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Handheld Haptic Grip Integrating Vibrotactile and Robotic-Touch Interfaces for Turn-By-Turn Pedestrian Navigation*

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***Abstract*— This paper presents a novel handheld grip-shaped haptic device that effectively integrates vibrotactile and robotic-touch interfaces for turn-by-turn navigation. Inspired by our common expressions used daily for directions like "turn right at the third corner," our system leverages vibration counts to indicate "how many corners ahead" and the direction change of a servo motor's horn (robotic-touch) to show "which way to turn." This approach provides a clearer and more situated instruction than existing systems that give only directions and/or subjective distances to the destination or those that just present the entire route at once. A systematic user study with 13 participants demonstrated the effectiveness of the proposed device over existing solutions that use either vibration or robotic-touch modalities alone. Specifically, our device allows users to navigate the multi-intersection environment significantly faster than the robotic-touch-only baseline. Subjective evaluations obtained from questionnaires further indicate that our device enhances "intuitiveness" and "efficiency" over the vibration-only system, and improves "reliability" and "safety" compared with the touch-only system.**

I. INTRODUCTION

Imagine you are in an unfamiliar, sprawling grocery store just before closing, late at night. You urgently need to buy medicine, oral rehydration solution, and other essential items for a family member who has suddenly fallen ill. However, the store's large and complex layout makes it difficult to locate yourself or find your items of interest, even with a map. Mobile navigation systems that efficiently take you to the shelves with those items would be helpful in such situations, as previously demonstrated in various similar settings at public buildings [1], offices [2], museums [3], or retail stores [4], [5]. However, effective indoor navigation requires more than simply knowing the destination location; it demands timely, context-aware guidance that adapts to the user's immediate needs and environmental constraints.

We are interested in navigation strategies that regularly and proactively inform pedestrians of their way to the destination in a *turn-by-turn* manner, just like how retail staff do: *"Follow this aisle, turn right at the third corner, go two more blocks, and you will find the medicine!"* Presenting such a sequence of short-term instructions in a timely manner is more suitable in environments with well-organized layouts such as stores and warehouses, compared to just presenting a complete route all at once. Nevertheless, visual or audio interfaces, although installed in many current devices, are not always optimal for frequent turn-by-turn instructions.

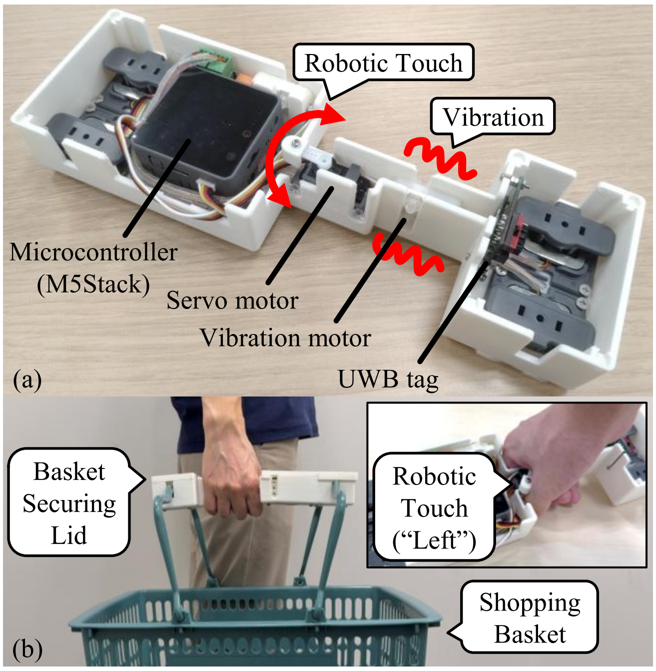

Fig. 1. Haptic grip integrating vibrotactile and robotic-touch interfaces. (a) Components and functions of the device. (b) Appearance of the device with lids securing a shopping basket, and robotic touch indicating "turn left".

Existing research has shown that visual displays significantly distract pedestrians [6], [7]. This distraction can lead to dangerous lapses in attention, potentially causing accidents or injuries due to collisions with other pedestrians or falls [8]. Additionally, when walking on crowded corridors, conversing with friends, or enjoying shopping, it can be difficult to obtain information from visual or auditory cues. These limitations of conventional interfaces have motivated exploration of alternative modalities for navigation guidance.

Among these alternatives, haptics has emerged as a particularly promising modality for navigation. The role of touch is less critical than sight or hearing while walking. Haptic feedback using vibration [9]–[11] or robotic touch [12], [13] can provide direct physical feedback to users. When designed to be portable and low-burden, haptic navigation systems have the potential to complement visual and auditory interfaces, especially when users need to direct their visual and auditory attention externally in crowded environments.

Building on these insights, we develop a new haptic navigation device shown in Fig. 1. It takes the form of a handheld grip that can easily be attached to personal bags or shopping baskets. The proposed device effectively integrates

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vibrotactile and robotic-touch interfaces to enable turn-by-turn navigation. Specifically, it informs users *"how many corners ahead"* by the number of motor vibrations, while *"which direction to turn"* by the directional change of a servo motor's horn (*i.e.*, robotic touch). This approach addresses a key limitation in current haptic navigation: the lack of anticipatory guidance. Unlike existing systems that present only subjective distance to the destinations or directional information such as which direction the destination is located [13]–[16], our approach delivers both advance notice and precise directional guidance.

We conducted a systematic user study with 13 participants to compare the proposed device against existing solutions that use vibration or robotic-touch modalities alone in navigation tasks. Our findings demonstrate the following:

- The combined interface enables faster navigation with significantly shorter arrival times, particularly for longer distances with multiple intersections.
- Subjective evaluations indicate that the proposed system enhances "intuitiveness" and "efficiency" compared to the vibration-only system, while improving "reliability" and "safety" compared to the robotic-touch-only system.
- As counting numerous vibrations can be cumbersome for users, it is preferable to use fewer vibrations to indicate actions at the nearest one or two intersections. This approach can reduce cognitive load and improve navigation experience.

II. RELATED WORK

Haptic navigation has emerged as a promising alternative to visual and auditory interfaces, which can address limitations in crowded environments where users must maintain situational awareness while receiving navigation guidance. Over the past two decades, numerous haptic navigation devices have been proposed [17], leveraging the human body's capacity to perceive tactile feedback through various body parts such as the hands, torso, and legs. Among these approaches, handheld devices have gained particular attention due to their convenience in public environments and the hand's high sensitivity to tactile stimuli. This section reviews the two primary categories of handheld haptic navigation interfaces: vibrotactile and robotic-touch systems.

A. Vibrotactile Interfaces

Vibrotactile interfaces have widely been studied in haptic feedback technologies. Most devices employ vibration stimuli from actuators in smartphones or their attachments, focusing on indicating walking directions or obstacles to avoid [9]. A widely adopted approach employs compass-like devices that point towards the destination or waypoints, providing vibrations when the angular difference falls below a certain threshold [18]–[20]. Some works have explored varying vibration pattern rhythms to convey meanings such as right/left turns, forward/backward movement, and stopping [14], [21]. Other works have proposed to present direction and distance simultaneously using a mobile phone, varying the time between vibrations [22] or vibration frequency [15] in addition to vibrations corresponding to directional error.

Beyond mobile phone-based systems, alternative approaches include palm-sized haptic compasses that generate torque around an axis perpendicular to the palm by accelerating an internal mass using brushless motors [23]. Other devices leverage pseudo-attraction forces created by accelerating a small mass above the threshold for a short time and below the threshold in the opposite direction for a long time [24], [25].

While vibration has been used in many navigation devices thanks to its simple, compact, and cost-effective approach for providing tactile cues, prolonged use can be distracting and uncomfortable for users [10]. Furthermore, a single vibration motor cannot clearly convey directional information, thus multiple vibration motors must be used to provide directional and distance information [11]. This limitation restricts the spatial resolution and the amount of information that can be displayed by these devices.

B. Robotic-Touch Interfaces

Compared to vibrotactile interfaces, robotic-touch haptic devices are considered to provide more intuitive feedback [12]. This is because humans can skillfully perceive the shape of objects held in their hands with relatively low cognitive load. Specifically, by deforming part of the device, it is possible to provide direction and distance information for navigation [13]. Users can perceive both the absolute shape of the device and its relative changes, regardless of their movement.

Representative robotic-touch implementations include seesaw-like haptic displays that push the user's palm to reproduce the pressure distribution of a sliding handrail for indicating directional changes [26], "Tactile Compass" systems that provide continuous directional feedback through a rotatable needle pointing toward the planned direction [27], and shape-changing devices that extend along one axis to indicate proximity [28] or provide 2-DOF spatial information through rotational and elongational deformation [13], [29], [30]. They tested a similar device outdoors and compared its guidance performance with a device that provided direction and proximity information through different vibration motors [12]. More recent work has developed a handheld interface with a form factor suitable for integration with other mobility aids, such as guide canes for the visually impaired or smartphone cases. This device provides 2-DOF spatial information in a continuous workspace using linear actuators [16]. Another recent work has developed a shape-changing interface that can bend in the user's hand with two degrees of freedom to represent direction in 3D space [31].

These robotic-touch devices enable the system to continuously convey information without actively stimulating the user. However, their navigation methods only indicate the immediate direction from the current position and/or the perceived distance to the destination, requiring users to process this information sequentially. This approach can lead to anxiety about future movements, such as uncertainty about when to turn or where they are being guided, potentially necessitating more cautious movement.

III. HAPTIC INTERFACE

A. Design Principle

When using screen- and sound-based route navigation, particularly in environments where we must attend to our surroundings, such as pedestrians or obstacles, we typically receive instructions that reference landmarks and future waypoints (*e.g.*, “turn right at the third corner”). This type of navigation is called *turn-by-turn* navigation, and implementing it with haptic interfaces can enable more proactive, safe, and reassuring movements.

Our approach centers on a novel haptic interface that combines two complementary feedback modalities, as illustrated in Fig. 1. The system employs vibrotactile cues to convey the number of intersections ahead, while robotic-touch feedback indicates the required turning direction through servo horn movement. By providing both advance notice and directional guidance, this dual-modality approach addresses key limitations of conventional haptic navigation systems that rely solely on immediate directional cues or distance estimation.

B. Device Design

The device is designed as a palm-sized grip that enables users to carry shopping baskets or bags while receiving navigation guidance. We focus primarily on indoor retail environments, such as grocery stores and supermarkets, where targeted marketing [32]–[34] and in-store navigation [5], [35] can significantly contribute to sales when easily integrated into existing retail infrastructures. The approach also extends to other domains, including visitor experience enhancement in museums and theme parks [3], and assistive navigation technologies [9], [30].

As shown in Fig. 1, the device consists of four main components: a microcontroller (CoreS3, M5Stack, CN), a servo motor (Servo Kit 180° Brick-compatible, M5Stack, CN), a vibration motor (Light Vibrator Unit, Akita, JP), and an Ultra-Wideband (UWB) tag for wireless positioning (Trimension SR040, NXP, NL). The vibration motor is attached to the rear of the grip, primarily targeting the ring and little fingers. Vibration intensity is adjusted to ensure sufficient perceptibility using PWM signal control. The servo motor is mounted at the front of the grip and controls a horn attached to the gear via PWM signals, providing tactile feedback to the thumb or index finger during rotation. The housing is designed for right-hand operation and fabricated using 3D printing (Chiron, Anycubic, CN). The device dimensions are 280×85×35 mm, with a total weight of 328 g including all components. The UWB tag operates on a coin-type battery and communicates with a UWB anchor (Trimension SR150, NXP, NL) connected to a laptop PC, enabling 3D position calculation through distance and angle-of-arrival measurements.

We deliberately employed a single servo motor and vibration motor so that all actuators could be housed in the gripping part of the device. This configuration enables us to evaluate the navigation performance as a minimal haptic interface. Future devices may use multiple servo motors and vibration motors to provide richer navigation information.

C. Interface Design

To enable turn-by-turn navigation, the developed haptic device effectively integrates the following vibrotactile and robotic-touch interfaces:

- *Vibrotactile Interface*: The number of vibrations indicates which corner to turn at along a straight path. For example, three consecutive vibrations mean to turn at the third corner.
- *Robotic-Touch Interface*: The direction in which the servo horn rotates indicates the direction of the turn. For example, the horn rotating to the right (*i.e.*touching to the index finger) means to turn right.

We configured the vibrotactile parameters with a single vibration duration of 250 ms and inter-vibration intervals of 250 ms. For the robotic-touch interface, the servo horn rotation angle was set to 50° with a transition time of 250 ms for both directions, optimized for comfort and tactile clarity during finger contact.

IV. USER STUDY

To evaluate the effectiveness of the proposed turn-by-turn haptic navigation system, we conducted a systematic user study comparing the integrated vibrotactile and robotic-touch approach against single-modality baselines. We recruited 13 healthy adults (10 males and 3 females, age: 30.9 ± 3.9 yrs, height: 1.70 ± 0.09 m, all right-handed) to investigate whether the combined interface enables more confident navigation compared to using vibration or robotic touch alone. The study was approved by the ethics committee of CyberAgent, Inc. (CAE-2024-04) and all participants provided informed consent before the experiment.

A. Study Design

The experimental environment was designed as shown in Fig. 2, featuring four intersecting aisle rows crossing a single straight corridor, resulting in a total of eight destinations. Participants stood at the starting position and held the haptic device while lifting the shopping basket with their right hand. After receiving start cues, they walked at a natural pace, turned at the indicated corner, and stopped at the destination. This study examined the following three conditions:

- *Vibration Only* (Vib): Participants received vibrations at the starting point indicating the number of corners to turn ahead. Upon reaching each target corner, they oriented their body left and right until a confirmation vibration indicated the correct direction, then walked to the destination.
- *Robotic Touch Only* (Touch): Participants began walking upon verbal instruction such as “Start”. Just after passing the previous row and before reaching the destination row, robotic touch cues indicated the turning direction. They then walked to the destination.

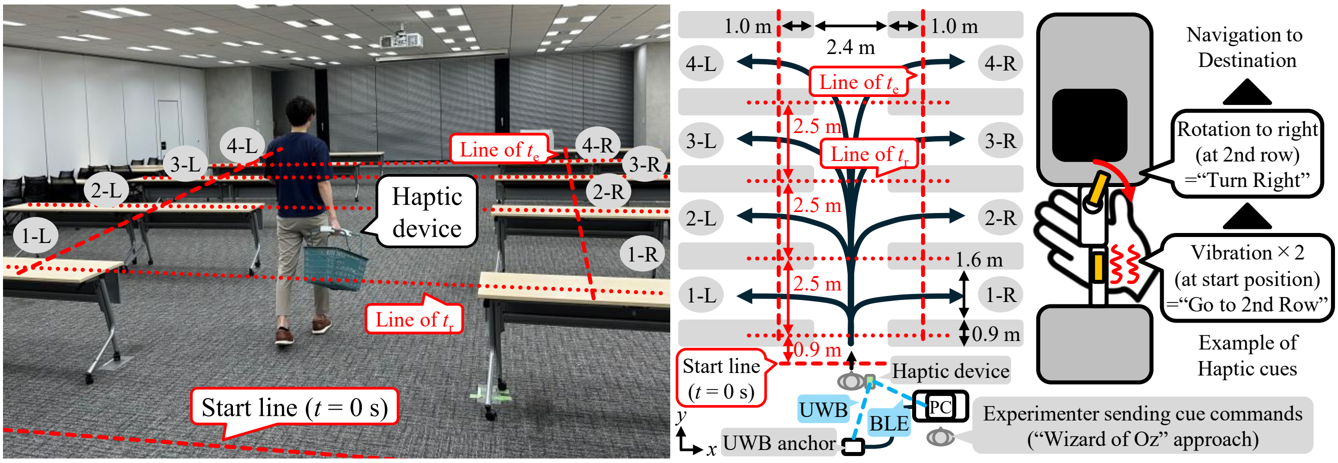


Fig. 2. Experimental environment, schematic walkway, and example of haptic cues (for the destination on the right side of the second row).

- *Vibration and Robotic Touch* (Vib+Touch): This condition combined both modalities—initial vibrations conveyed the number of corners ahead, while robotic touch provided directional guidance at the appropriate turning locations. Participants then walked to the destination.

We implemented a Wizard of Oz control system to evaluate the effectiveness of turn-by-turn navigation with combined vibrotactile and robotic-touch interfaces. In this approach, an experimenter monitored participant movements and transmitted navigation commands to the device at appropriate locations and timing. The commands were sent as characters from a laptop PC to the microcontroller via BLE communication, triggered by experimenter keyboard inputs. The positioning module served exclusively for route evaluation purposes.

Each participant was navigated to eight destinations under each condition, completing a total of 24 trials. The order of conditions was pseudo-randomized, and the destination locations were also randomized for each condition. All participants practiced walking with haptic navigation for at least one minute before starting trials of each condition to ensure full understanding of the haptic cues. As a result, none of the participants ended up at incorrect destinations.

During each trial, the position of the UWB tag was recorded at approximately 5 Hz. After completing all trials, participants answered a questionnaire rating the three conditions on five items: "Intuitive," "Comfortable," "Efficient," "Reliable," and "Safe" on a scale of 1 to 10 (10 being the best score). They also provided written responses describing their experiences when comparing the three conditions.

B. Data Analysis

We analyzed movement performance using time-series position data from the UWB tracking system. The data were first resampled at 200 ms intervals and denoised using a median filter with a window size of three. Subsequently, a Kalman filter assuming constant velocity linear motion was applied to smooth the trajectories.

To evaluate movement timing, we set $t = 0$ s as the moment participants crossed the start line shown in Fig. 2. We calculated the following performance metrics to assess participants' movement efficiency:

- t_r: Time until participants reached the destination row (when their y-axis position exceeded 2.5, 5, 7.5, and 10 m, respectively).
- t_e: Time from t_r until participants sufficiently entered the destination aisle (when their x-axis position exceeded ± 2.2 m) after turning.

For statistical analysis, we compared t_r and t_e between the proposed method (Vib+Touch condition) and baseline methods (Vib and Touch conditions) for each destination. We first conducted Shapiro-Wilk normality tests and found that data for some destinations did not follow a normal distribution. Therefore, we applied the Wilcoxon signed-rank test to compare paired data across different conditions for each destination. The Bonferroni correction was used to adjust p-values for multiple comparisons. The same statistical procedures were applied to analyze questionnaire results.

V. RESULTS

Fig. 3 shows the results of t_r (the time taken to reach each row after passing the start line) and t_e (the time taken to sufficiently enter each destination from t_r). Statistically significant differences between conditions after the Bonferroni correction are displayed by asterisks ($* : p < 0.025$, $** : p < 0.005$, $*** : p < 0.0005$). For t_r, no significant differences were observed in the first and second rows. However, as the distance (i.e., the number of intersections) increased, the Vib+Touch condition resulted in significantly shorter reaching times at the destination row compared to the Touch condition ($p < 0.025$ for the third row, $p < 0.005$ for the fourth row). For t_e, regardless of distance, participants entered the destination aisle with significantly shorter time from t_r in Vib+Touch condition compared to Vib condition ($p < 0.0005$). There were no significant differences between the Touch and Vib+Touch conditions for all destinations.

Fig. 4 shows the movement trajectories until t_e and their time series data on the y-axis for two participants. The trajectory of the Vib condition is disrupted during turning because participants stopped in a body orientation that blocked the

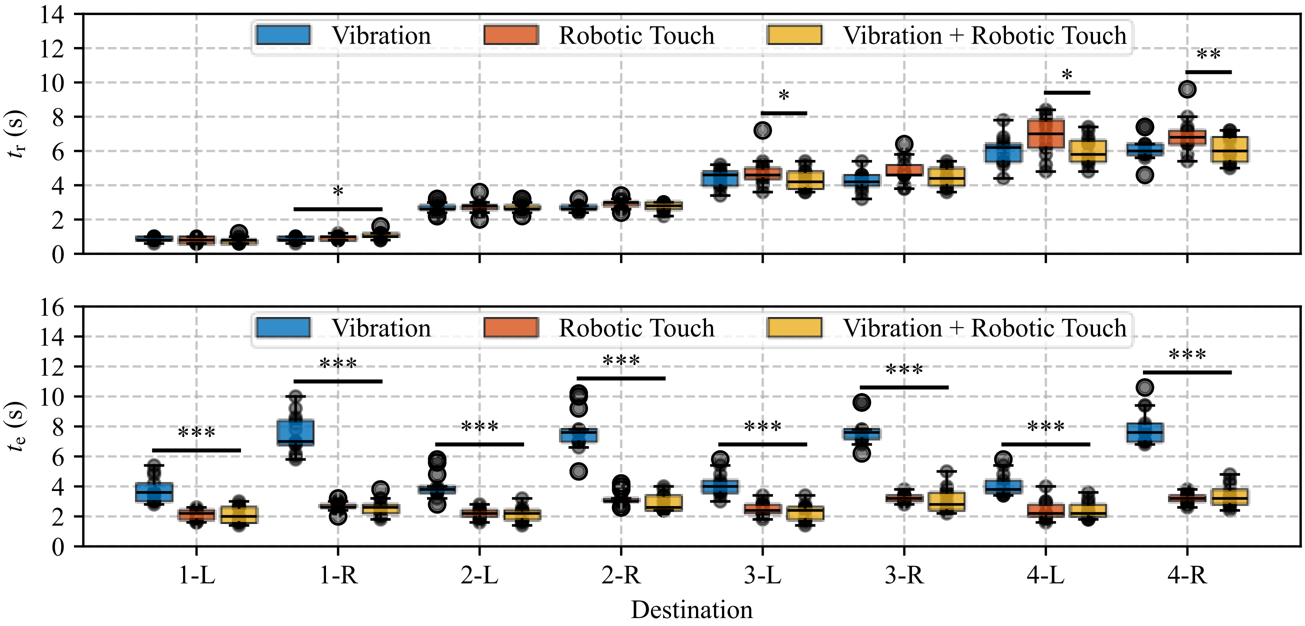
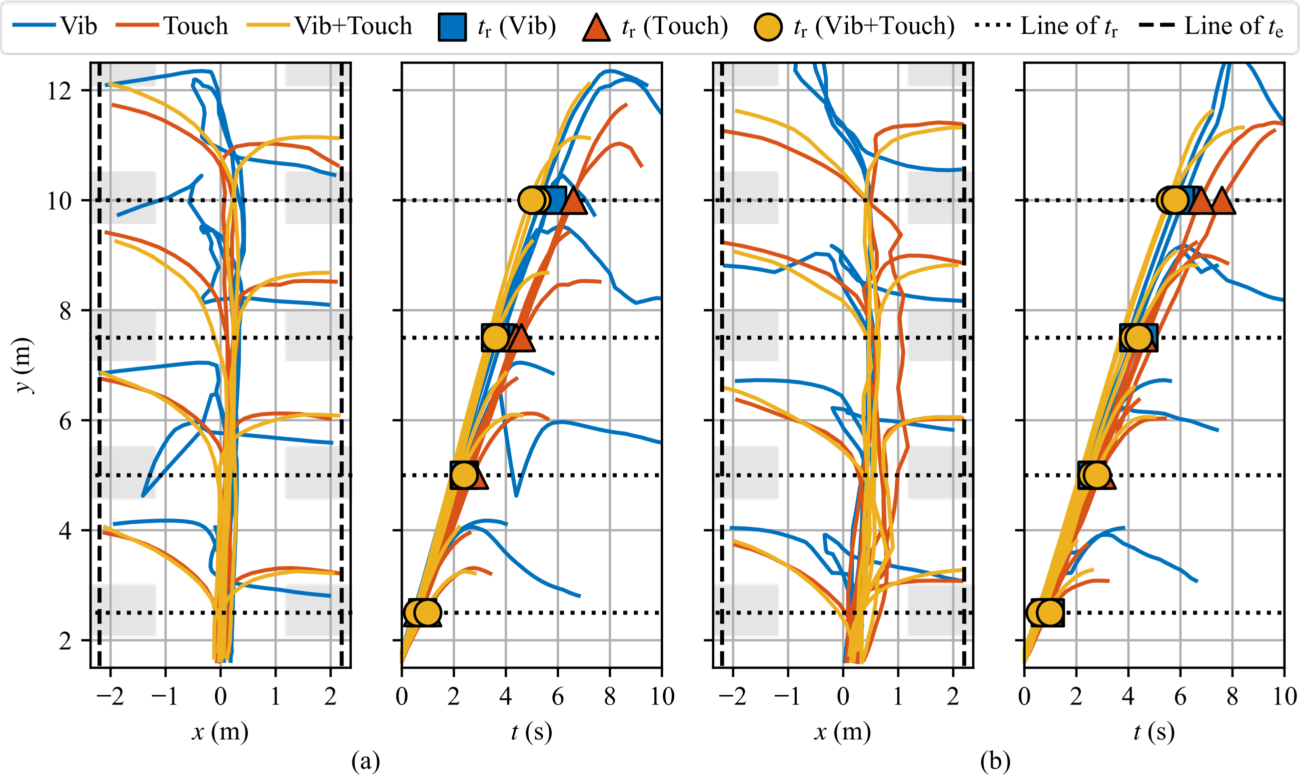


Fig. 3. Results of t_r, the time taken to reach each row after passing the start line ($t = 0$ s), and t_e, the time taken to sufficiently enter each aisle of the destination from t_r.



(a)

(b)

Fig. 4. Examples of the navigated trajectories to each destination for two participants (a, b). Each trajectory displays data until t_e. In the time-series position results on the y-axis, the data at t_r are displayed using square, triangle, and circle plots.

UWB signals while waiting for the vibration cue at the destination row. Conversely, the results for t_r, which are not affected by this disruption, show that the Vib and Vib+Touch conditions enabled participants to reach the aisles faster compared to the Touch condition for farther destinations.

Fig. 5 shows the questionnaire scores. These results indicate that the Vib+Touch condition significantly improved scores in the “Intuitive” and “Efficient” categories ($p < 0.025$) and slightly improved the “Reliable” category when compared to the Vib condition. When comparing Vib+Touch to Touch, there were no significant differences in scores across all categories. However, the “Comfortable” and “Ef-

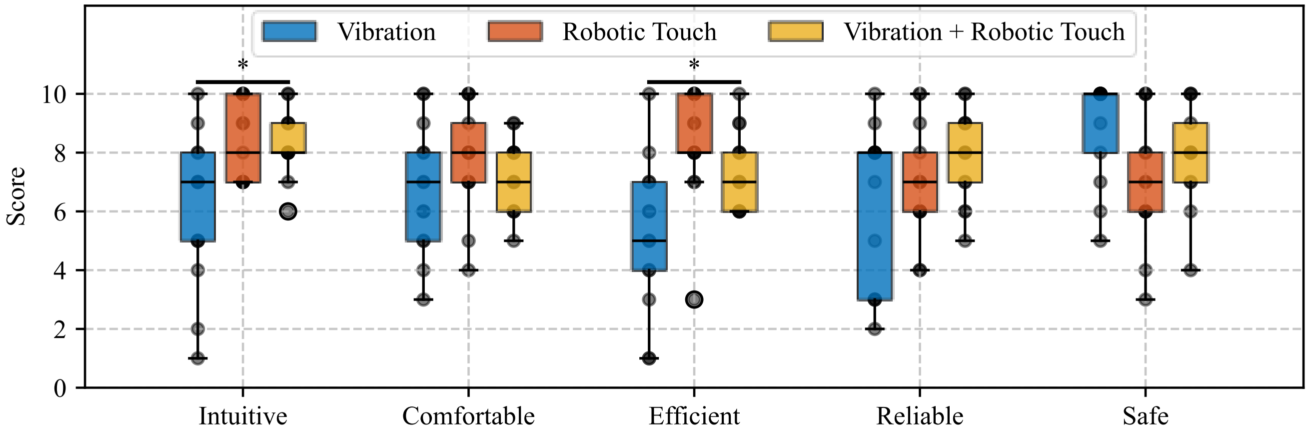


Fig. 5. Results of the questionnaire rating the three conditions on five items on a scale of 1 to 10 (10 was the best score).

ficient" scores were slightly lower, while the "Reliable" and "Safe" scores were slightly higher. The summarized findings from comments for the three conditions are as follows:

- Many participants felt that the Vib condition was cumbersome and required concentration due to the need to count the number of vibrations.
- The Touch condition was felt as intuitive and easy to understand by many participants, although some found it challenging to predict the exact timing of turns.
- Some participants felt that the Vib+Touch condition allowed for more accurate path comprehension, with vibration serving as preliminary notice and robotic touch providing directional guidance.
- Many participants perceived the directional guidance through robotic touch as clearer and more easily understood compared to vibration.

VI. DISCUSSION

The performance analysis reveals distinct advantages of the combined vibrotactile and robotic-touch (Vib+Touch) approach. Although Vib+Touch showed no significant improvement in t_r (time to reach destination aisles) compared to the Vib-only condition, it demonstrated a substantial enhancement in t_e (time to enter destination aisles from t_r), as shown in Fig. 4. This gain aligns with subjective evaluations (Fig. 5), where the integrated interface received significantly higher ratings for both "Intuitive" and "Efficient" categories. This enhancement addresses the fundamental limitation of vibration-only navigation: participants were uninformed about directional requirements until physically confronting a turn. While existing vibrotactile encoding schemes (e.g., single/double pulses for turns [14], [21]) offer directional cues, their use would conflict semantically with our intersection counting methodology, imposing additional cognitive overhead from processing multiple abstract encoding rules simultaneously. Further comparisons with existing vibrotactile navigation systems [23] are left for future work.

When comparing the Vib+Touch condition to touch-only navigation, the combined approach demonstrated significant advantages, particularly for longer distances. As shown in Figs. 4 and 5, participants achieved faster arrival times with Vib+Touch, with this performance advantage increasing as destinations became more distant. Subjective ratings also showed improvements in "Reliability" and "Safety." These results support the hypothesis that advance vibratory cues fundamentally change navigation behavior by informing users of upcoming turns, enabling them to move with greater confidence and speed.

Nevertheless, the integration of vibrotactile feedback introduces usability challenges that warrant consideration. Scores for the "Comfortable" and "Efficient" categories in the Vib+Touch condition were lower compared to the Touch condition, aligning with participant comments stating that "counting vibrations is cumbersome and requires concentration." Particularly, three or four vibrations may be redundant compared to everyday smartphone vibration patterns, and a high number of vibrations may increase cognitive load. Moreover, perception of vibration stimuli decreases during walking due to body movements [36]. One possible modification of the system would be to limit vibration counts to two or fewer and providing a combination of a single vibration and robotic touch when approaching the target corner. Additionally, since vibrations are similar to the haptic modality of commonly used smartphones, a different modality (*e.g.*, robotic touch) might be necessary to express which corner to turn at.

This study employed the Wizard of Oz method, where navigation cues were manually triggered by the experimenter. This approach constitutes a limitation regarding system autonomy, as the observed performance does not account for the real-time sensing delays or positioning errors inherent in a fully autonomous system. Consequently, accurate and robust real-time position measurement is essential for delivering stimuli at the appropriate moment in actual navigation.

VII. CONCLUSION

We have developed a novel haptic interface that combines vibrotactile and robotic-touch feedback to enable turn-by-turn navigation in indoor environments. This system allows users to receive advance notice of upcoming turns through vibrations, while robotic touch provides clear directional guidance at the appropriate turning locations. Future research will improve the system to enable a full autonomous navigation system that integrates real-time positioning technologies, such as inertial measurement units or beacons, to enable long-distance, turn-by-turn navigation with multiple direction changes in wide-ranging and complex areas with many intersecting corridors.

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