



HAL
open science

Multi-actuator Haptic Handle Using Soft Material for Vibration Isolation

Pierre-Antoine Cabaret, Antoine Bout, Maxime Manzano, Sylvain Guégan,
Claudio Pacchierotti, Marie Babel, Maud Marchal

► **To cite this version:**

Pierre-Antoine Cabaret, Antoine Bout, Maxime Manzano, Sylvain Guégan, Claudio Pacchierotti, et al.. Multi-actuator Haptic Handle Using Soft Material for Vibration Isolation. 2024 - Eurohaptics conference, H. Kajimoto, P. Lopes, C. Pacchierotti, C. Basdogan, M. Gori, B. Semail, M. Marchal, Jun 2024, Lille, France. pp.1-13. hal-04553415

HAL Id: hal-04553415

<https://inria.hal.science/hal-04553415>

Submitted on 20 Apr 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License

Multi-actuator Haptic Handle

Using Soft Material for Vibration Isolation

Pierre-Antoine Cabaret¹, Antoine Bout¹, Maxime Manzano¹, Sylvain Guégan⁴,
Claudio Pacchierotti², Marie Babel¹, and Maud Marchal^{1,3}

¹ Univ Rennes, INSA Rennes, IRISA, Inria, CNRS – Rennes, France

² CNRS, Univ Rennes, Inria, IRISA – Rennes, France

³ Institut Universitaire de France (IUF) – Paris, France

⁴ Univ Rennes, INSA Rennes, LGCGM – Rennes, France

`firstname.lastname@irisa.fr`

Abstract. We present a new handheld multi-actuator haptic device, which provides localized vibrotactile feedback in a small form-factor. To isolate the vibrations generated from the different actuators, we design an original 3D printed deformable structure integrated into the handle. We evaluate the benefits of our isolation structure in a vibrometry study, comparing the proposed version to a rigid structure. A perception study is also conducted to evaluate the distinct perception of vibrations between the two versions of the handle by 12 human users. Finally, we showcase the use of the proposed handle in a virtual navigation task, showing its capabilities for applications where multiple and distinct haptic stimuli need to be provided to the user’s hand.

Keywords: Handheld interface · Multi-actuator · Vibration · Cutaneous haptics.

1 Introduction

Multi-actuator vibrotactile devices have shown to be effective in various applications such as Virtual Reality (VR) interactions [2] or navigation assistance [6]. The multiple points of stimulation they offer can be used to provide rich information more easily and rapidly than with single-actuator devices, which rely more on temporal patterns (e.g., Tactons [7]), intensity or duration. Indeed, the location of the stimuli can already provide an information by itself, which can be enriched using the properties of the localized vibration.

In order to be easily identified, stimuli must be isolated from each other. Therefore, one of the main challenge of multi-actuator feedback is to generate haptic stimuli that could be easily and quickly differentiated depending on the feedback location. Isolation between the different tactile signals is in fact related to the type of devices. Thus, multi-actuator vibrotactile devices are most often wearable ones [15], as the stretch of the fabric on the skin ensures a good distribution of the actuators, thus stimuli isolated from each other. Examples of

wearable devices include Tactile Glove [10], in which an array of up to ten motors in a fabric glove provides localized feedback on the back of the hand, plus one located on the palm. Belts and armbands [1,11,8,6] are other well-known examples of multi-actuator devices. In these specific cases, the actuators are generally well spaced. Paneels et al. [16] designed a watch-sized casing with six points of stimulation for the wrist. The structure within the device is designed to prevent the propagation of vibration within the device, but only at a single frequency.

However, wearable devices can be cumbersome, uncomfortable, or even inappropriate for users with physical disabilities. In these cases, other types of in-hand interfaces can be more suited. For example, T-hive [20] is a spherical multi-actuator display which can be used as a joystick. Vibration panels on the surface of the sphere are isolated with a layer of vibration absorber material. Directions are however difficult to identify for some parts of the hand (i.e., the palm or thumb), with score ranging from 99% to 45%. Another approach for localized feedback is to use vibration interferences [4], but the influence of the hand must be taken into account as it might influence vibration propagation.

Actuators can also be integrated into existing devices: white canes can benefit from multi-actuator feedback [14,17], as well as other mobility assistance devices. For example, Lacote et al. [13], proposed a haptic handle fitted with five custom made voice coil actuators, designed to be used with a walker or wheelchair. The question of isolation is nevertheless not addressed.

Finally, multi-actuator devices can be entirely handheld. Cabaret et al. [2,3] used up to five actuators in handheld tangible objects to provide localized cues in Virtual Reality interactions, but did not isolate the actuators between them. Similarly, Multivibes [18] is a ten-actuator handle for interaction in virtual reality. Actuators use a mobile part in contact with the user's skin, separated from the handle frame to avoid vibration transmission within the handle. Spiers et al. [22] evaluated a holdable navigation device in which three actuators are isolated by keeping faces separated. The size of the interface still is quite large for three points of stimulation.

Overall, vibrations in handheld interfaces can be isolated or attenuated using several techniques such as using a layer of dampening material [20], keeping the actuated parts physically separated [22] or having a directional actuator in direct contact with the users' skin [18,13]. Some approaches do not consider isolation at all (e.g., tangibles with embedded voice-coil actuators[2]), in which case sensations are more diffuse.

Despite it all, to provide localized vibrotactile cues within the hand, propagations through the hand itself must be considered. Dandu et. al. [5] measured the propagation of vibrations elicited at the fingertip through the hand using a multi-point vibrometer. They showed that propagation decreases quickly with frequency. Similar observations can be made from measurements taken with the accelerometer array from Shao et. al. [21]. In that respect, these properties of the hand must be taken into account in the design of a device and the haptic sensations it provides.

In this paper, we present the design of a multi-actuator handle, providing localized vibrotactile feedback within the user hand thanks to four actuators on its sides, isolated with a deformable structure. Compared to existing devices, both the handle and the isolation structure are fully 3d printed, aiming at an easily replicable design based on cheap and widely available actuators and materials. This design also has the benefit of not requiring a complex assembly process, and being easily adaptable to other actuators. We evaluate the design of the handle and its flexible structure with a vibrometry study, comparing it with its rigid (i.e., non-isolated) counterpart, as well as with a perception study where participants have to discriminate localized haptic cues. Finally, we illustrate the potential application of our handle through a navigation use case in Virtual Reality.

2 Multi-actuator Handle Design

The proposed multi-actuator handle is illustrated in Fig. 1. Its structure is fully 3d-printed. Four ERM actuators (Vybronic VZ6DL2B0055211) are located symmetrically around the cylindrical structure. We used widely available ERM actuators so that the handle could be easily replicated and customizable. These ERMs are able to produce sinusoidal vibrations between 50 and 200 Hz. Vibration frequency and intensity are linearly linked to the input voltage. The handle is designed to be simply held in the hand or plugged onto a gaming joystick (see Fig. 3).

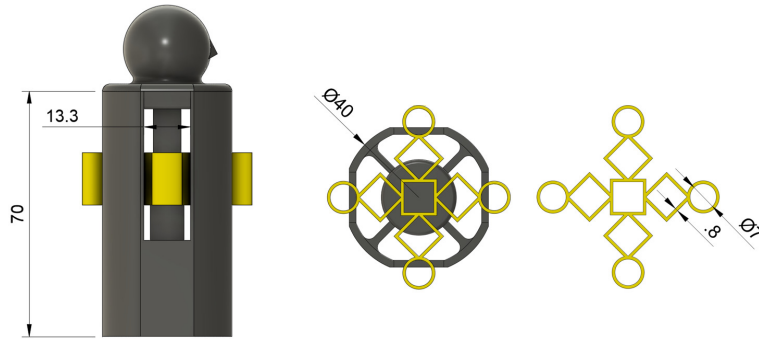


Fig. 1. The proposed multi-actuator haptic handle is made of three 3d printed parts. The shell and cap are printed in rigid PLA (grey in the Figure) while the inner structure is printed using soft TPU (yellow). This latter soft structure houses four vibrating actuators in 7mm-diameter cylinders at its extremities. Dimensions are in millimeters.

The outer shell of the handle is 40 mm in diameter (grey in Fig. 1), topped with a removable spherical part resembling a head, with a tactile indent on one side, resembling a nose. Doing this, haptic cues from the handle can be easily

mapped to a direction relative to the user in, e.g., navigation tasks. Both of these parts are printed out of PLA. Within this rigid shell, we designed a deformable structure made of four modules (yellow in Fig. 1), inspired by the cells used in metamaterials mechanisms [12]. Each module houses one of the four ERM actuators of the handle. We printed this structure using TPU Filament Filaflex 82A, with a width of 0.8 mm for all elements (see Fig. 1). Such a material has already been used in printing spring-like structure [9]. The soft modules can deform when compressed (see Fig. 2), pushing the actuators against the users fingers. They play two key roles: first, they ensure a permanent contact between the actuator and the user’s skin. Secondly, they greatly reduce vibration propagation from the motors to the other parts of the handle, thus helping the user better identifying the stimuli source. When held in hand, the handle provides localized stimuli on the thumb, palm, index and middle finger (see Fig. 2). The structure parameters were chosen iteratively, resembling 3d printed lattice cellular structures which were shown to have vibration isolation properties [19,23].

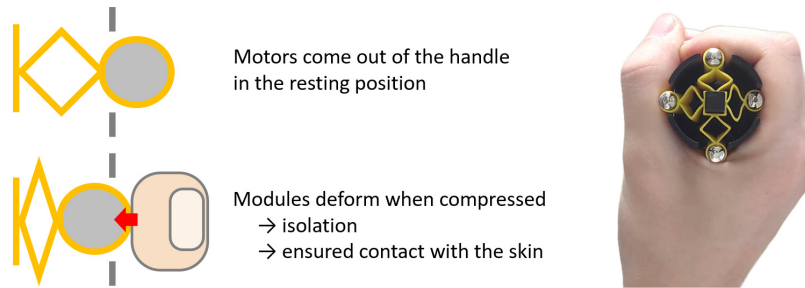


Fig. 2. The soft structure within the handle is 3d-printed with TPU. Each module holds one of the actuators and plays a dual role: ensuring the contact between the user’s hand and the motor while also isolating vibrations from the rest of the handle.

An ESP32 micro-controller controls the four motors using PWM signals between 0V and 4V. Commands can be sent using a serial connection or wirelessly via ROS2 when connected to a battery.

3 Vibrometry Study

We conducted a vibrometry study to evaluate the effectiveness of our design to isolate vibrations within the handle. An optical vibrometer was used to collect velocity and frequency of skin vibrations at four locations of the hand while holding the handle. To assess the repeatability of measures, 6 participants (5M-1F, Ages 18-47, all right-handed) took part in the study. Hand sizes ranged from 190 to 170 mm, from the wrist to the tip of the index finger.

3.1 Experimental Setup

Skin vibrations were measured using a laser doppler vibrometer (VibroFlex Neo, Polytech). Participants held the handle with their right hand, placing the vibrating motor at the front of the handle, in-between the intermediate and distal phalanges of their index. The laser was then targeted at the desired measuring point, i.e., on the finger at the level of the actuator (see Fig. 3-right). We selected four points of measurement (see Fig. 3-left):

- (A) on the intermediate phalanx of the index;
- (B) on the proximal phalanx of the index;
- (C) on the back of the hand, between the thumb and index;
- (D) on the proximal phalanx of the thumb.

Measurements were taken at these points while always activating the same actuator placed under the intermediate phalanx of the index (point A). Measurements are repeated three times for each point at (i) ten levels of increasing input voltage (from 0.7 to 3.7V with 0.3V increases, spanning the full actuation space of the motors), (ii) two levels of grasping force (loose grip and tight grip), and (iii) with the proposed isolating structure vs. with a rigid version of the structure (i.e., non-isolating) made of rigid PLA. For the rest of this paper, these two versions will be referred to as the “flexible handle” and the “rigid handle”, respectively. The rigid handle was designed to have the actuators at a similar location than with the flexible handle when it was compressed.

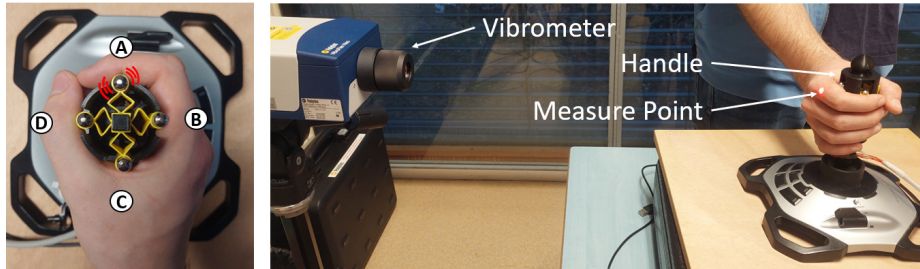


Fig. 3. (Left) The velocity of skin vibration was measured at four different locations on the hand, while activating the motor at point A. (Right) We used a laser doppler vibrometer pointed at the hand to measure the skin vibration due to the motor actuation.

Subjects were asked to grasp the handle as in Fig. 3 at the two considered levels of grasping force. Force levels were visually monitored based on the deformation of the structure (at the maximum level of force, the modules are fully pushed inside the handle). Each measure cycle was repeated three times to ensure consistency.

During the study, commands were sent to the handle via a Matlab script. Once in position, the motor is successively activated at the ten levels of vibration intensity for two seconds each. A dSPACE (DS1104) controller board was used to record velocity data from the vibrometer as well as the input voltage of the motor. Data is captured at 10 kHz, with a range of 100 mm/s. Preliminary tests were performed on the motors to ensure their performance and reproducibility of their signals over time.

3.2 Results

The data is composed of 480 recordings per participant: three repetitions of each combination of conditions (input voltage, measuring point, grasping force, handle), for a total of 2880 measures. We extracted, from each record, the Root Mean Square (RMS) velocity of the skin, a metric also used in [5]. Data for each participants across conditions can be seen in Fig. 4.

Overall, RMS velocity of skin vibration ranges from 0.8 mm/s to 69 mm/s. As seen in Fig. 4, mean velocity with the flexible handle at point A increases rapidly with the input voltage, from 5 mm/s to a maximum of 35 mm/s. A clear attenuation can also be seen between point A and the three other measuring points B, C, and D, as expected. For the highest vibration intensity, velocity at point A is up to 11 times higher than at the other points. In comparison, velocity is much lower when considering the rigid handle, with mean values ranging from 2 mm/s to 13 mm/s. The difference between points around the hand is much lower in this case: values at point B, C, and D range between 0.5 and 1 times the velocity at point A. This result show how the proposed isolating design significantly improve the localization of the vibrations with the handle.

As the index finger is in contact with the vibration source, located at point A, we observe higher velocities at point B than with other fingers: this is due to the propagation of vibration through the finger. As shown by Dandu et al. [5], this propagation through the finger decreases as frequency increases. This can indeed be observed at point B with the flexible handle and loose grip force, where velocity rises at lower frequencies before dropping at higher frequencies.

Between the two levels of grasping force, we can observe that the velocity is higher in the non-stimulated fingers when the handle is held tightly with the flexible handle. This might be due to the isolating structure being less effective when fully compressed, or the hand conducting vibrations more effectively when closed firmly. Differences in RMS velocity is also clear between the two handles: at point A, where the vibration originates, the flexible handle shows 2 to 3.5 times higher vibration velocities than with the rigid handle.

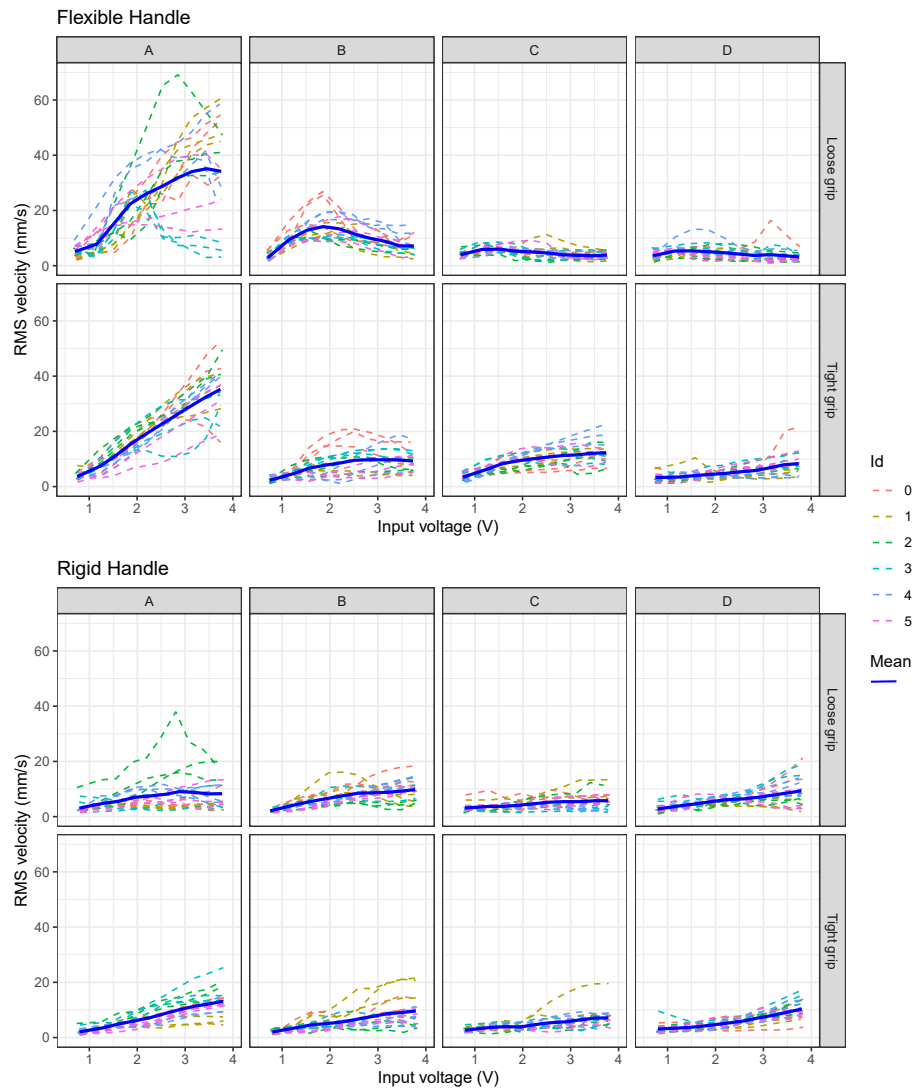


Fig. 4. RMS velocity of skin vibration for each of the four measure points, for the flexible (top) and rigid (bottom) handles. Individual participant data are shown in dashed lines. Mean RMS velocity value is shown in a solid blue line.

4 Perception Study

In addition to the vibrometry study, we conducted a user study with 12 participants (5M, 7F, 10 right-handed, aged 20-66, mean age 37.5) to evaluate the discrimination of haptic cues provided by our handle in comparison to the rigid version.

4.1 Experimental Setup

This study was performed with participants sitting at a desk and the haptic handle mounted on a joystick (as in Fig. 5). A screen displayed relevant information during the experiment, and a keyboard was used to answer each trial. Participants were presented with the handle and were instructed on how to place their dominant hand on the handle before a familiarization phase with the vibrations. A headset displayed noise throughout the experiment to hide potential audio cues from the actuators.

Participants performed two series of 40 trials in which they had to identify the location of 0.2-s-long vibrations between the four possible ones (left, right, front, and back actuators). Each of the four vibration locations was presented 10 times. Trials order was randomized across participants. Participants performed the first series of trials with one of the two handles (i.e., flexible and rigid), and the second series with the other one. The presentation order for the type of handle was counter-balanced across participants.

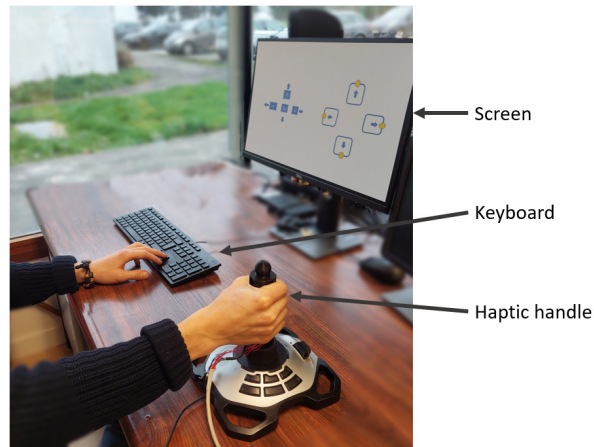


Fig. 5. Experimental setup for the perception study. Participants sat at a desk, holding the handle in their dominant hand. A keyboard was used to select the location at which they felt the vibration.

4.2 Results

Overall, participants were able to identify the vibration location most of the times, with success rates ranging from 81% to 98% for the flexible handle and 68% to 93% for the rigid one (see the confusion matrix in Fig. 6). We used a generalized linear mixed model to study participants responses with respect to the vibration location and type of isolation of the handle. Participants were

considered as a random effect in the model. Analysis of deviance of the answers showed significant effects of both the vibration location and the isolation type ($p < 0.001$). A post-hoc analysis on the different conditions was performed using a Tukey test. Trials with the flexible handle had significantly higher correct answer rates compared to when the rigid one was used ($Z = 4.81$, $p < 0.001$). Correct answer rates were lower for the back location compared to the front and left locations ($p < 0.001$), as well as for the right location compared to the left and front location ($p < 0.001$).

After each series of trials, participants were asked to rate whether vibrations were difficult to locate on a 7-item Likert scale (1=Totally disagree, 7=Totally agree). A Wilcoxon signed rank test showed a significant difference ($p < 0.001$) between the evaluated difficulty with the flexible (mean=2.83, SD=0.937) and rigid (mean=4.42, SD=1.44) handles (see Fig. 6).

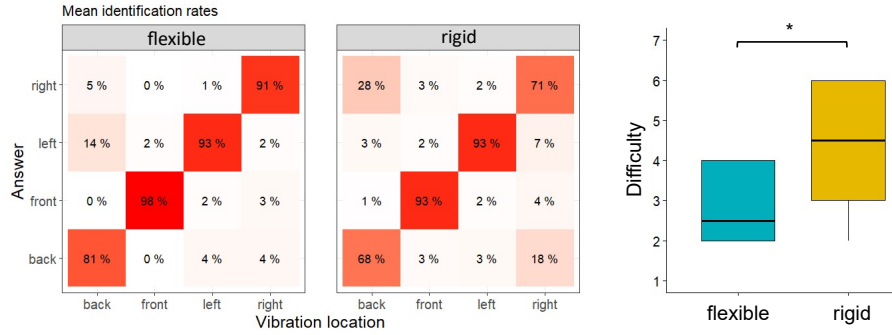


Fig. 6. (Left) Confusion matrix for the perception experiment: identification rates for each vibration location with the flexible and rigid handles. (Right) Participants evaluation (7-item Likert scale) of the difficulty to identify the vibration location on both handles.

5 Discussion

The results of the vibrometry study showcases a clear difference between the two versions of the handle. Indeed, vibrations are much more intense at the stimulated location with the flexible handle, while keeping vibrations on the other fingers at a much weaker level. While the grasping force on the handle appears to lower the intensity of vibrations at the stimulated point, it stays well above the intensity of other points on the hand. Some improvements in the shape of the handle, such as a more ergonomic form factor and a more complex soft lattice structure could add more control to the modules deformation, and also mitigate the propagation of vibrations through the hand.

While we observed a large difference between the flexible and rigid handles in vibration velocity in our vibrometry study, participants of the perception study were still able to accurately identify the vibration locations in both handles. Still, results with the flexible handle were better than those with the rigid one. Back and left locations showed slightly lower identification rates, likely due to the lower sensitivity of the palm and thumb compared to the index.

Finally, even if they were successful in both conditions, participants found the task to be (much) easier with the flexible handle. This is also supported by comments from the participants, who found the vibrations from the flexible handle to be clearer.

In that respect, our design of a flexible isolating structure within the handle was shown to be effective. In practice, this would allow us to design easily identifiable localized haptic cues with a larger range of vibration intensities in the users' hand. Even if location identification is possible without isolation, our design facilitates the perception of the haptic cues provided by the handle. In addition, during the perception study, participants were solely focused on identifying the vibration location. We can expect that results would be lower if this was only a secondary task. For instance, it would be the case if the handle is used in navigation scenarios where users would have to also focus on other tasks, e.g., interacting with the environment or other users. In such a case, having more easily-identifiable haptic cues would be beneficial. Moreover, people with lower tactile sensitivities could also benefit from better-contrasted tactile cues with such a multi-actuator device.

Given the structure simplicity, the proposed handle design could be adapted to other actuators of different size or shape. However, each module needs space to deform freely, which limits the applicability of this design in existing interfaces (e.g., VR controllers).

6 Use-Case: Navigation in Virtual Reality

Our two studies showed the benefits of our multi-actuator isolation design and the ability of participants to identify the vibration location easily around the handle. In this section, we illustrate the use of our haptic handle in a navigation scenario in Virtual Reality.

In this scenario, participants are able to navigate in a virtual environment displayed on a screen in front of them, with the handle placed on a joystick. The virtual environment is composed of a series of three mazes, through which the haptic handle provides directional cues (front, left, right, or back) to guide the user to the exit. The same twelve participants who carried out the perception study also participated in this demonstration.

Overall, participants were successful in following the guidance cues provided by the haptic handle and did not get lost in the mazes, as can be seen on [Fig. 7](#), where trajectories only deviate occasionally from the main path. When asked to rate the difficulty to follow the haptic guidance from 1 to 7, most participants found the task to be relatively easy ($M = 2.08$, $SD = 1.67$).

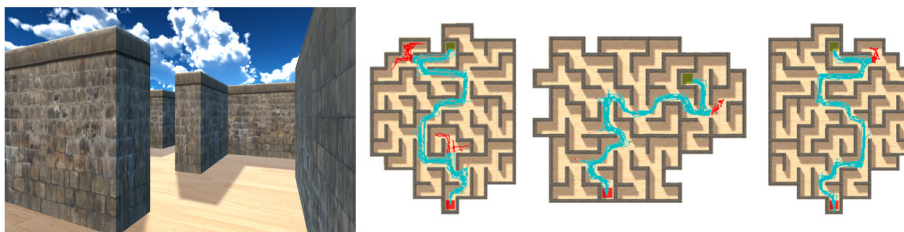


Fig. 7. (Left) A view of the virtual environment in which participants follow the guidance from the haptic handle to find the exit of the virtual mazes. (Right) The three mazes explored by the participants, and their trajectories within them. When on the correct path, positions are shown in blue; when outside of the correct path, positions are shown in red.

7 Conclusion

This paper presented the design of a multi-actuator haptic handle. It features a custom deformable structure at its center to hold the four actuators, so as to better isolate their vibrations. We evaluated the benefits of this design in a vibrometry study, where we showed an increased vibration intensity at the point of stimulation, and with a perception study, where participants found that the isolated handle facilitated location identification. Finally, we showcased the use of the handle in a navigation scenario, where vibration location on the handle indicated directions to follow in a virtual maze.

As future work, we could adapt our approach to other types of devices which could benefit from localized vibrations, such as VR interfaces. We could also investigate the use of our haptic handle in navigation assistance scenarios, where clear localized cues could be beneficial for more intuitive guidance. Further investigations into the isolating structure parameters could also be conducted.

Acknowledgements This project has received funding from Inria – Défi “DORNELL” and the European Union (ERC, ADVHANDTURE, 101088708). The study has been approved by Inria’s ethics committee (COERLE, No. 2023-48). The authors would like to thank Thomas Voisin for his work on the design and printing of the handle.

Disclosure of Interests The authors have no competing interests to declare.

References

1. Aggravi, M., Pause, F., Giordano, P.R., Pacchierotti, C.: Design and Evaluation of a Wearable Haptic Device for Skin Stretch, Pressure, and Vibrotactile Stimuli. *IEEE Robotics and Automation Letters* **3**(3), 2166–2173 (2018)

2. Cabaret, P.A., Howard, T., Gicquel, G., Pacchierotti, C., Babel, M., Marchal, M.: Does Multi-Actuator Vibrotactile Feedback Within Tangible Objects Enrich VR Manipulation? *IEEE Trans. on Visualization and Computer Graphics* pp. 1–13 (2023)
3. Cabaret, P.A., Howard, T., Pacchierotti, C., Babel, M., Marchal, M.: Perception of Spatialized Vibrotactile Impacts in a Hand-Held Tangible for Virtual Reality. In: *Haptics: Science, Technology, Applications*. pp. 264–273. *Lecture Notes in Computer Science* (2022)
4. Coe, P., Evreinov, G., Ziat, M., Raisamo, R.: Generating Localized Haptic Feedback over a Spherical Surface. *Proc. Int. Conf. on Computer Vision, Imaging and Computer Graphics Theory and Applications* pp. 15–24 (2021)
5. Dandu, B., Shao, Y., Stanley, A., Visell, Y.: Spatiotemporal Haptic Effects from a Single Actuator via Spectral Control of Cutaneous Wave Propagation. In: *Proc. IEEE World Haptics Conf., (WHC)*. pp. 425–430 (2019)
6. Devigne, L., Aggravi, M., Bivaud, M., Balix, N., Teodorescu, C.S., Carlson, T., Spreters, T., Pacchierotti, C., Babel, M.: Power Wheelchair Navigation Assistance Using Wearable Vibrotactile Haptics. *IEEE Trans. on Haptics* **13**(1), 52–58 (2020)
7. Elvitigala, D.S., Matthies, D.J.C., Dissanayaka, V., Weerasinghe, C., Nanayakkara, S.: 2bit-tactilehand: Evaluating tactons for on-body vibrotactile displays on the hand and wrist. In: *Proc. Augmented Humans Conference*. pp. 1–8 (2019)
8. Gay, J., Umfahrer, M., Theil, A., Persson, N.K., Korn, O., Buchweitz, L., Lindell, E., Guo, L.: Keep Your Distance: A Playful Haptic Navigation Wearable for Individuals with Deafblindness pp. 1–4 (2020)
9. Gunarathna, C.H., Ranasinghe, A.D., Piyumal, N.A., Kulasekera, A.L., Jayaweera, N.D.: Design and characterization of a 3d printed wave spring for use in a flexible robotic arm. In: *2022 Moratuwa Engineering Research Conference (MERCon)*. pp. 1–6. *IEEE* (2022)
10. Günther, S., Müller, F., Funk, M., Kirchner, J., Dezfuli, N., Mühlhäuser, M.: Tactileglove: Assistive spatial guidance in 3d space through vibrotactile navigation pp. 273–280 (2018)
11. Heuten, W., Henze, N., Boll, S., Pielot, M.: Tactile wayfinder: A non-visual support system for wayfinding. *ACM International Conference Proceeding Series* **358**, 172–181 (2008)
12. Ion, A., Frohnhofen, J., Wall, L., Kovacs, R., Alistar, M., Lindsay, J., Lopes, P., Chen, H.T., Baudisch, P.: Metamaterial Mechanisms. In: *Proc. of the Annual Symposium on User Interface Software and Technology (UIST)*. pp. 529–539 (2016)
13. Lacôte, I., Pacchierotti, C., Babel, M., Gueorguiev, D., Marchal, M.: Investigating the Haptic Perception of Directional Information Within a Handle. *IEEE Trans. on Haptics* (2023)
14. Nasser, A., Keng, K.N., Zhu, K.: ThermalCane: Exploring Thermotactile Directional Cues on Cane-Grip for Non-Visual Navigation. *Int. ACM SIGACCESS Conf. on Computers and Accessibility (Oct 2020)*
15. Pacchierotti, C., Sinclair, S., Solazzi, M., Frisoli, A., Hayward, V., Prattichizzo, D.: Wearable Haptic Systems for the Fingertip and the Hand: Taxonomy, Review, and Perspectives. *IEEE Trans. on Haptics* **10**(4), 580–600 (2017)
16. Paneels, S., Anastassova, M., Strachan, S., Van, S.P., Sivacoumarane, S., Bolzmacher, C.: What’s around me Multi-actuator haptic feedback on the wrist. *Proc. World Haptics Conf. (WHC)* pp. 407–412 (2013)

17. Pyun, R., Kim, Y., Wespe, P., Gassert, R., Schneller, S.: Advanced Augmented White Cane with obstacle height and distance feedback. In: IEEE Int. Conf. on rehabilitation robotics (ICORR). pp. 1–6 (2013)
18. Richard, G., Pietrzak, T., Argelaguet, F., Lécuyer, A., Casiez, G.: MultiVibes: What if your VR Controller had 10 Times more Vibrotactile Actuators? In: IEEE International Symposium on Mixed and Augmented Reality (ISMAR). pp. 703–712 (2023)
19. Rifaie, M.A., Abdulhadi, H., Mian, A.: Advances in mechanical metamaterials for vibration isolation: A review. *Advances in Mechanical Engineering* **14**(3), 16878132221082872 (2022)
20. Ryu, D., Yang, G.H., Kang, S.: T-Hive: Bilateral haptic interface using vibrotactile cues for presenting spatial information. *IEEE Trans. on Systems, Man and Cybernetics Part C: Applications and Reviews* **42**(6), 1318–1325 (2012)
21. Shao, Y., Hu, H., Visell, Y.: A Wearable Tactile Sensor Array for Large Area Remote Vibration Sensing in the Hand. *IEEE Sensors Journal* **20**(12), 6612–6623 (2020)
22. Spiers, A.J., Dollar, A.M.: Outdoor pedestrian navigation assistance with a shape-changing haptic interface and comparison with a vibrotactile device. *IEEE Haptics Symposium* pp. 34–40 (2016)
23. Yin, H., Zhang, W., Zhu, L., Meng, F., Liu, J., Wen, G.: Review on lattice structures for energy absorption properties. *Composite Structures* **304**, 116397 (2023)