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Electrifying Obstacle Avoidance: Enhancing Teleoperation of Robots with EMS-Assisted Obstacle Avoidance

Ambika SHAHU [a,1], Khaled KASSEM [a], Leonhard ZEHETGRUBER [a], Philipp WINTERSBERGER [b], Florian MICHAHELLES [a]
[a] *TU Wien,* [A] *{ambika.shahu, khaled.k.kassem, e11810914, florian.michahelles}@tuwien.ac.at*
[b] *FH Hagenberg,* [B] *philipp.wintersberger@fh-hagenberg.at*

Abstract. We investigate how the use of haptic feedback through electrical muscle stimulation (EMS) can improve collision-avoidance in a robot teleoperation scenario. **Background:** Collision-free robot teleoperation requires extensive situation awareness by the operator. This is difficult to achieve purely visually when obstacles can exist outside of the robot's field of view. Therefore, feedback from other sensory channels can be beneficial. **Method:** We compare feedback modalities in the form of auditory, haptic and bi-modal feedback, notifying users about incoming obstacles outside their field of view, and moving their arms in the direction to avoid the obstacle. We evaluate the different feedback modalities alongside a unimodal visual feedback baseline in a user study ($N = 9$), where participants are controlling a robotic arm in a virtual reality environment. We measure objective performance metrics in terms of the number of collisions and errors, as well as subjective user feedback using the NASA-TLX and the short version of the User Experience Questionnaire. **Findings:** Unimodal EMS and bi-modal feedback outperformed the baseline and unimodal auditory feedback when it comes to hedonic user experience ($p < .001$). EMS outperformed the baseline with regards to pragmatic user experience ($p = .018$). We did not detect significant differences in the performance metrics (collisions and errors). We measured a strong learning effect when investigating the collision count and time.**Key insights:** The use of EMS is promising for this task. Two of the nine participants reported to experience some level of discomfort. The modality is best utilized for nudging rather than extended movement.

Keywords. Robot, Teleoperation, Virtual reality, Electrical muscle stimulation, User study, Human-in-the-loop, Human-robot collaboration

1. Introduction

Robot teleoperation has applications in many domains, including search and rescue (1), space exploration (2), mining (3), tele-manufacturing (4), or surgery (5). The use of robot teleoperation allows for a combination of human and robotic traits to be utilized in a variety of settings, aiming to improve safety, efficiency, and productivity. This is especially valuable to combine the advantages of both humans (creativity, problem-solving, fast

[1]Corresponding Author: Ambika Shahu e-mail: ambika.shahu@tuwien.ac.at

adaptation, etc.) and robots (speed, precision, safety-critical environments, etc.). However, it is challenging to achieve the situational awareness required for collision avoidance (6; 7). Multimodal interfaces may help the human operator better perceive, understand, and predict the environment around the robot, leading to improved situational awareness and more informed decision-making. Vision can be used to provide the operator with a view of the surroundings, touch can help the operator accurately control the robot's movements and sound can provide important auditory cues about the environment. Haptic feedback can warn the operator of the presence of obstacles or other objects in the robot's path. The major focus of this study is haptic feedback, more specifically electrical muscle actuation.

Because haptic (and especially kinesthetic) feedback interfaces depend on mechanical actuators to exert force, they are often bulky and expensive (8). Electric muscle stimulation (EMS) has the potential to provide feedback in a cost-effective and lightweight way, by applying small electrical stimuli leading to muscle contractions.

We investigated the potential of EMS on obstacle avoidance during robot teleoperation. To accomplish this, we developed a virtual reality (VR) simulation of a robotic arm being controlled by a human user, where we compared bi-modal feedback with unimodal auditory and haptic feedback, as well as a baseline condition without support. The haptic feedback was provided through EMS being applied to the biceps and triceps of the user. We hypothesize that bi-modal feedback improves collision avoidance and user experience, compared to relying solely on visuals.

2. Related Work

When operating a robot remotely, operators' awareness of their surroundings often relies solely on the sensor and camera data, which may limit their understanding of the environment. Definition of situational awareness (SA) describes it as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future" (9). Maintaining a high level of SA has been reported to be the most difficult part of many jobs(10). One of the most critical factors in decision-making by the operator squarely depends on how well the operator perceives the robot's environment(11). Operators must not only be aware of their surroundings, but they must also process large amounts of information quickly and make decisions based on that information. Remote teleoperation may also require operators to switch between different views or modes of operation, which can add to the cognitive load. The cognitive workload that the operator has to analyze and interpret during teleoperation has a direct bearing on their performance(11). The difficulty increases when the task also involves real-time obstacle avoidance(7). Opiyo highlighted the importance of providing sufficient visual and force feedback to the operator to create a feeling of presence in the robot's environment, as well as using a good quality network, to improve the navigation efficiency and task accomplishment of mobile ground robots(11).

Prior research has shown that teleoperation interfaces heavily rely on visual information (1). Yet, it might be challenging to establish the SA required for teleoperation using solely visual cues (6). Che and colleagues designed a mechatronic device that allows bi-directional communication between a human and a robot follower (12). The device has two parts: a haptic interface that gives users feedback from the robot and a command interface for remote control. The haptic feedback helped users understand the robot better, reduced mental effort and improved performance on other tasks. The bi-directional communication strengthened the bond between the user and the robot follower. Kassem and team conducted an assessment to determine the impact of various types of feedback, including audio, visual, haptic, and 3-way multimodal feedback (13). Objective and subjective measures were collected and analyzed, and the results showed that 3-way multimodal feedback led to the best user experience and lowest task load. The use of multiple feedback channels did not increase cognitive load. The majority of teleoperation research focuses on improving the operator's sense of presence in a remote environment through various techniques, including the use of head-mounted displays (HMDs) and force feedback (11). According to Wildenbeest, when it comes to tasks that are familiar but imprecise, operators mainly depend on vision. In contrast, for tasks that are precise, unfamiliar, or not visually optimal, the significance of the haptic sensory channel becomes more critical (14). Sagardia and team found that while completion time was mostly similar, the average collision force was substantially lower when using force feedback (15). Pamungkas found that adding electro-tactile feedback from both force and distance sensors can help with avoiding obstacles in cluttered environments as well as with placing a peg in a hole when teleoperating a robotic arm (16). The study appears to use only tactile feedback, and no published research on using EMS-based feedback for obstacle avoidance in robotic arm teleoperation was found at the time of writing the paper.

According to Faltaous, EMS is effective in eliciting a prompt response while enabling users to concentrate on their task, as demonstrated by the reduced over-crossed distance and improved reaction time compared to visual and auditory feedback (17). Before any physical contact with objects occurs, Lopes has used EMS to build affordances for objects that do not express them adequately otherwise (18). Similarly, EMS has been used to provide force feedback for walls and heavy objects in virtual reality (19), to improve human reaction speed (20), and to control the up- and downward movement of another human's arm (21). Therefore we believe EMS can be used for robot teleoperation as it can elicit a quick response while allowing users to focus on their task.

According to Rea's research, the cognitive burden of teleoperation is significant for both expert and non-expert operators, with most studies focusing on two primary issues: situation awareness and robot control (22). User-centered solutions that process data and provide knowledge, rather than just information, could reduce workload and improve the ability of non-expert operators (22). To improve teleoperation interfaces, Adamides created guidelines covering system design, communication, control, display, feedback, and user experience (23). These guidelines aim to enhance the usability and effectiveness of teleoperation interfaces, especially in situations where the operator controls the robot from a distance.

Drawing upon insights from prior research, the present study was designed to investigate the effects of obstacle avoidance on the objective and subjective quality of remote robot control, through the utilization of distinct feedback modalities - namely, auditory and haptic feedback. We framed our research questions as follows:

- **RQ 1:** What is the objective effect of using audio and haptic feedback on collision avoidance?
- **RQ 2:** How do the different modalities influence the subjective hedonic and pragmatic qualities of user experience?
- **RQ 3:** In what way do the different modalities affect task workload?

3. Method

We developed a user study in which participants operated a robot in VR. A within-group study design was employed. To address the potential bias caused by repeated practice, a balanced Latin square design of size 4 was implemented to randomize the order in which participants experienced the four experimental conditions. The balanced Latin squares helped to control for the order effect and allowed for a more accurate evaluation of the impact of each feedback modality on task performance. Participants are placed in a tutorial environment to familiarize themselves with the task and controls before the measurements begin, and they are encouraged to practice until the conveyor belt reaches maximum speed in the tutorial environment.

3.1. Task Description

The study required participants to use virtual reality (VR) to control a stationary robotic arm to perform a task at a simulated remote location. The location had a conveyor belt, and the robotic arm was positioned beside it. Boxes moved along the conveyor belt from right to left, from the perspective of the robot when the end effector was pointing towards the belt (shown in Figure 1a). The participants had a third-person view of the robotic arm, which included a view of the boxes moving and a partial view of the robotic arm being controlled. The participants had to control the robotic arm to scan a simulated object on the top face of the boxes when they came within the reach of the end effector (Depicted in Figure 1b).

The movements of the robotic arm were controlled by the position and rotation of the VR controller, which were mapped to the position and rotation of the end effector. As the boxes moving along the conveyor belt were of different heights, the end effector had to move up and down to avoid colliding with the boxes. Participants had to press the designated button on the VR handheld controller to scan the object when the end effector was within a volume above the top face of the box. If the scan was not performed within this volume, it was considered an error.

Each box required a secondary scanning action further down the conveyor belt. The secondary scanning action was done through a different stationary downward-facing scanner situated above the conveyor belt (shown in Figure 1c). Participants had to press a different button on the controller when the box was immediately below the scanner (depicted in Figure 1d). Performing the secondary scan before or after the box was immediately below the stationary scanner was considered an error. The task difficulty increased over time, as the speed of the conveyor belt ramped up while decreasing the interval at which new boxes came onto the belt. The robot operator had to simultaneously give sufficient attention to both the primary and secondary scanning actions to avoid errors while the boxes were in motion.

3.2. Apparatus

For interacting with the robot in VR, we used a commercial HMD equipped with stereo speakers and dual wireless hand-held controllers[2]. For the purpose of our study, we relied only on one controller for controlling the vertical position of the robot end effector. We

[2]Meta Quest 2 https://www.meta.com/quest/products/quest-2/

built the virtual environment inside the Unity 3D engine[3]. Inside the virtual environment, we used a common industrial collaborative robot[4]. The VR application communicates with the EMS circuit via an Adafruit Feather 32u4 Bluefruit LE microcontroller, which controls two relays to open or close the circuit for the desired muscle stimulation. A standard two-channel EMS device provides the electrical current, and the control circuit is carried in a small bag by participants and connected to the PC with a USB cable.

3.3. Feedback and Conditions

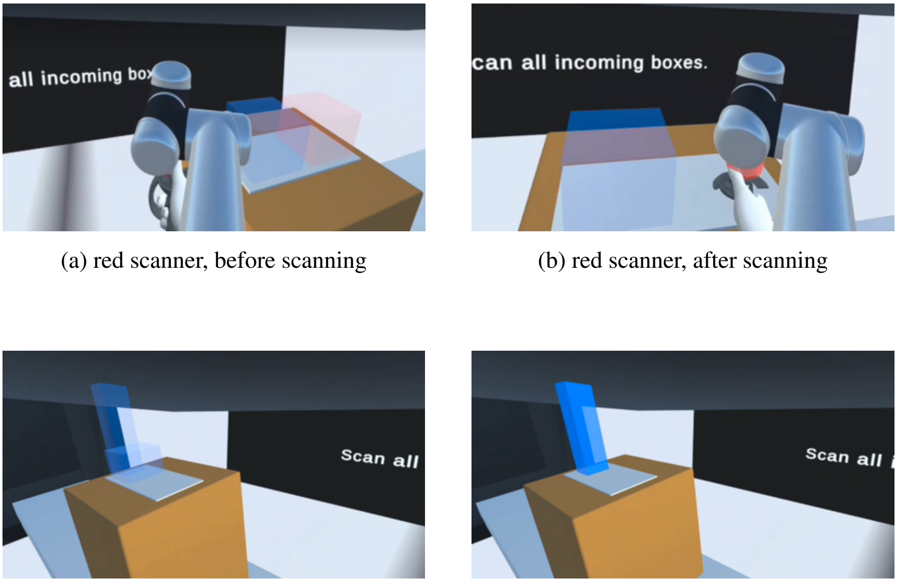
The study's participants were tasked with controlling a stationary robotic arm in VR to complete a task at a simulated remote location. As boxes moved along a conveyor belt, participants had to move the arm up or down to avoid collision with the boxes or low ceiling. The participants received feedback through three modalities: visual (through the VR headset), auditory (through the integrated speakers on the headset), and haptic (through the nudges of the EMS system). To avoid any cascade effect, the collision with boxes was programmed to allow the robotic arm to pass through them, and the affected boxes' color turned red to indicate collision.

The task is presented in four different conditions:

- **Baseline:** No feedback was given, and participants had to rely solely on visual perception.
- **Auditory feedback:** Participants received feedback to move their arm up or down through a voice saying "up" or "down", respectively.

[3] https://unity.com/

[4] UR5e https://www.universal-robots.com/products/ur5-robot/



(a) red scanner, before scanning (b) red scanner, after scanning

(c) blue scanner, before scanning (d) blue scanner, after scanning

Figure 1. Views of the two subtasks, right before and after scanning.

- **Haptic feedback:** Participants received a nudge through the two pairs of electrodes on their biceps and triceps, stimulating the biceps to nudge the participant's forearm upwards and the triceps to nudge it downwards.
- **Multimodal:** Participants received both auditory and haptic feedback simultaneously.

During the task, participants had to simultaneously attend to both scanning actions while avoiding errors caused by the boxes' motion.

3.4. Participants

The study recruited 9 right-handed participants (mean age 23.9, SD 1.6) who did not have specific medical conditions or metal implants, and were not pregnant or using an insulin pump, with the additional requirement of not wearing glasses that were incompatible with the VR headset. All participants signed a consent form indicating their willingness to take part in the study and to allow their data to be collected and analyzed. They received compensation in the form of a voucher. To calibrate EMS, the stimulation intensity was slowly increased and participants were asked to indicate when they felt a slight but noticeable movement in the direction required, and the resulting intensity was then maintained throughout the study, with adjustments made to the electrode placement or intensity if the stimulation became uncomfortable. The specific voltage and current levels used for each channel were independently adjusted to achieve the desired level of stimulation for each muscle group, which depended on the individual's muscle size and sensitivity.

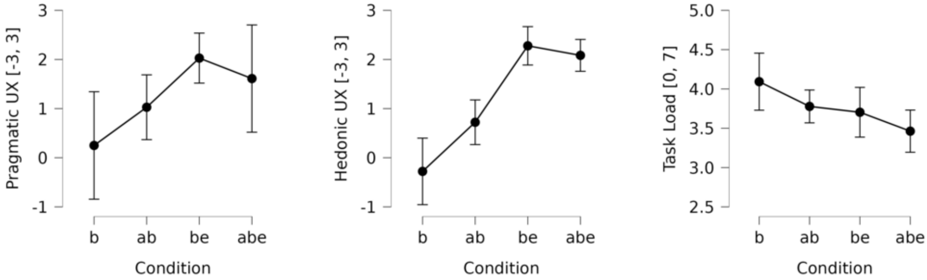
3.5. Measurements

The primary performance metrics of interest are the *collision count* and *collision time*, while the *error rate* (the ratio of incorrectly to correctly scanned boxes) is also measured to ensure that collision avoidance does not have a significant negative impact on task execution performance. After completing a task under specific conditions, the participants filled out a set of condition-specific questionnaires, which included the User Experience Questionnaire (24) and NASA TLX (25).

4. Results

The data was evaluated using JASP 0.16.3-Debug (26).

Performance Metrics : The trends indicate that using EMS and a combination of auditory and haptic feedback leads to fewer *collision count* and shorter *collision time*. The Friedman test shows no significant differences across the four conditions for any of *collision count* ($\chi^2(3) = 0.771$, $p = 0.856$, $N = 9$), *collision time* ($\chi^2(3) = 1.042$, $p = .791$, $N = 9$) and *error rate* ($\chi^2(3) = 4.724$, $p = .193$, $N = 9$). This could be due to the limited number of participants involved in the study or the potential influence of a learning effect.



(a) Pragmatic Quality (b) Hedonic Quality (c) Perceived Task Load

Figure 2. Plots of the means and 95% confidence intervals of the two UEQ-S scales and of the Task load - [b : Baseline, ab : Auditory, be : EMS, abe : Bi-modal auditory-haptic]

User Experience Questionnaire :

- Pragmatic Quality. A repeated measures ANOVA shows a significant difference in pragmatic quality ($F(3,24) = 4.104$, $p = .017$) between at least two conditions (Illustrated in Figure 2a). Bonferroni-corrected pairwise comparisons revealed a significant difference only between the baseline and EMS condition ($mean = -1.778$, $p = .018$).
- Hedonic Quality. A repeated measures ANOVA shows a significant difference in hedonic quality ($F(3,24) = 33.488$, $p < .001$) between at least two conditions. Post-hoc tests with a Bonferroni-correction revealed that the hedonic quality was significantly worse in the baseline than in any other condition (Baseline-Auditory): $mean = -1.000$, $p = .014$; (Baseline-EMS): $mean = -2.556$, $p < .001$; (Baseline- bi-modal auditory-haptic): $mean = -2.361$, $p < .001$). Furthermore, the hedonic quality of the audio-only condition was significantly worse than either condition involving EMS (Auditory - EMS): $mean = -1.556$, $p < .001$; (Auditory - bi-modal auditory-haptic): $mean = -1.361$, $p < .001$). There was no significant difference between the EMS-only and the combined condition (Illustrated in Figure 2b).

Task Load : A tendency of feedback to lower the task load can be seen in Figure 2c. The repeated measures ANOVA shows no significant difference across the four conditions ($F(3,24) = .777$, $p = .518$).

5. Discussion

The study found that using EMS feedback combined with auditory feedback can potentially result in fewer collisions and shorter collision time (RQ1). The use of EMS feedback is advantageous due to its quick and intuitive nature, allowing users to react promptly to changes in their environment. The combination of auditory and haptic feedback can also provide multiple sources of information, enabling users to better understand their surroundings. However, further research with larger sample sizes is necessary to establish more definitive results.In terms of user experience (RQ2), the study revealed that haptic feedback was preferred over other feedback modalities, indicating that it received the highest rating in both pragmatic and hedonic quality scales. The immediacy of EMS feedback was also found to be more favorable than processing visual or auditory information. Additionally, all three cuing conditions were rated to have a lower task load than the baseline, suggesting that any additional feedback can reduce the perceived task load of the remote operator (RQ3). However, some participants expressed that the combination of EMS and auditory feedback was overwhelming, raising concerns about whether the bi-modal feedback could be better designed to prevent sensorial overload. Although the sample size was small, the study offers a valuable starting point for further research and provides insightful information. Notably, the study highlights the importance of learning in the task, as participants demonstrated improvements in collision avoidance and error rates over time, refining their overall strategies to facilitate better collision avoidance. However, the measures taken to mitigate the effects of learning were inadequate. Overall, the study suggests that muscle actuation feedback, such as EMS, can be a promising approach to enhancing teleoperation performance by providing additional sensory information to the operator. Nonetheless, more research is needed to fully understand the potential benefits and limitations of this approach

Limitations and Future work To better understand the usefulness of EMS feedback in robot teleoperation for obstacle avoidance, a user study with larger sample size is needed to uncover any significant differences. To improve the quality of the EMS feedback, a simple spring-damper model could be implemented to adjust the stimulation intensity based on the proximity to obstacles, which may increase both performance and user comfort (27). The study was affected by a learning effect because the task was not complex enough. To reduce this effect, the authors propose modifying the task setup in future experiments.The study did not explore other potential methods of evaluating situational awareness, which may be more effective. Additionally, it would be intriguing to compare EMS with electro-tactile feedback.

6. Conclusion

Using teleoperation to control robots can be challenging due to the lack of physical presence and direct interaction. To address this, our research proposed using EMS as a haptic feedback source in combination with auditory and haptic feedback to improve obstacle avoidance. The study showed that using EMS feedback led to fewer collisions and shorter collision times, as well as reducing task load compared to no feedback. Haptic feedback was rated the highest in both pragmatic and hedonic quality scales, followed by bi-modal auditory-haptic feedback. The use of muscle actuation technology was reported to offer a positive user experience for obstacle avoidance. Although the sample size was small, the study serves as a foundation for future research, and increasing the number of participants may produce more positive results. Muscle actuation feedback may be used to communicate information about the robot's applied force or torque, as well as the shape or texture of the remote environment. Overall, muscle actuation feedback shows promise in improving teleoperation performance by supplementing operators with additional sensory information.

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