic thread. The main application then sends, through this OSC link, the type of haptic feedback to produce. This organization is versatile, allowing accurate haptic rendering, yet, easy implementation of the haptic feedback within multiple applications.

Finally, the integration of E-Vita with the teleoperation system was performed using the ROS platform. The communication between RAPOSA-NG and E-Vita was accomplished using a WebSocket communication protocol. E-Vita was connected to the teleoperation PC, via ethernet, and the operator could control the movement of the robot (Section III-B.2) and receive haptic feedback regarding the traction state of the UGV (Section III-B.3). A scheme of the integrated teleoperation architecture is presented in Fig. 5.

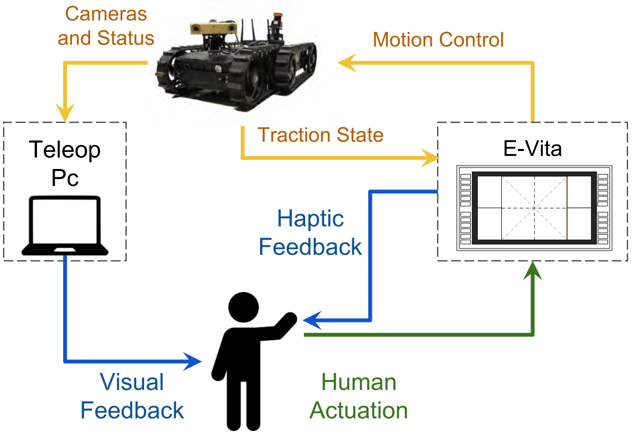
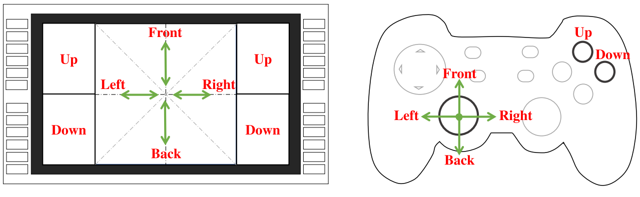


FIGURE 5. Functional architecture proposed in this paper, incorporating: (1) the UGV, (2) the laser-based traction detector module, and (3) the haptic tablet to control the UGV and receive haptic feedback.



(a) E-Vita. (b) Gamepad

FIGURE 6. Representation of the available controls concerning the robot motion. Here, the arrows represent the motion of the finger and the words indicate the implications in the motion of the robot: Front/back the robot moves forward/backward; left/right the robot rotates do the left/right; up/down the angle of frontal body of the robot increases/decreases.

2) THE CONTROL METHOD: VIRTUAL JOYSTICK

With the tactile screen of E-Vita, the operator can control the velocity and the frontal body of RAPOSA-NG. Here, alternatively to buttons and joysticks, the operator controls the robot by sliding the finger on various areas of the screen. These areas of the screen and gestures were chosen in a way that resembled the controls of the gamepad, shown in Fig. 6, creating this way a virtual joystick.

Two main areas of the screen were defined. First, the Virtual Joystick (VJ) area, that maps the translation (front/back) and rotation (left/right) of the robot. Second, the button area, that raises (up) and lowers (down) the frontal body of the UGV. The button area was placed symmetrically on both sides of the screen to take into account right and left-handed operators. The VJ area was placed in the center of the screen. In this area, vertical movements of the finger on the screen yields translation of the robot, horizontal movements yield rotation, and diagonal movements yield the combination of these two motions. The position of the finger, in relation to the center of the screen, was decomposed in two components: horizontal and vertical, which were then mapped to each component of the velocity of the robot, translation and rotation respectively.

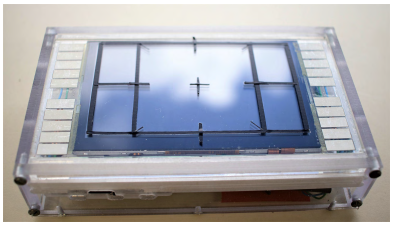


FIGURE 7. **Haptic aids placed in the screen of the tablet for the user to know the limits of the screen areas, the center of the screen and direction of the motion.**

Previous research [13] has shown that users are accustomed to haptic feedback, such as spring-loaded buttons and gimbals, even from a non-force-feedback joystick controller. Participants had to visually pay attention to where the virtual joystick was placed relative to the direction they wanted the robot to move because they lacked haptic cues. When using a touch tablet this kind of feedback is not available. Therefore, a set of simple haptic aids, created with narrow bands of duct tape, were added to the screen as shown in Fig. 7. This way, the user can know the limits of the screen areas (VJ or button area), the center of the screen and direction of the motion (front/back and/or left/right) without the need to look at the screen of the tablet. Moreover, no apparent difference was found in texture perception due to the addition of these aids to the screen.

3) THE HAPTIC FEEDBACK: TACTILE TEXTURES

In addition to controlling the motion of the robot, E-Vita is also used to provide haptic feedback to the user. This feedback conveys, to the human operator, information about the traction state of the robot. Our detection approach defines three possible traction states: normal, stuck, and sliding. Hence, it was necessary to design three different haptic textures to transmit each possible traction state:

- **Normal**: No friction is displayed on the screen. In this case, E-Vita works as a conventional touch screen. This way we can minimize the fatigue, due to high friction, during the normal operation of the robot.
- **Stuck**: A very rough (high friction) texture is displayed in the VJ area when the user slides the finger along the screen (Fig. 8a). Because the stuck state was the most common and critical traction loss situation, it was necessary to generate a strong texture through a high friction pattern.
- **Sliding**: A piano-like texture is displayed in the VJ area (Fig. 8b). This texture was chosen to create a distinguishable texture when comparing to the stuck texture. Here, instead of modifying only the displayed friction, we designed a pattern where the user feels slight protrusions as the finger slides along the screen.

IV. EVALUATION

A. DESIGN

We conducted an user study to evaluate the architecture presented in Section III-B. The goal of this user study is to evaluate the viability of using E-Vita to control RAPOSA-NG and receive feedback regarding its traction state. With this user study, we intend to answer one research question:

> *How is driving performance and traction awareness influenced by the use of a tactile tablet (E-Vita)?*

To answer to this question, the UGV's teleoperation was evaluated in two teleoperation setups. In the first one (*EV*), the participants use E-Vita to teleoperate the robot and to receive haptic feedback regarding the traction state of the UGV, shown as different textures in the screen. In the second one (*GP*), the participants use the gamepad to control the robot and without any haptic feedback.

The evaluation of the proposed system was performed using a gamepad without feedback for two main reasons:

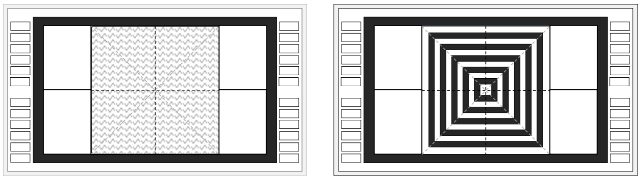
- The literature reveals diverse approaches concerning UGV input modalities. One of the most mainstream input modalities in UGV teleoperation is the joystick and button based gamepad (without haptic feedback) [7], [2], [29].
- Previous research compared input and feedback devices with a gamepad (without feedback), particularly when evaluating touch interfaces. [13], [28], [30]. Thus, with this user study design, we intended to maintain the same baseline for comparison purposes.

By comparing these two teleoperation setups, *EV* and *GP*, we intend to evaluate the use of a haptic tablet (E-Vita) in teleoperation of an UGV in comparison to a widely used and well established interaction method (Gamepad). To perform this comparison, we used a within-subject design with all participants using both the E-Vita (*EV*) and Gamepad (*GP*) control methods.

B. EXPERIMENTAL APPARATUS

During the user study, each participant sat in front of a desk containing the teleoperation computer and the control device (Gamepad or E-Vita). We called this area the *teleoperation station*. During the two trials, the teleoperation computer displayed the image from the camera onboard the robot (visual feedback), placed in the *exploration area*.

The *exploration area* (see Fig. 9 and 10) was built with the intention of resembling, in a simplistic way, a search and rescue environment. This area (3 × 3.50 meters) was built in such way that along the path the UGV had a high probability



(a) In the "stuck" state, a very rough texture is displayed.

(b) In the "sliding" state, a piano-like texture is displayed.

FIGURE 8. **Representation of the textures provided by E-Vita to the operator when UGV loses traction.**

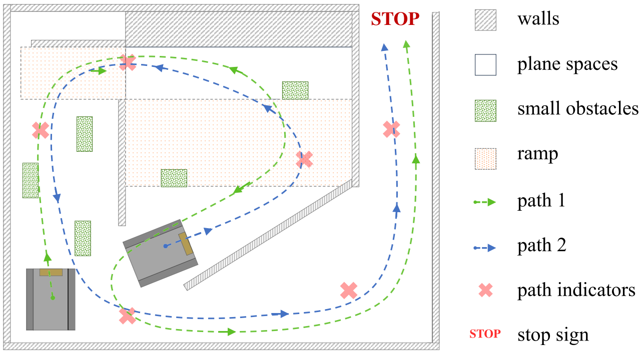


FIGURE 9. **Representation of the space components of the *exploration area* shown in Fig. 10.**

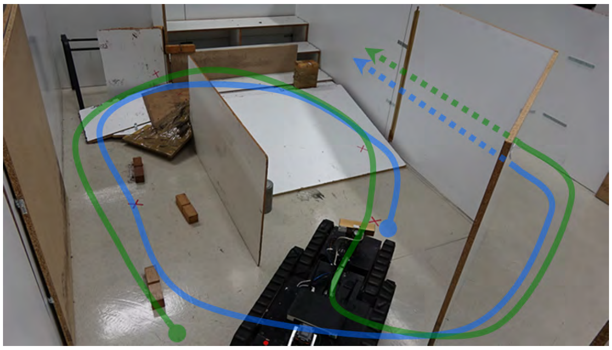


FIGURE 10. **Photo of the *exploration area* used during the user study. Here, the colored lines correspond to the exploration paths represented in Fig. 9.**

of going through all of the possible traction states (normal, stuck, and sliding). There was no way to ensure that every participant had exactly n occurrences of each traction state in all trials since this variable depended on the performance of each participant. Therefore, the scenarios were designed to have areas where the probability of occurrence of a specific traction state was higher. For example, there was an area with small obstacles and another with small navigation spaces to increase the probability of the robot becoming stuck, and two areas with ramps to increase the probability of the robot sliding. In the *exploration area*, were marked several red "X" to provide guidance to the participants regarding the path to take. The marked "X" intended to make sure that the participants took the path that would promote plenty of traction loss occurrences.

C. PROCEDURE

1) PARTICIPANTS

Twenty unpaid subjects aged between 21 and 62 years voluntarily participated in the user study. The required amount of participants was the result of a power analysis performed prior to the beginning of the study. The analysis revealed that it was required a minimum of 10 samples per condition (two conditions, total 20 participants). The participants were on average 30 years old. Regarding gender, five participants were female and fifteen male. Eighteen of the participants were right-handed and two were left-handed. All participants were non-english native speakers. Six participants had prior experience teleoperating RAPOSA-NG, nine had prior knowledge regarding the maps to be explored during the several trials and none of the participants was an expert operator.

2) INSTRUCTIONS AND DEMOGRAPHIC QUESTIONNAIRE

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. This demographic questionnaire included questions regarding age, nationality, dominant hand, previous experience teleoperating RAPOSA-NG and knowledge about the *exploration area*.

3) TRAINING SESSION

Before every trial, the participants completed one training session. During the training session the participants got familiarized with the teleoperation interface, the robot operation, and the control device to be used in that trial (Gamepad or E-Vita). During this period (minimum of 15 minutes) the participants had direct visual contact with the robot and were free to control it while having access to the visual feedback from the on-board cameras and the control device. Instructions about the available controls (move front/back, rotate left/right and change the arm position) were explained and demonstrated by the experimenter of the user study. Additionally, the participants were shown the different possible traction states of the robot, their implications for the robot's movement and possible actions required for the robot to overcome such states (stuck and sliding). Finally, to ensure the proficiency in the control device (gamepad and e-vita), the participants were asked to overcome a small obstacle while the robot was not in line of sight.

4) LOCOMOTION CHALLENGES

After the training session, each participant completed two navigation trials: Gamepad with no feedback (*GP*) and E-Vita with haptic feedback (*EV*) in one of the two trial orders: (*EV*, *GP*) and (*GP*, *EV*). During the trial, the participant had to follow multiple red "X" signs placed on the walls and floor of the exploration area until finding the "Stop" sign. Moreover, the participant had to accomplish the given task within the shortest amount of time possible. In each trial the robot had to traverse one of the two available paths. Due to the existence of space limitations, these two paths were created in the same asymmetric exploration area as illustrated in Fig. 9 and Fig. 10. These two paths included positioning the robot in different starting positions and explore the arena through different orientations to reach the same end position. These paths were also considered in the trials permutations to eliminate learning effects.

After crossing the "Stop" sign the participants pressed the "S" key, on the keyboard of the teleoperation PC, to terminate the task. The trial had a time limit of six minutes. If after the six minutes the participant did not crossed the "Stop" sign, the trial would be automatically terminated (time out). A trial was classified as successful when the participant reached the end of the path and pressed the key to stop the trial. Hence, every time out is recorded as a failed trial.

5) POST-TRIAL QUESTIONNAIRES

After each trial, the participants answered a post-trial SA Rating Technique (SART) questionnaire [35] to assess their SA during the trial. Once the two trials were completed, participants were inquired regarding their preference and comments on positive and negatived aspects of the control devices.

D. MEASURES

Experimental methods for measuring SA fall into three categories [10], [38]:

1) Subjective: participants rate their own SA (e.g. SAGAT or SART [35]).
2) Implicit performance: Experimenters assess task performance, with the assumption that the performance of the participant correlates with SA. Furthermore, that improved SA will lead to improved performance.
3) Explicit performance: Experimenters directly probe the SA of the participants by asking questions during short halts of the task (e.g. SPAM [36]).

To evaluate E-Vita device in comparison to the Gamepad, we chose to use mainly implicit measures. This way, we could associate the task outcome with the SA of participant without interrupting the natural flow of the task by using online or freezing probes. Alternatively, previous research explored the use of an eye tracker device to obtain implicit measures of the operator SA [37]. However, in this particular application (traction state awareness) may not have sufficient visual clues, in the image from the onboard camera, to fully assess the awareness of the operator regarding traction loss, and corresponding state, since this one requires the integration of several elements that may or may not be visible in the image (e.g. obstacles blocking the tracks).

Therefore, to assess the SA of the participants, we recorded the task completion time, mean duration of each traction state, and the frequency of returning to each traction state. Here we assume that, a lower task completion time, a lower mean duration of the traction states, and a lower frequency of each traction state, implies a better SA. Regarding state occurrence frequency, we assume that a lower value of this variable implies a greater performance and SA. Participants that less frequently lose traction (stuck or sliding) will reach the end of the course faster, thus have a higher performance. Ideally, the human operator, teleoperating the UGV, would have such high performance that the UGV would never lose traction.

Additionally, the participants performed a post-task subjective assessment of their performance through a SART questionnaire. However, we did not assign significative importance to this subjective assessment, as this one is highly subjective [13].

V. RESULTS AND DISCUSSION

To analyze the data collected during the trials, a three-way ANOVA was performed for each measure. In the cases where the assumption of sphericity was violated, we performed a Greenhouse-Geisser correction. When an interaction between factors was found, we performed a *post hoc* pairwise comparison. All statistically significant results are presented below. Moreover, learning effects regarding traverses paths were tested for all measures. The analysis showed no interaction between the factor *Paths* and the remaining factors.

A. DURATION OF TRACTION STATE (DTS)

An analysis of the *duration of traction state* (*DTS*) with the following factors: *Traction State* (3 levels), *Device* (2 levels), and *Paths* (2 levels) was performed.

1) INTERACTION BETWEEN TRACTION STATE AND DEVICE

The data regarding *DTS* violated the assumption of shphericity ($p = 0.028$). The consequent analysis showed an interaction between the factors *Traction State* and *Device* ($F(1.256, 11.305) = 5.018, p = 0.040$). *Post hoc* tests using the Bonferroni correction revealed that, for the stuck state, the GP condition had a higher duration than the EV condition ($0.724 \pm 0.054\ s$ vs $0.484 \pm 0.028\ s$, respectively). These results are presented in Fig. 11 and were statistically significant ($p = 0.001$).

The fact that participants spent less time in stuck state and more time on the normal state when using E-Vita, compared to the GP condition, show us, in an implicit way, that the use of E-Vita improved the traction awareness of participants. Regarding the sliding state, there was no statistically significant results.

Additionally, these results show that using haptic tablets in UGV teleoperation could be useful to reduce the time that human operators are stuck. This is useful to reduce confusion and frustration, felt by human operator when the robot is unable to move due to traction loss.

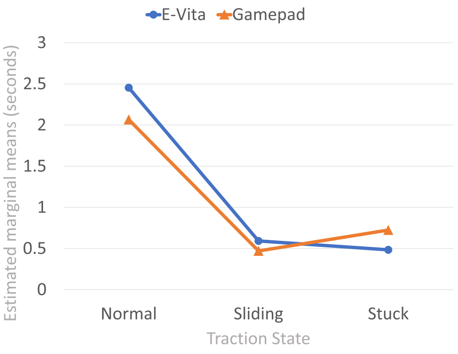


FIGURE 11. **Results from the DTS measure. Statistically significant interaction between the factors *Traction State* (normal, stuck, and sliding) and *Device* (E-Vita, and Gamepad). For the stuck state, the GP condition had a higher DTS than the EV condition.**

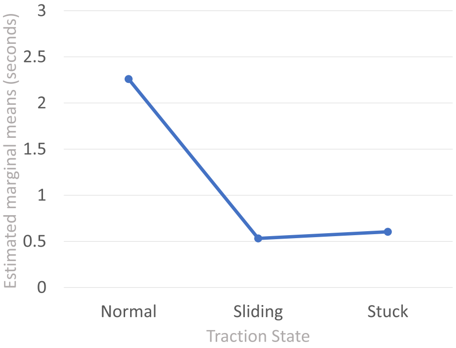


FIGURE 12. Results from the DTS measure. Statistically significant difference between levels of the factor *Traction State* (normal, stuck, and sliding). DTS on the normal state was greater than DTS on the sliding and stuck states.

2) DIFFERENCE BETWEEN TRACTION STATES

The data regarding *DTS* violated the assumption of sphericity ($p = 0.004$). The consequent analysis showed a statistically significant difference between the three levels of *Traction State* ($F(1.140, 10.261) = 106.476, p < 0.0001$). *Post hoc* pairwise comparison revealed: (1) participants spent, on average, 1.728 seconds more in the normal state than in the sliding state ($p < 0.0001$), and (2) participants spent, on average, more 1.656 seconds in the normal state than in stuck ($p < 0.0001$). These results are shown in Fig. 12.

B. TASK COMPLETION TIME (TCT)

An analysis of the *task completion time* with the following factors *Traction State* (3 levels), *Devices* (2 levels), and *Paths* (2 levels), no statistically significant difference was reported.

These results show that, even though the participants spent less time in stuck state when using E-Vita, the total task time was not influenced by the choice of device. Additionally, it confirms that the extra time spent on stuck state in the GP in relation to EV condition, is in detriment of the time spent on the normal state.

Regarding the success or failure of the task, there was insufficient data to perform a reliable analysis. During the execution of the study, every trial was classified as successful when the participant reached the end of the path and pressed the key to stop the trial. However, some participants reached the end of the course, forgot to press the key to stop the trial and waited for the time-out. Moreover, there were cases where participants reached the end of the course close to the time out and did not have time to press the key. Nevertheless, given the recorded data regarding failed trials, a Wilcoxon signed-rank test showed that the device (EV or GP) did not elicit a statistically significant change in success or failure of the navigation tasks.

C. TRACTION STATE OCCURRENCE FREQUENCY (TSOF)

An analysis of the *traction state occurrence frequency* (*TSOF*) with the following factors: *Traction State* (3 levels), *Devices* (2 levels), and *Paths* (2 levels) was performed.

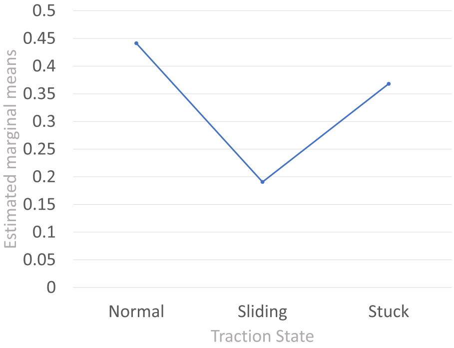


FIGURE 13. Results from TSOF measure. TSOF of the normal state was greater than the sliding and stuck states. TSOF of the stuck state was greater than sliding.

The data of the metric *TSOF* violated the assumption of sphericity ($p = 0.042$).

There was a significant difference between traction states regarding the *traction state occurrence frequency* ($F(1.029, 0.009) = 116.406, p < 0.0001$). The statistically significant differences between the different levels of the *Traction State* were: (1) the frequency of the normal state was 25.1% greater than the sliding state ($p < 0.0001$), (2) the frequency of the normal state was 7.3% greater than the stuck state ($p < 0.0001$), and (3) the frequency of the stuck was 17.7% greater than the sliding state ($p < 0.0001$). These results are presented in Fig. 13. No difference was found between levels of the remaining factors (*Devices* and *Paths*). No interaction was found between the three factors (*Traction State*, *Device*, and *Path*).

The results regarding the interaction between the different levels of the factor *Traction State* (normal, stuck, and sliding) confirm our previous observations of RAPOSA-NG during field operations. The human operators are more frequently in a state with traction (normal operation of the UGV) than the one without traction (stuck and sliding). Also, the operators more frequently go through the stuck state than sliding.

D. POST-TASK QUESTIONNAIRE - SART

To analyze the data collected from post-task questionnaire, we used a one-way repeated measure ANOVA. An analysis of the *SA Scores*, obtained from the SART questionnaire, with factor *Device* (2 levels) was performed. No interaction between the *SA Scores* and the *Devices* (E-Vita and Gamepad) was found.

Participants commented that, due the high complexity of the queries of the SART questionnaire, they add difficulty framing the question within context of the performed task and could not provide an accurate answer. Therefore, we did not assign a significant importance to this subjective measure.

E. PARTICIPANTS AND DEMOGRAPHIC INFORMATION

After the statistical analysis of all the above metrics, we analysed the influence of the demographic characteristics of the participants in the obtained results. Because we verified that there was no interaction between the factor *Path* and all the remaining factors, for the study of the demographic data we did not considered this factor to simplify the analysis. The following analyses were performed:

- three-way repeated measures ANOVA analysis for measure of DTS with factors: *Previous Experience with RAPOSA-NG* (2 levels), *Device* (2 levels), *Traction State* (3 levels).
- three-way repeated measures ANOVA analysis for measure TSOF with factors: *Experience with RAPOSA-NG* (2 levels), *Device* (2 levels), *Traction State* (3 levels).
- two-way repeated measure ANOVA analysis for measure TCT with factors: *Experience with RAPOSA-NG* (2 levels), *Device* (2 levels).
- two-way repeated measure ANOVA analysis for measure TCT with factors: *Previous Knowledge about the Path* (2 levels), *Device* (2 levels).

No interaction was found between the demographic information and any of the listed analysis. However, there was a slight tendency for smaller total task time when participants knew the scenarios (36 seconds).

F. PREFERENCE OF DEVICES

When asked what device they preferred, 85% of the participants chose the gamepad (statistically significant difference). Most participants justified their preference of the gamepad over the E-Vita, by saying that the gamepad was more familiar, ergonomic, and required less effort. Still, the gamepad lacked the information about traction, which was useful. In the future it would be interesting to have stronger textures and convey textures that do not require the user moving the finger. Participants still prefer the gamepad over a tactile tablet in teleoperation. These results are similar to the preference shown by the participants in previous use of touch interfaces for UGV teleoperation [13], [30].

G. RESEARCH QUESTIONS AND LESSONS LEARNED

With this user study, we intended to evaluate the use of a haptic tablet in the teleoperation of a UGV, when compared with the use of a gamepad. To do so, we defined one research question: *How is driving performance and traction awareness influenced by the use of a tactile tablet?*

As mentioned in Section IV-D, to evaluate the SA of the participants we recorded several implicit measures: DTS, TCT, and TSOF. Results showed that participants spent significantly less time in stuck state and more time on the normal state when using E-Vita, compared to the Gamepad condition. Consequently, we can conclude that traction awareness improved when using E-Vita.

Regarding driving performance, we evaluated this factor based on the TCT measure. Because the goal of the task was navigating through the scenario and reach the stop sign as fast as possible, we correlated the performance of the participants with the TCT measure. Here, a smaller task completion time implies better performance. Thus, experimental results show no significant change in driving performance when using E-Vita.

With this user study, we learned several lessons. Firstly, the need for constant movement of the finger to control the UGV can lead to fatigue. Henceforward, it would be advantageous to have haptic tablets able to provide texture feedback that do not require the user to move the finger. Secondly, the use of the haptic aids on the screen helped the participants to be aware of the screen area they were touching. When asked about this aspect of the interface, some participants commented that they did not feel any difficulty. This was particularly useful because it allowed the participants to concentrate on the available feedback (visual and haptic) rather than focusing on the control inputs.

VI. CONCLUSIONS

In this paper we presented a functional architecture for UGV teleoperation that integrates: (1) a tracked wheel UGV, (2) a laser-based traction detector module that discriminates between traction losses (stuck and sliding) and (3) a haptic tablet (E-Vita) to control the UGV and convey the detected traction state to the human operator through different tactile patterns. The presented architecture aims at enhancing the SA of the human operator during UGV teleoperation. In particular, we focused on situations where a UGV lost traction, thus rendering it unable to comply with the given commands.

We used the human haptic channel to provide feedback to the operator, thus reducing the visual overload imposed by some GUIs.

We assessed the advantages of the presented teleoperation architecture by means of a user study. This evaluation compared the use of a tactile tablet with a conventional gamepad for the teleoperation of a UGV, deployed on locomotion challenging scenarios. During the tasks (navigation challenges) the UGV was less time stuck when participants used E-Vita, as a consequence of improved traction awareness of participants. Moreover, no difference was found regarding the completion task time. Thus, the performance of the participants was not affected by the device. Similarly to the literature, most participants still preferred the use of a gamepad, over a tactile tablet, due to its greater familiarity and ergonomy. However, due to the growing use of touch devices (smartphones, tablets, PCs), the familiarity with this type of device and the need for richer feedback may increase in the future.

Finally, the novelty of our approach consists of the successful integration of haptic cues, regarding traction state, to the use of touch interfaces for UGV teleoperation in unstructured environments. Although a USAR UGV was used as a case study, the extent of the presented work goes beyond USAR operations and can be applied to various UGV teleoperation applications.

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