2023 IEEE International Conference on Robotics and Automation (ICRA 2023)
May 29 - June 2, 2023. London, UK

# HaPPArray: Haptic Pneumatic Pouch Array for Feedback in Hand-Held Robots

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*Abstract*— **Haptic feedback can provide operators of hand-held robots with active guidance during challenging tasks and with critical information on environment interactions. Yet for such haptic feedback to be effective, it must be lightweight, capable of integration into a hand-held form factor, and capable of displaying easily discernible cues. We present the design and evaluation of HaPPArray — a haptic pneumatic pouch array — where the pneumatic pouches can be actuated alone or in sequence to provide information to the user. A 3x3 array of pouches was integrated into a handle, representative of an interface for a hand-held robot. When actuated individually, users were able to correctly identify the pouch being actuated with 86% accuracy, and when actuated in sequence, users were able to correctly identify the associated direction cue with 89% accuracy. These results, along with a demonstration of how the direction cues can be used for haptic guidance of a medical robot, suggest that HaPPArray can be an effective approach for providing haptic feedback for hand-held robots.**

## I. INTRODUCTION

Hand-held, or ungrounded, robots represent a promising class of robotic devices. They have the potential to combine the benefits of direct human operation for gross movements, with the precision of robotic control for fine motions. Smaller than their grounded counterparts, these robots can be manipulated in a manner and workflow similar to using manual tools or instruments [1].

To date there have been several examples of hand-held robots, particularly for medical applications. For instance, hand-held medical robots have been designed for tremor suppression, which is especially important in microsurgical applications that require high precision [2], [3]. In addition, several hand-held, articulated devices with increased dexterity have been developed for laparoscopic and orthopaedic applications [4], [5]. And recently, there has been work on the creation of hand-held continuum robots, which aim to provide surgeons with added dexterity to improve the maneuverability and ease of procedures [6], [7], [8].

The final main category of hand-held medical robots consists of ones designed to provide haptic feedback to the operator. This feedback is typically designed either to provide active guidance to the surgeon in order to constrain motion towards or away from some pre-defined area or trajectory, or to provide information on robot-environment interactions [1].

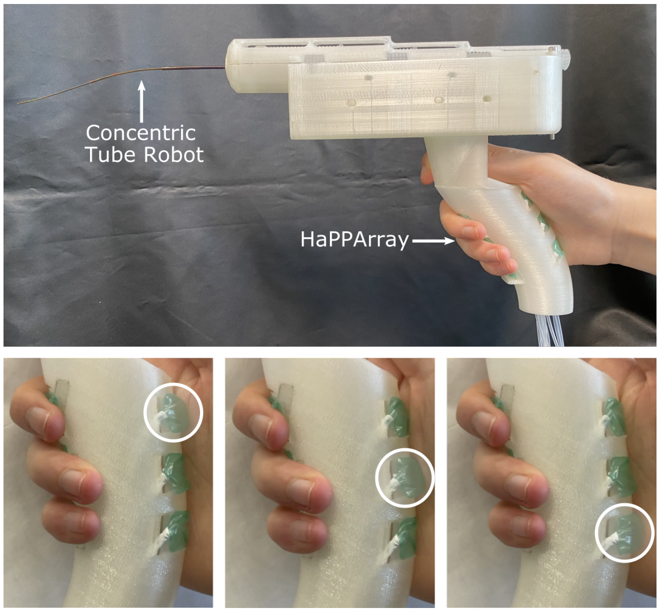

Fig. 1. HaPPArray is integrated into the handle of a hand-held medical robot (top). Directional cues are conveyed by sequentially actuating sets of three pneumatic pouches (bottom).

The ability to provide effective haptic feedback to surgeons is widely viewed as important for minimizing injuries and maximizing the success of surgical procedures [9]. Unlike traditional teleoperated robotic systems, where the human and the robot are physically decoupled, hand-held robots maintain a degree of natural haptic feedback. Yet these reflected forces may be too small and the relevant information could be masked or distorted by other interaction forces [10].

Recent work has therefore investigated methods for actively providing ungrounded haptic feedback — including both kinesthetic and cutaneous feedback. Ungrounded, kinesthetic feedback approaches have utilized the gyroscopic effect [11] as well as weight shifting [12], and have been investigated mainly for applications in virtual reality and pedestrian navigation. However, it is challenging to provide realistic feedback without mechanical grounding and in a sufficiently portable form factor. An alternative to fully ungrounded kinesthetic feedback is body-grounding, where the device is braced to another part of the user's body, such that forces can be generated between the two body parts [13]. However, the resulting reaction forces can potentially lead to confusing signals due to the required reaction forces [14].

The final approach to ungrounded haptic feedback is to provide cutaneous, or tactile, feedback. The majority of these devices use vibration to convey information. Although

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*This work was supported in part by National Science Foundation under Grant 2146095.

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they are often monolithic, meaning that a single actuator is used to vibrate the entire device [15], there has been some investigation of integrating multiple actuators into a hand-held device with the goal of presenting spatial or directional information [16], [17]. However, it has been shown that users can sometimes experience discomfort or desensitization to vibrotactile feedback if used over an extended period [18]. Recent work has looked at using skin stretch [19] and pin arrays [20], [21] as alternative methods, yet implementing these approaches in compact, lightweight form factors remains challenging.

In this paper, we propose HaPPArray — a haptic pneumatic pouch array that easily integrates into the handle of a hand-held robotic device. Pneumatic actuation offers the potential for a lightweight and comfortable approach for displaying haptic feedback, and has been shown to be capable of providing salient haptic cues when leveraged in wearable haptic devices [22], [23], [24]. The proposed interface, shown in Fig. 1, is designed to provide direction cues in a manner that is comfortable, intuitive, and safe. We describe the design and fabrication of HaPPArray, along with its integration into a hand-held device. We then illustrate its effectiveness at conveying both information on single points of contact, as well as direction cues, by conducting a formal user study. Finally, we demonstrate the potential for HaPPArray to be used to guide operators during navigation of a hand-held medical robot.

## II. DESIGN AND FABRICATION

For hand-held robots, it is critical that any haptic feedback modality remain both lightweight and comfortable. Although these are generally important parameters for any haptic feedback system, they are particularly essential for hand-held devices, which are not grounded and can therefore cause significant fatigue. Pneumatic pouches are therefore well-suited to such applications since they add minimal weight and are comfortable due to their inherent compliance. The following design and fabrication process can be used to create pouch arrays specific for a desired hand-held robot, and we illustrate it here in the context of integration into the handle of a hand-held concentric tube robot [8].

### A. Pneumatic Pouches

The pneumatic pouches are designed and fabricated as individual units, which can then be integrated into any given hand-held robotic device. The 2-D shape of the pouches is first designed in CAD, and consists of two main features: the inflatable surface of the pouch itself and the tube attachment region. In order to ensure the pouches can be fabricated repeatably and efficiently, even at a small scale, a laser welding method is used. This approach, which was previously used to make soft actuators and branching vine robots [25], [26], enables simultaneous cutting and sealing of two layers based on a digital design. To fabricate the pouches, two layers of 37 $\mu$m thick thermoplastic polyurethane (TPU) (Stretchlon 200 High Stretch Bag Film) are first heat pressed together for 30 seconds, which ensures that they are fully in contact but not permanently bonded (Fig. 2a). The double layered TPU is then laser welded using a laser cutter (Glowforge) at 30% power and at a speed of 400/500 (Fig. 2b). The resulting pouches, which are both sealed and cut, are removed from the laser cutter and manually cut along the bottom edge (Fig. 2c). The final step is to insert and seal the tubing through the opening in the bottom (Fig. 2d). A flexible silicone rubber tubing with an outer diameter of 2 mm and an inner diameter of 1 mm is used. A small amount of silicone glue is applied to the outside of the tubing prior to insertion, and a layer of Teflon tape is wrapped around the region to secure the tubing in place.

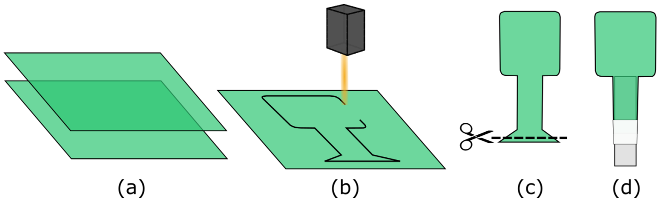

Fig. 2. Fabrication process for the individual pouches consists of (a) heat pressing two layers of TPU, (b) laser welding the 2-D shape, (c) cutting an opening for the pneumatic tubing, (d) inserting and sealing the tubing in place.

### B. Device Integration and Control

The pneumatic pouches can then be integrated into any given hand-held device. In this work we design and integrate an array into a simple handle that represents a potential user interface for our hand-held concentric tube robot [8]. The handle is designed to keep the thumb and index finger free, in order for them to be used to operate a trackball/joystick and trigger/button, respectively. The handle is therefore designed to be comfortably held with the remaining three fingers and rest of the hand.

There are two key features designed for pouch integration. First, there is an inset created for each pouch that is designed to allow the pouch to sit relatively flush when deflated, while ensuring that users can easily feel the sensation when the pouch is inflated without causing movement of the hand or fingers. Second, at the edge of each inset, there is a cutout that allows the pneumatic tubing to be routed through the inside of the handle. This feature ensures that the user does not feel the tubing and that their hand and fingers instead interact solely with the pouches themselves. A 3x3 array of pouches is integrated into the handle as described above. They are arranged such that one column of pouches runs along the fingers, one runs along the length of the palm, and one runs along the length of the bottom of the hand (Fig. 4).

The architecture of the pneumatic control system is shown in Fig. 3. It is designed to enable independent control over the actuation of each pouch. An airsource is set at 15 psi and connected to a pneumatic manifold. This pressure level was determined based on preliminary tests, where pouches were inflated to pressures between 5 psi and 20 psi to test for comfort and noticeability. The pneumatic manifold connects the flexible silicone tubing of each pouch to a solenoid valve (NITRA solenoid valve) that controls airflow into the

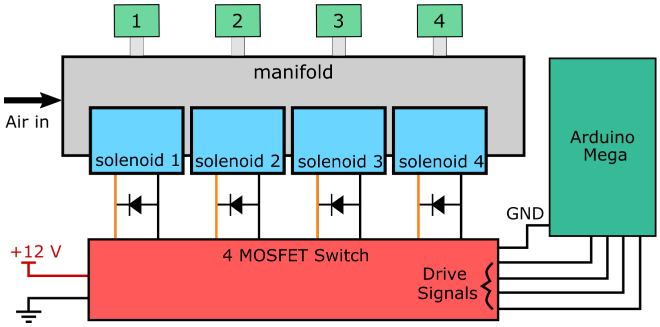

Fig. 3. The pneumatic control system enables each pouch to be independently actuated. The architecture is shown for just four pouches here, but is repeated for all nine pouches.

associated pouch. It should be noted that the pouches are not actively deflated, but rather naturally deflate when the pressure is turned off. The opening and closing of each solenoid valve is controlled using a MOSFET, whose signal is controlled via an Arduino Mega. As shown in Fig. 3, a four-channel MOSFET switch, powered by a 12 V DC power supply, is used here. The same architecture is repeated for all nine pouches.

In addition to simply a single inflation of a pouch, which leads to a normal force being applied to the hand, an individual pouch can also be inflated repeatedly and a sequence of pouches can be inflated in rapid succession. The rate of actuation of each pouch can be controlled, and here we propose to use frequencies between 10-20 Hz. These signals are at a much lower frequency than those typically produced by vibration actuators, such as eccentric rotating mass motors and linear resonant actuators, which are usually above 100 Hz [27]. As a result, unlike standard vibration actuators that primarily activate the Pacinian corpuscles, whose large receptive fields make it challenging to distinguish between actuators placed close together, the signals from HaPPArray should be sensed by the mechanoreceptors known as Meissner corpuscles [28], whose smaller receptive fields should help to better localize signals [29].

## III. POUCH IDENTIFICATION AND DIRECTION CUE USER STUDIES

Ten right-handed users (4 male and 6 female, 18 to 33 years old) participated in the following set of user studies. In the first study, participants identified which pouch was being actuated, and in the second study, they identified the direction cue displayed via a sequence of pouch actuations. The experimental protocol was approved by the University of California San Diego Institutional Review Board, and all participants gave informed consent prior to the study.

### A. *Experimental Methods*

Users held the device in their right hand, placing their middle, ring, and pinky fingers across the top, middle, and lower rows, respectively. In the first part of the study, users were asked to identify which of the nine pouches (Fig. 4a) was providing the haptic cue. Individual pouches were actuated by inflating 10 times at a rate of 10 Hz. For the second part of the study, users were asked to identify six different direction cues: tilt right, tilt left, tilt backwards, tilt forward, twist clockwise, and twist counterclockwise. For each cue, a set of three pouches was sequentially inflated at a rate of 20 Hz, as shown in Fig. 4b. Each pattern was displayed three times in a row, with one second in between. This sequential actuation of sets of pouches induces a sensation of motion in a given direction. The particular sequences and mappings to directional cues were selected based on feedback during pilot studies.

All users performed the pouch identification task, followed by the direction cue identification task, with training sessions prior to both. During training blocks (which took around 10 minutes each), users provided their response aloud and were immediately provided feedback indicating the pouch or direction that had been displayed and if they had been correct. During experimental blocks, participants used their left hand to input their response on a computer keyboard and received no feedback on the correctness of their response. Participants wore noise canceling headphones playing white noise to mask the sound of the solenoid valves. A cloth was also used to block sight of the device in order to ensure no visual indicators could be used.

For the pouch identification task, users completed 30 practice trials, followed by 90 experimental trials. During the practice trials, the pouches were first actuated in numerical order for the first 20 trials, and they were then pseudorandomly actuated for the subsequent 10 trials. Users then completed the 90 experimental trials, consisting of 10 instances per pouch, where each participant received a unique, pseudorandom set.

For the direction cue identification task, users completed 18 practice trials, followed by 60 experimental trials. During the practice trials, the directions were first actuated in a predefined order for 12 trials to help familiarize the participants with the mappings, and they were then pseudorandomly actuated for the subsequent 6 trials. Users then received a unique, pseudorandom set of 60 direction cues for the experiment itself, consisting of 10 instances of each cue.

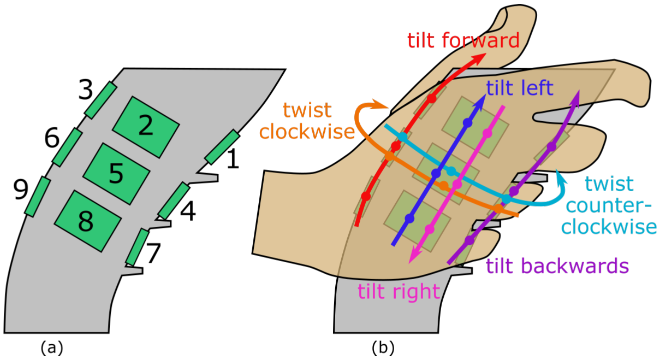

Fig. 4. Mappings used for (a) the individual pouch identification study and (b) for the direction cue study. A given direction was conveyed by actuating a specific sequence of three pouches in a row. Each colored arrow represents a direction cue, where the pouches are actuated in the order as signified by the direction of the arrow shown.

TABLE I

CONFUSION TABLE FOR POUCH IDENTIFICATION

|  | **Actuated Pouch** |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|
| **Response** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 1 | 89 |  |  | 1 |  |  |  |  |  |
| 2 | 1 | 66 |  |  | 1 |  |  |  |  |
| 3 |  | 4 | 88 |  |  | 9 |  |  | 1 |
| 4 | 10 | 1 |  | 87 | 1 | 2 |  |  |  |
| 5 |  | 29 | 1 | 5 | 85 | 2 |  | 1 |  |
| 6 |  |  | 11 | 1 |  | 83 |  | 1 | 2 |
| 7 |  |  |  | 5 | 1 |  | 98 | 12 |  |
| 8 |  |  |  | 1 | 11 |  |  | 83 | 2 |
| 9 |  |  |  |  | 1 | 4 | 2 | 3 | 95 |

## B. Results

*1) Pouch Identification:* As shown in Table I, users were able to identify the majority of the actuated pouches correctly. Over a total of 900 trials, users identified the correct pouch with 86% accuracy. It should be noted that users had the most difficulty with identifying the actuation of pouch 2, often mistaking it for pouch 5, which is located right below it. Interestingly, when pouch 5 was actuated, the most common mistake was to identify it as pouch 8, which is again located one spot below. Despite some challenges with identifying pouch 2, the overall accuracy still remained high.

*2) Direction Cue:* As shown in Table II, users were able to identify the direction cues with high accuracy, particularly for the right, left, backward, and forward directions. The overall accuracy across the 600 trials was 89%. Despite the lower accuracy shown for identifying the clockwise and counterclockwise cues, we note that the majority of these errors came from one participant consistently mixing up the two cues. With additional training, the overall accuracy could be significantly increased. The time taken for participants to identify the direction cues was also recorded and is shown in Fig. 5. The response times were consistent across all direction cues. It should be noted that this time was computed based on the difference between the time when the cues started to display and the time when the user keyed in their response via the keyboard, which required pressing two keys (the key associated with their response, and the 'enter' key).

## C. Post-study Survey

In a post-study survey, participants were asked to rate both the comfort of the device and the noticeability of the sensation. On a five-point Likert scale, where 1 corresponded to "not comfortable" or "not noticeable" and 5 corresponded to "very comfortable" or "very noticeable", the average user ratings were 4 and 4.25, for comfort and noticeability, respectively. Based on qualitative feedback on the size and shape of the device, it seems that having handles that are better fit to different sized hands could help to improve the overall experience and performance with the device.

## D. Discussion

We demonstrated the ability of HaPPArray to be integrated into a hand-held form factor and used to effectively convey haptic feedback. Users could correctly identify the majority of the individual pouches with high accuracy. Although one pouch was difficult to identify compared to the others, additional training could likely improve this accuracy. Beyond identifying individual pouches, the high accuracy of users in identifying direction cues demonstrates the potential of HaPPArray for delivering effective haptic guidance. In particular, the ability of users to correctly identify the right, left, forward, and backward direction cues even with very little training, suggests that they are intuitive for users. The fact that the clockwise and counterclockwise cues were sometimes mistaken for one another, particularly by a single participant, indicates that perhaps these signals are less easily interpreted and require more training time. It is also possible that for different direction cues, different rates of actuation are easier to interpret than others, and this parameter should be further investigated.

TABLE II

CONFUSION TABLE FOR DIRECTION CUES

|  | **Displayed Direction** |  |  |  |  |  |
|---|---|---|---|---|---|---|
| **Response** | Right | Left | CW | CCW | Back | Forw. |
| Right | 93 | 4 | 1 |  | 1 |  |
| Left | 6 | 94 |  | 2 | 1 | 2 |
| CW |  |  | 78 | 19 |  | 1 |
| CCW |  |  | 21 | 79 | 1 | 2 |
| Back | 1 | 1 |  |  | 97 |  |
| Forw. |  | 1 |  |  |  | 95 |

## IV. TARGET REACHING DEMONSTRATION

This section demonstrates the potential of HaPPArray to provide haptic guidance during operation of a hand-held medical robot.

## A. Setup and Procedure

The hand-held medical robot used for this demonstration is a concentric tube robot (CTR). CTRs are a class of continuum robot that consist of a set of nested, precurved,

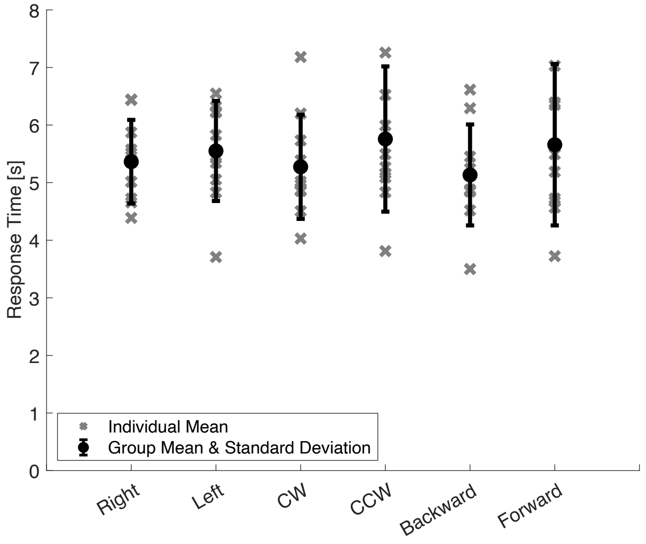

Fig. 5. Mean response times for individuals, as well as the entire group of participants, for the direction cue study.

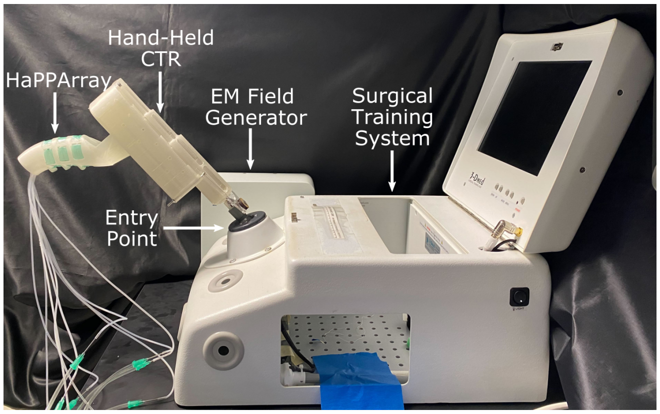

Fig. 6. Setup used for the target reaching demonstration. HaPPArray is integrated into a hand-held CTR and guides users to eight different targets.

elastic tubes [30], [31]. The shape of the robot depends on the mechanical interaction between the tubes, however, for this demonstration, the tubes themselves are not actively modified. The robot maintains a constant, but curved shape in 3-D, which makes the task even more challenging than if a straight device were used. We replace the handle originally presented in [8] with the HaPPArray.

The hand-held CTR is placed through an entry point, or port, in a surgical training system (3-D Med), which serves as the experimental setup (Fig. 6). The CTR is constrained to rotational movements within the port, and users are tasked with navigating the robot tip to eight different target locations. In order to track the position of the tip of the CTR in real time, an electromagnetic (EM) sensor is attached to the CTR tip and tracked using the Aurora system (NDI). Users cannot visually see the targets and instead navigate via the haptic guidance cues alone.

Based on the difference between the measured tip position and the desired target, the necessary direction cue is generated. Based on pilot testing, these cues are given as motions that the hand should take relative to the entry point as a pivot point. Therefore, if the CTR tip must move up or down, the “tilt backwards” or “tilt forwards” cues are used, respectively. And if the CTR tip need to move left or right, the “twist counter-clockwise” or “twist clockwise” cues are used, respectively. For movements of the CTR tip along a diagonal direction, a series of two directional cues are used. For example, if the CTR tip needs to move in a northeast direction, the “tilt right” cue and the “tilt backwards” cue are given consecutively. Users are told that for these compound cues, which all start with either “tilt right” or “tilt left”, they should aim for 45° rotation of the handle in the proper direction. The feedback is adjusted based on the movements of the user, and the trial is considered successful when the CTR tip reaches within 1 cm of the target. Three users familiarized themselves with the cues and the corresponding movements through three training rounds (approximately 15 minutes) and were then asked to navigate to all eight targets.

### B. Results and Discussion

All three users were able to successfully navigate to the eight target locations, and an example set of paths taken by one of the users is shown in Fig. 7. Users were generally able to easily identify the direction cues corresponding to up, down, left, and right motion of the CTR tip, making navigation to the corresponding targets relatively straightforward. With the exception of one user along one of these directions, the paths taken were therefore quite direct. The diagonal movements, however, proved more challenging for users to interpret, which makes sense given that they were conveyed via a compound set of two directional cues. Paths taken to reach the targets along the diagonal were generally longer and required more time to complete as users made adjustments based on the updated cues along the way. It is interesting to note that the user who seemed to complete the task the fastest, appears to have used a different strategy, which included more movements along the cardinal directions, rather than always moving along the diagonal directly. Despite some challenges with interpreting the diagonal cues, users were still able to successfully navigate the tip of the CTR, illustrating HaPPArray’s potential for haptic guidance.

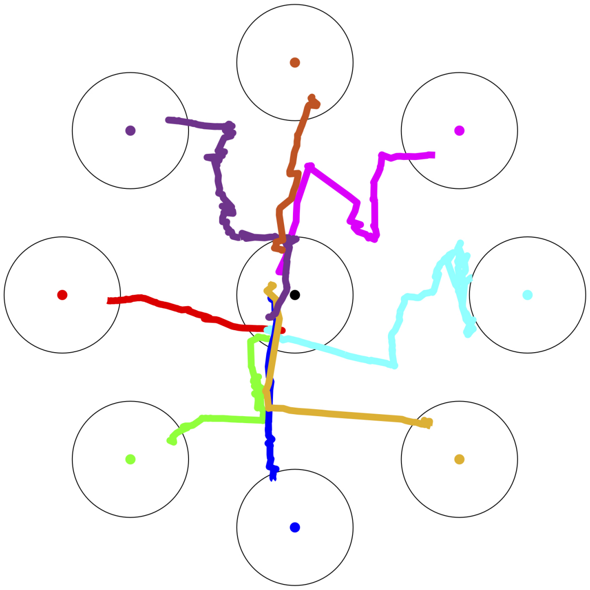

Fig. 7. Paths taken by one user based on haptic cues received during the target reaching demonstration. Paths are shown in the color corresponding to the desired target. Targets were considered to be successfully reached if the CTR tip position was within 1 cm, as designated by the black circles.

## V. CONCLUSIONS AND FUTURE WORK

In this paper, we presented the design, fabrication, and evaluation of HaPPArray, designed to provide haptic feedback during operation of a hand-held robotic device. This approach enables a comfortable, lightweight system capable of conveying intuitive haptic cues. Compared to traditional vibration actuators, HaPPArray produces lower-frequency signals that activate mechanoreceptors with smaller receptive fields. When actuated individually, users were able to correctly identify the pouch being actuated with 86% accuracy, and when actuated in sequence, users were able to correctly identify the associated direction cue with 89% accuracy. We also demonstrated the ability of HaPPArray to effectively guide users to various target locations during the navigation of a hand-held medical robot.

There are several directions for future work, along with many potential applications for HaPPArray. For instance, additional sequences of pouch actuations should be investigated to determine whether there are any that are more intuitive for users. In particular, different mappings from pouch actuations to directional cues, along with new approaches to directly convey movement along a diagonal should be explored. In addition, the effects of various pouch parameters, including size, number, and placement, can be evaluated, along with the size and shape of the handle itself. HaPPArray can also be evaluated in more clinically-relevant tasks, including, for example, ones that involve interaction with tissues in the surrounding environment. In these scenarios, HaPPArray could also potentially be used to notify users if they are approaching sensitive areas and even help guide them back towards safer operating regions. Finally, the applications of HaPPArray could be expanded beyond use in hand-held medical robots to include other hand-held devices, such as controllers for virtual and augmented reality.

## VI. ACKNOWLEDGEMENT

The authors would like to thank Connor Watson and Ayush Giri for their help with the software and mechatronic systems, and Heather Culbertson (University of Southern California) for her insights regarding study design.

## REFERENCES

[1] C. J. Payne and G.-Z. Yang, "Hand-held medical robots," *Annals of biomedical engineering*, vol. 42, no. 8, pp. 1594–1605, 2014.

[2] R. A. MacLachlan, B. C. Becker, J. C. Tabarés, G. W. Podnar, L. A. Lobes Jr, and C. N. Riviere, "Micron: an actively stabilized handheld tool for microsurgery," *IEEE Transactions on Robotics*, vol. 28, no. 1, pp. 195–212, 2011.

[3] W. Latt, U.-X. Tan, C. Shee, and W. Ang, "A compact hand-held active physiological tremor compensation instrument," in *Int. Conf. on Advanced Intelligent Mechatronics*. IEEE, 2009, pp. 711–716.

[4] F. Focacci, M. Piccigallo, O. Tonet, G. Megali, A. Pietrabissa, and P. Dario, "Lightweight hand-held robot for laparoscopic surgery," in *Int. Conf. on Robotics and Automation*. IEEE, 2007, pp. 599–604.

[5] J. Shang, D. P. Noonan, C. Payne, J. Clark, M. H. Sodergren, A. Darzi, and G.-Z. Yang, "An articulated universal joint based flexible access robot for minimally invasive surgery," in *Int. Conf. on Robotics and Automation*. IEEE, 2011, pp. 1147–1152.

[6] R. J. Hendrick, S. D. Herrell, and R. J. Webster, "A multi-arm hand-held robotic system for transurethral laser prostate surgery," in *Int. Conf. on Robotics and Automation*. IEEE, 2014, pp. 2850–2855.

[7] B. Tan, L. Wu, and H. Ren, "Handheld flexible robot with concentric tubes aiming for intraocular procedures," *Flexible Robotics in Medicine: A Design Journey of Motion Generation Mechanisms and Biorobotic System Development*, p. 149, 2020.

[8] C. Girerd and T. K. Morimoto, "Design and control of a hand-held concentric tube robot for minimally invasive surgery," *IEEE Transactions on Robotics*, vol. 37, no. 4, pp. 1022–1038, 2020.

[9] A. M. Okamura, "Haptic feedback in robot-assisted minimally invasive surgery," *Current opinion in urology*, vol. 19, no. 1, p. 102, 2009.

[10] M. Zhou, J. Perreault, S. Schwaitzberg, and C. Cao, "Effects of experience on force perception threshold in minimally invasive surgery," *Surgical endoscopy*, vol. 22, no. 2, pp. 510–515, 2008.

[11] J. M. Walker, H. Culbertson, M. Raitor, and A. M. Okamura, "Haptic orientation guidance using two parallel double-gimbal control moment gyroscopes," *IEEE Transactions on Haptics*, vol. 11, no. 2, pp. 267–278, 2017.

[12] A. Zenner and A. Krüger, "Shifty: A weight-shifting dynamic passive haptic proxy to enhance object perception in virtual reality," *IEEE transactions on visualization and computer graphics*, vol. 23, no. 4, pp. 1285–1294, 2017.

[13] G. Stetten, B. Wu, R. Klatzky, J. Galeotti, M. Siegel, R. Lee, F. Mah, A. Eller, J. Schuman, and R. Hollis, "Hand-held force magnifier for surgical instruments," in *Int. Conf. on Information Processing in Computer-Assisted Interventions*. Springer, 2011, pp. 90–100.

[14] D. Prattichizzo, F. Chinello, C. Pacchierotti, and M. Malvezzi, "Towards wearability in fingertip haptics: a 3-dof wearable device for cutaneous force feedback," *IEEE Transactions on Haptics*, vol. 6, no. 4, pp. 506–516, 2013.

[15] S. Choi and K. J. Kuchenbecker, "Vibrotactile display: Perception, technology, and applications," *Proceedings of the IEEE*, vol. 101, no. 9, pp. 2093–2104, 2012.

[16] G.-H. Yang, M.-s. Jin, Y. Jin, and S. Kang, "T-mobile: Vibrotactile display pad with spatial and directional information for hand-held device," in *Int. Conf. on Intelligent Robots and Systems*. IEEE, 2010, pp. 5245–5250.

[17] P.-A. Cabaret, T. Howard, C. Pacchierotti, M. Babel, and M. Marchal, "Perception of spatialized vibrotactile impacts in a hand-held tangible for virtual reality," in *Int. Conf. on Human Haptic Sensing and Touch Enabled Computer Applications*. Springer, 2022, pp. 264–273.

[18] A. U. Alahakone and S. A. Senanayake, "Vibrotactile feedback systems: Current trends in rehabilitation, sports and information display," in *Int. Conf. on Advanced Intelligent Mechatronics*. IEEE, 2009, pp. 1148–1153.

[19] A. Guzererler, W. R. Provancher, and C. Basdogan, "Perception of skin stretch applied to palm: Effects of speed and displacement," in *Int. Conf. on Human Haptic Sensing and Touch Enabled Computer Applications*. Springer, 2016, pp. 180–189.

[20] D. K. Chen, J.-B. Chossat, and P. B. Shull, "Haptivec: Presenting haptic feedback vectors in handheld controllers using embedded tactile pin arrays," in *CHI Conference on Human Factors in Computing Systems*, 2019, pp. 1–11.

[21] S. Yoshida, Y. Sun, and H. Kuzuoka, "Pocopo: Handheld pin-based shape display for haptic rendering in virtual reality," in *CHI Conference on Human Factors in Computing Systems*, 2020, pp. 1–13.

[22] M. Raitor, J. M. Walker, A. M. Okamura, and H. Culbertson, "Wrap: Wearable, restricted-aperture pneumatics for haptic guidance," in *Int. Conf. on Robotics and Automation*. IEEE, 2017, pp. 427–432.

[23] N. Agharese, T. Cloyd, L. H. Blumenschein, M. Raitor, E. W. Hawkes, H. Culbertson, and A. M. Okamura, "Hapwrap: Soft growing wearable haptic device," in *Int. Conf. on Robotics and Automation*. IEEE, 2018, pp. 5466–5472.

[24] W. Wu and H. Culbertson, "Wearable haptic pneumatic device for creating the illusion of lateral motion on the arm," in *IEEE World Haptics Conference*. IEEE, 2019, pp. 193–198.

[25] A. A. Amiri Moghadam, S. Alaie, S. Deb Nath, M. Aghasizade Shaarbaf, J. K. Min, S. Dunham, and B. Mosadegh, "Laser cutting as a rapid method for fabricating thin soft pneumatic actuators and robots," *Soft robotics*, vol. 5, no. 4, pp. 443–451, 2018.

[26] P. E. Glick, I. Adibnazari, D. Drotman, D. Ruffatto III, and M. T. Tolley, "Branching vine robots for unmapped environments," *Frontiers in Robotics and AI*, vol. 9, 2022.

[27] H. Culbertson, S. B. Schorr, and A. M. Okamura, "Haptics: The present and future of artificial touch sensation," *Annual Review of Control, Robotics, and Autonomous Systems*, vol. 1, no. 1, pp. 385–409, 2018.

[28] R. S. Johansson and J. R. Flanagan, "Coding and use of tactile signals from the fingertips in object manipulation tasks," *Nature Reviews Neuroscience*, vol. 10, no. 5, pp. 345–359, 2009.

[29] A. B. Vallbo, R. S. Johansson *et al.*, "Properties of cutaneous mechanoreceptors in the human hand related to touch sensation," *Hum neurobiol*, vol. 3, no. 1, pp. 3–14, 1984.

[30] R. J. Webster, A. M. Okamura, and N. J. Cowan, "Toward active cannulas: Miniature snake-like surgical robots," in *Int. Conf. on Intelligent Robots and Systems*. IEEE, 2006, pp. 2857–2863.

[31] P. Sears and P. Dupont, "A steerable needle technology using curved concentric tubes," in *Int. Conf. on Intelligent Robots and Systems*. IEEE, 2006, pp. 2850–2856.