Design of A Wearable Haptic Arm Band for Obstacle Avoidance During Teleoperation

Parker Knopf, Yarah Feteih, and Yun (Anna) Xu

***Abstract*— This work introduces a novel haptic armband designed to mimic obstacle collisions of a 2D RR manipulator during task space teleoperation. The proposed device delivers normal skin indentation cues on both sides of the user's upper and lower arms, aiding in spatial awareness of obstacles when visual feedback is limited. To achieve this, we devised a CAM mechanism that achieves varying amplitude normal skin indentation corresponding to the proximity of the obstacle. A user study involving 12 subjects was conducted, tasking them with searching for a target and minimizing collisions with a simulated RR manipulator in a cluttered environment, relying solely on the field of view of the end effector. The results demonstrate that compensating for the lack of visual feedback with haptic feedback enables users to reduce the frequency of collisions with the environment.**

I. INTRODUCTION

Robotic Minimally Invasive Surgery (RMIS) holds the potential for enhancing patient outcomes by minimizing surgical impacts [1]. Current commercial systems, such as Intuitive Surgical's DaVinci, require surgeons to teleoperate a follower robot from a master console. A limitation is the restricted field of view (FOV) to the end effector of the follower robot, leaving surgeons unaware of larger backend movements and risking unintended collisions with the environment. To mitigate this, we propose conveying collision information through haptic feedback and introducing a device tailored for a simplified 2D toy problem.

A. Haptic Communications

Haptic communication between users and devices typically involves two approaches: motion guidance and sensory augmentation [2]. In the motion guidance approach, step-by-step instructions guide the user, directing them toward a desired target location [3], [4]. Continuous feedback in this approach reduces human decision-making, which is advantageous in scenarios like assistive needle insertion, where restricting the user's motion is essential [5]. Conversely, the sensory augmentation approach avoids continuous feedback, delivering haptic stimulation only when necessary [6]. This approach is suitable when users are allowed to explore their environment with minimal interference. Our device adopts the latter communication type, ensuring users remain undistracted from higher-priority tasks.

B. Tactile Devices for Upper Limbs

State-of-the-art tactile devices for the arms are designed to convey a variety of stimuli such as pressure, vibration, indentation, and stretching of the skin [7]–[11]. Typically, these arm-mounted devices consist of an actuation housing unit secured with straps around the arm. The actuation mechanisms vary depending on the desired stimulus. For instance, several groups have proposed different mechanisms to deliver normal skin indention, including a belt drive mechanism [10], a servo-pulley mechanism [7], [8], as well as a linear actuator [9]. In our research, our primary focus is on normal skin indentation due to its more intuitive mapping for real-world collisions compared to stimuli like vibration or pressure. In addition, [12] reported that in the forearm the JND of norm skin indentation is $\approx 3mm$.

C. Contributions

The contributions of this paper are as follows. First, we give an overall system overview of the device and the virtual environment (VE) with which the user interacts. We then provide a comprehensive overview of the device's actuation mechanism, followed by an in-depth description of the haptic stimulus design. Finally, we present the findings of a preliminary user study that demonstrates the effectiveness of our proposed haptic armband device in assisting the user with collision avoidance through an unseen environment.

II. METHODS

In this section, we first describe the VE that interacts with the user, then introduce the haptic device design and the haptic stimulus characterization. An overview system diagram is shown in Fig. 1.

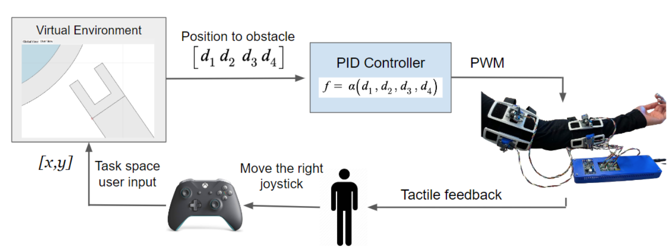
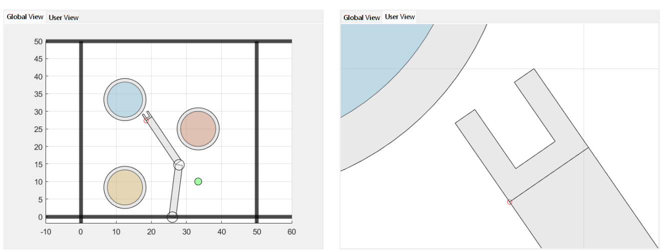


Fig. 1: Overall system diagram of the haptic device in a teleoperation scheme

A. Virtual Environment Teleoperation

The virtual environment (VE) consists of a planar, RR manipulator in a cluttered, 2D environment which serves as a proxy for the user's arm. The end effect position (in x,y) of the manipulator is controlled with a joystick on an Xbox controller, and the robot body will also move accordingly by computing the inverse kinematics. The user's goal is to search for a target (denoted with a green circle in the VE, see Fig. 2) with their proxy robot's end effector while avoiding contact with obstacles in the environment. The VE is rendered in MATLAB with two visualization modes (see Fig. 2): a global view of the entire VE, and another with a limited field of view (FOV) that follows the end effector. During device evaluation, the latter view will be provided to the user to intentionally limit their visual knowledge of obstacles in the VE. For simplicity's sake, we choose to represent all obstacles in the VE as equivalent-sized circles that are placed freely in the VE. The grey boundary around each obstacle is a warning zone where the user will start to feel haptic feedback from the device. If either side of the links enters the warning zone, the Euclidean distance between the closest point on the link to the obstacle, $d_i, i = 1, 2, 3, 4$, is computed and sent via serial to the controller board. If either side of the links collides with an obstacle, the manipulator in the VE visualization will appear to be "stuck", and will be "unstuck" if and only if the joystick control sends a feasible end-effector position allows the links to no longer collide with the obstacle.



(a) Global View (b) User View

Fig. 2: Illustration of the global and user view rendered in the VE. During the experiment the user is provided with the second view during navigation

B. Haptic Device Design

We propose a body-mounted tactile feedback device attached to both the user's upper and lower arms as shown in Fig.3. Each armband contains a set of two actuator units mounted by adjustable VELCRO straps that tighten to secure the units to the user's arm. In total, there are 4 actuator units fixed to the inner/outer sides of both upper/lower arms, corresponding to the left/right sides of the robot links in the 2D VE.

1) Actuator Unit Design: An actuator unit consists of a base plate mounted to the user and an actuator to deliver normal skin indentation through an oscillating motor and lever arm (a CAM mechanism). Each motor is fitted with

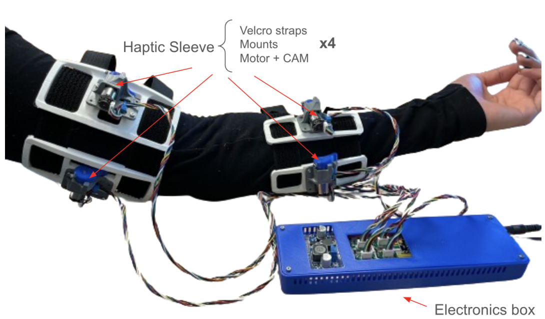


Fig. 3: Haptic Device Design

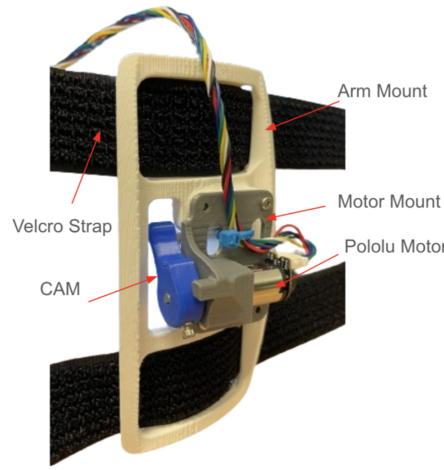


Fig. 4: Single Actuating Unit of the Device Prototype

an incremental quadrature encoder. The motors used for this study were 6V Pololu micro-metal DC motors with a $5.0kg * cm$ stall force. For this prototype, the shear force of the actuator on the user was determined as insignificant and thus ignored. We choose a ball-point lever arm of $22mm$ shown in Fig. 3 to deliver larger pressure points to the user with a surface area that is roughly $42mm^2$. This is designed to counter the reaction forces created due to being mounted on the arm. Large strap sizes were also used to counteract this reaction force on the user.

To ensure these actuators align perpendicular to the skin, the curvature of the base plate is designed with a simplified human arm model (an ellipse that is $100mm$ wide and $80mm$ tall) in mind, and the placement of the actuator angle was also carefully chosen for normal alignment to the skin as shown in Fig 5.

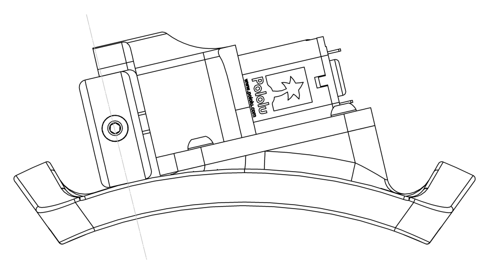


Fig. 5: Side view of CAD drawing of one actuating unit with normal line to skin curvature

2) Device Control: The prototype device is controlled via a control unit, consisting of a Teensy 4.0 microcontroller board and motor drivers. Communications between the microcontroller and the main computer operating the virtual environment are established through serial communication. The motors in the actuation units are controlled by a PID controller to drive the motor to desired angles (which are obtained by procedure detailed in Section II-C). The specific controller constants used are $kp = 4$, $ki = 0.5$, and $kd = 2$.

C. Haptic Stimulus Characterization

To determine the appropriate haptic stimulus, we consider inversely scaling the amount of normal indentation into the skin to the distance away from an obstacle in the VE. The amount of normal indentation to the skin is bounded between $[0, c_{Rad}]$, where c_{Rad} is the CAM's radius. A smaller amount of indentation corresponds to a greater distance away from the obstacle, whereas a larger amount of indentation corresponds to proximity to the obstacle. The linear relationship between the distance to an obstacle for either side of the robot links, $d_i, i = 1, 2, 3, 4$, and the amount of skin indentation on either side of the upper/lower arm, $h_i, i = 1, 2, 3, 4$, is related by

$$h_i = c_{Rad} - (c_{Rad}/d_{Max}) * d_i, \tag{1}$$

where d_{Max} is the size of the boundary surrounding the obstacles, which is set to $1mm$ for the experiment. The amount of skin indentation, h_i, is then converted to a motor angle via the equation $h_i = c_{Rad} * sin(\alpha_i)$, where α_i is the desired motor angle for the corresponding actuation unit. To address users' acclimation to a sustained skin indentation, we introduce an additional tapping stimulus following an initial phase of constant skin indentation. This tapping stimulus adheres to a standard duty cycle with a period of 10 counts and a duty cycle of 50%. The "ON" value is determined as the indentation calculated from Eqn. 1, while the "OFF" value is set at 25% of the calculated indentation. The resulting sensation will be a displacement following a pulsing motion, thus resolving the issue of the user getting acclimated to a constant pressure being applied. A graphical example of the tapping stimulus is shown in Fig. 6.

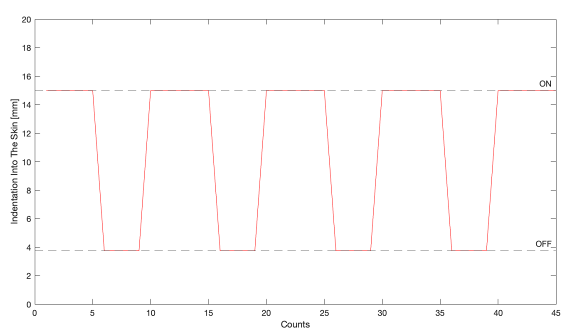


Fig. 6: Tapping Stimulus for a mapped normal indentation of 15mm

III. EVALUATION

In this section, we first describe the setup of our user study, then the experimental procedures that were followed.

A. Experimental Setup

A demonstration of the experiment setup is shown in Fig. 7. The user faces a computer monitor that displays the VE while holding an Xbox controller to control the end effector position of the robot arm with the right joystick. As seen in Fig. 7, the device is secured on the upper and lower arm of the user.

Fig. 7: User Study Experimental Setup

B. Experimental Methods

To assess the effectiveness of our proposed haptic device, users were tasked with locating a target using the end effector of their proxy manipulator, beginning from an identical initial robot configuration. User performance during this search task was measured across three distinct scenarios within the VE. The first scenario served as the control, where users had access to both the global view and haptic feedback. In the second scenario, users were provided with a limited view without haptic feedback, while the third scenario involved a limited view combined with haptic feedback. For scenarios where users have limited view of the VE, they were given the general location of the target (ie. on the left/right side) to expedite the search process and reduce frustration.

The primary objective of this experiment is to evaluate whether our haptic device facilitated fewer collisions during the search process under limited visibility. To prevent users from becoming accustomed to the target/obstacle placements, we developed three separate preset environments (with an additional one for training). These environments are deliberately designed to challenge users in navigating to target locations while considering potential collision cases. Each user's trial took place in a different environment, with each user encountering every environment at least once, following a coordinated order. Conducting three trials resulted in six sequences of environments. This approach ensured data normalization across users, eliminating biases that may arise if certain environments were more challenging than others.

1) User Training: To begin the experiment the device was calibrated for every user. Calibrating the device ensured the actuator rested at the surface of the user's skin. Each of the 4 actuators was manually positioned by the user with some assistance. This calibration procedure allows every user to perceive the same normal skin deflection. With this step complete, each user was given some time to get acquainted with the system, specifically the teleoperation scheme and the expected haptic sensations. After becoming familiar with the system the user proceeded to the actual experiment. Next, we describe each different experiment scenario.

2) Full Visual with Haptic Feedback: Users were first asked to complete the search task with a global view of the environment and haptic feedback. In this case, the user is fully informed, through both visual and haptic feedback where the the obstacles are and when they may collide with one with their proxy robot links. The results of this scenario should give a best case of user performance and will operate as a baseline for later analysis.

3) Limited FOV with No Haptic Feedback: Then, users were asked to repeat the search experiment given a limited field of view and no haptic feedback. Since users are not made aware of the obstacles by any means, we expect that frequent collisions with the obstacles may occur.

4) Limited FOV with Haptic Feedback: Lastly, users were asked to repeat the search experiment again given limited field of view and haptic feedback. Since users are now made aware of the obstacles via haptic feedback, we expect fewer collisions with obstacles will occur.

C. Subjects

12 participants performed this experiment including 2 women, and 10 men ranging from ages 20-33, all college educated in STEM degrees. The experimenting team explained the procedures, helped mount the haptic device, and operated the experiment.

IV. RESULTS AND DISCUSSION

To compare the effectiveness of our proposed haptic device, we take into account for each trial the total length of the path traveled by the end effector, the occurrence of collisions, and the intuitiveness of the haptic device determined via a user survey.

1) Quantitative Metrics: We compute the total length of the path traveled by the end effector by summing the Euclidean distance between all consecutive points of the tip's trajectory recorded for every trial. we hypothesize that longer path lengths indicate more exploration from the user, due to a lack of awareness (visual or haptic) of the surrounding environment (See Fig. 8 for an example). The occurrence of collisions is measured as a percentage of the amount of time a collision happened out of the total time of the trial. The summary statistics of these quantitative evaluation metrics are shown in Table I.

As expected, we observe that users typically take more direct, shorter paths from the start to the target, and navigate with the least amount of collisions when they have full visual and haptic feedback. We also see that in scenarios where the visual feedback is limited, fewer collisions occur if haptic feedback is provided to the user in general. However, contrary to our hypothesis, we see that shorter paths are not necessarily taken in this scenario, which means that users are still exploring more of the environment even if they have haptic feedback. We remark that the observations drawn from this user study are by no means comprehensive, and there is a noticeably large spread of the data collected. This is likely due to the lack of prior training on the device, which could lead to user confusion during the actual experiment.

TABLE I: Quantitative Metrics Summary

Full Visual and Haptics					
Metric	Min	Median	Mean	Std deviation	Max
path length [mm]	23.55	28.74	33.39	8.526	75.62
collisions [%]	0	0	6.520	16.32	57.63
Limited Visual No Haptics					
path length [mm]	25.34	38.84	43.75	20.60	95.82
collisions [%]	0	30.75	29.71	17.66	61.43
Limited Visual with Haptics					
path length [mm]	22.37	37.64	50.46	32.12	137.8
collisions [%]	0	22.02	26.50	21.17	81.55

TABLE II: Quantitative Metrics Summary

Metric	Mean	Std deviation
Ease of Use	4.5	0.6741
Device Comfort	3.666	0.984
Ease of Learning	4.5	0.79
Usefulness	4.166	0.577

2) Qualitative Metrics: For a qualitative evaluation of our haptic device, we asked users to complete a questionnaire that rated the device on a scale from $1-5$ in terms of *Ease of Use*, *Device Comfort*, *Ease of Learning*, and *Device Usefulness*. The qualitative results are shown in Table II

Overall, we observe that users generally find the haptic device useful when navigating through a cluttered environment with a limited view after a short training period. However, we note that the current prototype does not provide maximal device comfort mainly due to the fabrication process of the base unit which could be uncomfortable when mounted on bare skin.

V. CONCLUSIONS

This paper presents a novel haptic arms band and its evaluation in a robot teleoperation scenario in unseen environments. This device provides normal skin indentation to the upper and lower arm, mimicking the proximity of the robot proxy to an obstacle in the VE. We carried out a preliminary user study to compare and contrast a search task performance under full visual feedback, limited visual feedback, and limited visual with haptics feedback. The results show that in general users encounter fewer collisions when haptic feedback is provided as they navigate through a mostly unseen environment, demonstrating the effectiveness of the proposed haptic system.

Future work extending our haptic device design involves upgrading the motors driving the actuation mechanism. The current prototype faces stalling issues at larger skin deflections due to insufficient torque to overcome the reaction force exerted by the user's arm. Additionally, we plan to explore a more sophisticated lever arm design that adapts to the placement of the actuation unit on the user's arm, considering the varying perceptible skin deflection on different parts of the upper/lower arm. Another avenue for improvement is

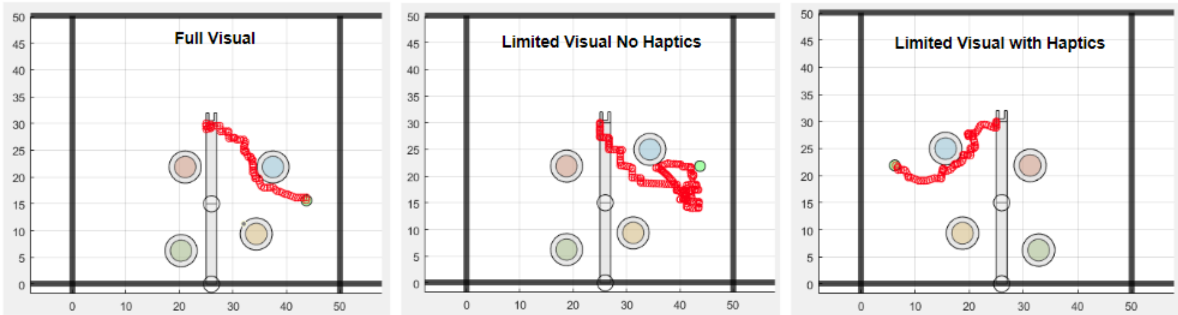


Fig. 8: Examples of the end effector trajectories (red circles) for each scenario. We note that more exploration occurred in the case where users have limited FOV and have no haptic feedback, whereas in the other cases, less exploration occurred since users were made aware of the surrounding obstacles.

to explore actuation units featuring an array of actuators along the length of the user's arm, offering more precise information about the location of obstacles.

ACKNOWLEDGMENT

The authors thank Dr. Morimoto and Mr. Anoush Sepehri for their feedback on the haptic device and experimental design.

REFERENCES

[1] M. J. Mack, "Minimally Invasive and Robotic Surgery," *JAMA*, vol. 285, no. 5, pp. 568–572, 02 2001.

[2] G. Paolocci, T. L. Baldi, L. Sampieri, and D. Prattichizzo, "Design and comparison of haptic policies for human guidance," in *2022 IEEE Haptics Symposium (HAPTICS)*, 2022, pp. 1–8.

[3] J. B. F. V. Erp, H. A. H. C. V. Veen, C. Jansen, and T. Dobbins, "Waypoint navigation with a vibrotactile waist belt," *ACM Trans. Appl. Percept.*, vol. 2, no. 2, p. 106–117, apr 2005. [Online]. Available: https://doi.org/10.1145/1060581.1060585

[4] T. Lisini Baldi, S. Scheggi, M. Aggravi, and D. Prattichizzo, "Haptic guidance in dynamic environments using optimal reciprocal collision avoidance," *IEEE Robotics and Automation Letters*, vol. 3, no. 1, pp. 265–272, 2018.

[5] M. Raitor, C. M. Nunez, P. J. Stolka, A. M. Okamura, and H. Culbertson, "Design and evaluation of haptic guidance in ultrasound-based needle-insertion procedures," *IEEE Transactions on Biomedical Engineering*, pp. 1–10, 2023.

[6] L. Devigne, M. Aggravi, M. Bivaud, N. Balix, C. S. Teodorescu, T. Carlson, T. Spreters, C. Pacchierotti, and M. Babel, "Power wheelchair navigation assistance using wearable vibrotactile haptics," *IEEE Transactions on Haptics*, vol. 13, no. 1, pp. 52–58, 2020.

[7] M. Aggravi, F. Pausé, P. R. Giordano, and C. Pacchierotti, "Design and evaluation of a wearable haptic device for skin stretch, pressure, and vibrotactile stimuli," *IEEE Robotics and Automation Letters*, vol. 3, no. 3, pp. 2166–2173, 2018.

[8] F. Chinello, C. Pacchierotti, N. G. Tsagarakis, and D. Prattichizzo, "Design of a wearable skin stretch cutaneous device for the upper limb," in *2016 IEEE Haptics Symposium (HAPTICS)*, 2016, pp. 14–20.

[9] M. Sarac, T. M. Huh, H. Choi, M. R. Cutkosky, M. D. Luca, and A. M. Okamura, "Perceived intensities of normal and shear skin stimuli using a wearable haptic bracelet," *IEEE Robotics and Automation Letters*, vol. 7, no. 3, pp. 6099–6106, 2022.

[10] D. D. Damian, M. Ludersdorfer, Y. Kim, A. Hernandez Arieta, R. Pfeifer, and A. M. Okamura, "Wearable haptic device for cutaneous force and slip speed display," in *2012 IEEE International Conference on Robotics and Automation*, 2012, pp. 1038–1043.

[11] S. Casini, M. Morvidoni, M. Bianchi, M. Catalano, G. Grioli, and A. Bicchi, "Design and realization of the cuff - clenching upper-limb force feedback wearable device for distributed mechano-tactile stimulation of normal and tangential skin forces," in *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2015, pp. 1186–1193.

[12] Z. A. Zook, J. J. Fleck, and M. K. O'Malley, "Effect of tactile masking on multi-sensory haptic perception," *IEEE Transactions on Haptics*, vol. 15, no. 1, pp. 212–221, 2022.