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KnuckleGuide: Mid-Air Haptic Guidance System Targeting Dorsal Hand Using Airborne Ultrasound

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***Abstract*—Ultrasound-based mid-air haptic guidance has gained significant attention as a contact-free solution for conveying direction information at a minimal distraction with high flexibility and robust environmental adaptability, particularly valuable when other modalities are limited or unavailable. Current research predominantly targets the palmar side of the hand, which becomes inaccessible for perceiving ultrasound-based haptic cues during critical interaction moments such as surface exploration or object gripping. This paper presents KnuckleGuide, a mid-air ultrasonic haptic navigation system focused at the dorsum hand while leaving the palmar side free for physical exploration. We propose two ultrasonic guidance strategies: a four-direction strategy (left, right, up, down) and an eight-direction strategy (including diagonals) and evaluate them through a user study with 16 participants performing surface navigation tasks. The effectiveness of the system was validated in three experiments, underscoring the feasibility of dorsum-targeted mid-air haptics for guiding surface exploration, offering new possibilities in assistive technologies and eye-free navigation.**

***Index Terms*—ultrasound; mid-air haptics; navigation assistance; haptic exploration**

I. Introduction

Haptic technology's ability to generate quick and subtle tactile sensations—haptic feedback—makes it a key building block for creating human-machine interfaces and assistive technologies for navigational tasks [2]. This technology could deliver directional cues that match natural movement direction; previous research has explored vibro- and electro-tactile stimulation that generates lateral sensations indicating left and right movements using hand and wrist-worn haptic devices [21] [28]. The subtle and tactile nature of haptic sensation minimizes cognitive load and attentional demands [1], allowing users to maintain focus on their primary tasks. This characteristic offers a unique advantage to haptic technology over visual or auditory technologies for navigation systems where such sensory channels are occupied for performing another task (*e.g.,* eyes-free dashboard control tasks during driving operations [3]) or not suitable (*e.g.,* a blind person guiding their hands on a tactile display).

Among haptic technologies, mid-air haptic devices offer unique advantages over wearable counterparts in designing human-machine interfaces. These devices could enhance user comfort and physically less restricted interactions by eliminating the need for physical devices worn on the body. Ultrasonic haptic transducers enable such mid-air haptic technology; the transducers generate focused ultrasound waves, create localized acoustic force in mid-air, and create tactile sensations on the skin when such acoustic force is targeted at human body parts. The acoustic force could be applied at high spatial resolution and controlled dynamically at a high refresh rate, allowing users to perceive subtle directional cues continuously.

However, the use of mid-air haptic devices for creating navigational technologies is limited despite the unique opportunities it brings. And importantly, the existing ultrasonic haptic systems for hand stimulus predominantly focus on stimulating the palmar side, requiring users to specifically orient their hands toward the device [24] [25] [26]. This orientation requirement creates significant functional limitations, especially during moments when the palmar side needs to be engaged with other tasks or in contact with objects. For instance, in cases such as visually impaired individuals reading Braille or drivers searching for specific control buttons on

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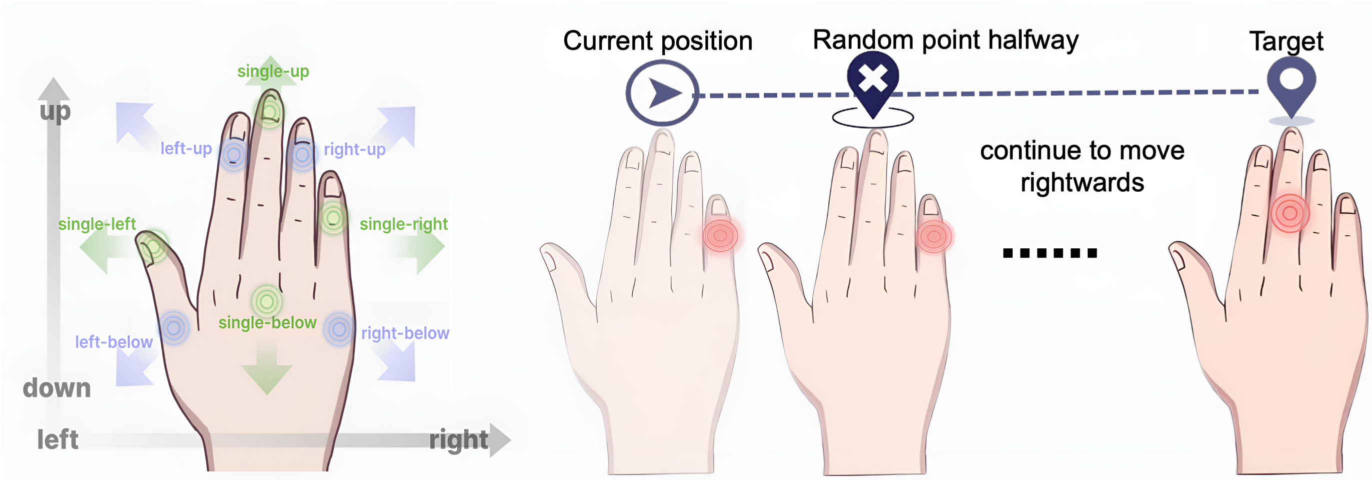


Fig. 1: Overview of KnuckleGuide: The system maps haptic feedback into directional cues with designed mapping strategies on the left, enabling users to navigate towards targets through ultrasound stimulus feedback of the dorsal hand.

a dashboard, users naturally orient their palms toward the surface, thereby interrupting the transmission and perception of ultrasonic haptic feedback. Meanwhile, though ultrasonic stimulation is perceived as less intense on the dorsal hand compared to the palm, the notable sensitivity of knuckles from the dorsal hand to ultrasound stimuli as identified in previous research [3] and in our pilot study, offers promising opportunities for dorsal hand-targeted haptic feedback applications.

We propose KnuckleGuide, a novel mid-air ultrasonic haptic navigation system that applies acoustic force to the back (dorsum) of the hand. The system maintains consistent haptic force on the dorsal skin while leaving the palm free for other physical exploration tasks. Using an ultrasound phased array, KnuckleGuide generates focused acoustic beams to create tactile stimuli at distinct positions on the dorsal hand, representing directional cues. Although named 'KnuckleGuide' to reference the dorsal hand region, our system strategically positions ultrasound emitters in the inter side adjacent to the knuckles to optimize signal transmission while maintaining proximity to the knuckle reference points that users intuitively understand. More specifically, the system can provide either four cardinal directions (left, right, up, and down) or eight directions (adding diagonal directions, left-up, left-down, right-up, and right-down), with the tactile stimuli corresponding to natural directional movements. The four-directions strategy aims to provide straightforward cardinal directions for unambiguous guidance, while the eight-directions strategy presents intermediate directions for more comprehensive and fine-grained spatial navigation.

To evaluate the effectiveness of both modes, we conducted a user study with 16 participants who completed three tasks that involved navigating their hands on a tactile display surface. The tasks ranged from static discerning tasks to dynamic target-reaching tasks of increasing complexity. The system achieved 96.7% accuracy with the four-directions strategy and 86.4% accuracy for eight-directions strategy in a static recognition condition and 93.5% accuracy with the four-directions strategy and 79.0% accuracy for eight-directions strategy in a hand moving condition. The ability of the system is further validated in Experiment 3 simulating real-world eyes-free map navigation in conveying directional cues and providing effective guidance. The results collectively showed the feasibility of navigating the user's hand by presenting tactile sensation on their dorsal hand skin. To summarize, our contributions in this paper are:

1. Proposed a novel mid-air tactile navigation assistance method utilizing ultrasound phased array targeted at the dorsal area of the hand. This approach addresses the limitations of traditional palm-side feedback and enables haptic guidance while hand exploring physical surfaces. For delivering directional instructions, we designed and implemented both four-directions strategy and eight-directions strategy.

2. Conducted a systematic user study investigating the performance of dorsal-area tactile feedback for directional guidance under different conditions, testing the viability of the proposed method for practical navigation applications.

II. Related Work

Recent haptic feedback research has explored navigation assistance through innovative approaches, focusing on (1) diverse body regions for tactile stimulation and (2)developing appropriate mapping strategies that translate spatial information into meaningful directional cues.

A. Body Parts of Haptic Feedback for Navigation

Navigation, as the process of determining and following a path from one location to another, encompasses a variety of scales and contexts, each requiring distinct sensory feedback and bodily engagement. Large-scale navigation scenarios, such as pedestrian wayfinding and vehicular navigation, inherently involve comprehensive bodily engagement in both locomotion and environmental perception. This has encouraged research into the implementation of directional haptic cues created by various types of stimulus across various body regions, namely the arms [6] [7], the back [9] and feet [8], the head [10] [11] and hands [12].

Meanwhile, localized-scale navigation tasks, such as exploring surfaces or reading Braille, often rely on hands for precise feedback. These tasks require detailed information effectively conveyed through hand-centered haptic feedback which can be applied across fingertips, wrist, dorsal hand and palm.

Fingertip-focused designs employ this region's high sensitivity to vibrations, electro-tactile stimulation, and forces besides the fact that fingertips serve as the most often used for grasping, manipulation, and probing the environment. Researchers have investigated directional haptic feedback through skin stretch, creating 3-DOF cues from tangential and normal skin deformation [17], and 4-DOF by combining tangential forces on thumb and index fingers [18]. Vibration feedback using ERM motors [19] and finger-mounted LRAs [20] has been implemented for directional guidance in basic reading tasks. Vo et al. explored fingertip-based localization using static focal points [13]. Despite their precision, finger-mounted devices impair dexterity, restrict natural movements, and become impractical when direct finger interaction is required.

The palm, with its glabrous skin, offers higher tactile sensitivity than hairy skin due to the distribution of distinct sensory endings [32] [33]. Though fingerpad innervation density exceeds the palm's [34], palm stimulation is preferred when fingerpad surface area is limited [35]. This has led to vibration-based designs conveying directional information [36] and extending spatial dimensions with dorsal vibrotactile stimulus [31]. Significantly, research demonstrates that ultrasound haptics are more effectively perceived at the palm's center than at fingertips with perception particularly enhanced when focal points remain stationary or move slowly rather than rapidly across the palm surface [37] [44], a property that has driven further exploration into utilizing ultrasound to create mid-air tactile sensations for navigation. Suzuki et al. used focused ultrasound waves to create mid-air tactile sensations, simulating a handrail to intuitively guide users along virtual paths [38] [23]. Similarly, Neate et al. developed dynamic ultrasound patterns with moving focal points and modulated intensity fields, enabling real-time tactile cues for spatial navigation and allowing users to trace targets in three-dimensional (3D) space [39]. In combination of visual modality, Freeman et al. implemented a cone-shaped haptic region towards the palm that dynamically changed in radius as users approached an optimal "sweet spot," reinforcing proximity and directions through both haptics and LED-based visual cues [14].While palm-based feedback systems are investigated towards many application scenarios, similar to finger-mounted systems, they similarly constrain practical applications by interfering with natural grasping and object manipulation, ultimately compromising hand dexterity.

The wrist offers promising advantages for directional haptic feedback, including natural rotational mapping, unimpeded hand functionality, and uniform tactile sensitivity. Raitor et al. developed a wearable system with thermoplastic pneumatic actuators achieving 99.4% accuracy in directional cue interpretation [27]. Researchers have also successfully implemented vibrotactile feedback through wrist-mounted motors for effective guidance in both two-dimensional [28] and three-dimensional contexts [29]. However, wrist-based systems face limitations from the relatively constrained surface area compared to the palm and lower tactile sensitivity, requiring stronger haptic signals that may cause fatigue during prolonged use.

Similarly, the dorsal areas of the hand are increasingly employed, ensuring that the palm and fingers remain unobstructed. This allows users to fully close their hands and grasp real objects without interference. Chase et al. introduced a skin-stretch method that employs a small, mobile tactor driven by miniature actuators. This system enables precise control of two-dimensional (2D) skin deformation, generating dynamic stretching sensations on the dorsal side of the hand [30] to facilitate four-directional navigations. Günther developed a vibrotactile glove designed for spatial navigation in three-dimensional (3D) space. This glove incorporates eight vibration actuators mounted on the dorsal area of the hand, which, through various layout configurations, provide directional cues for navigation across different axes [31]. Despite the prevalence of wearable haptic feedback systems, they present notable limitations including potential hygiene concerns in multi-user scenarios, and the need for users to consistently wear and manage additional devices, which may hinder spontaneous interactions. While mid-air haptic feedback could potentially address these limitations by providing contactless stimulation, this approach remains largely unexplored in the context of dorsal-hand based mid-air haptic feedback. Consequently, we initiate an investigation into an ultrasound-based mid-air haptic feedback system that targets the dorsal surface of the hand for directional guidance, aiming at advantages of contactless stimulation and enabling unimpeded object manipulation and gestural interactions during feedback delivery.

B. Designs for Mapping Haptic Feedback to Navigation Information

The strategies for encoding directional information through tactile feedback can be systematically classified into distinct categories: relative motion-based encoding, combinatorial patterns of fundamental tactile elements, and advanced spatiotemporal stimulation utilizing distributed arrays.

Relative motion-based tactile feedback has demonstrated efficacy in conveying directional information through the manipulation of stimulation positions/moving tendency in reference to a baseline position. Pittera et al. implemented this approach using focused ultrasound waves with the focal point moves smoothly but swiftly across the palm towards four directions [24]. Chase et al. developed a skin-stretch feedback system employing an actuator-driven tactor that generates directional cues through controlled moving trend from a reference position, successfully encoding four distinct directions through localized skin deformation patterns [30].

The mapping is also designed through establishing direct command correspondence between stimuli positions and intended directions of different complexity. Stearns mapped two positions to a one-dimensional direction by matching upper and lower vibration motor positions with corresponding up and below directional cues for finger alignment [20]. Raitor expanded this mapping concept by establishing a one-to-one correspondence between four distributed actuator positions in a wristband and four individual directions, where each flat pneumatic pouch position uniquely maps to a single directional cue [27]. Günther developed an even more sophisticated mapping system on the dorsum of the hand, proposing three mapping configurations: mapping four actuator positions at 90-degree intervals to cardinal directions, mapping six actuator positions to include diagonal directions, and ultimately mapping eight actuator positions at 45-degree intervals to achieve more granular directional mapping [31].

Another method builds upon the above strategy by defining several fundamental units of tactile stimulation and combining them to imply more complex directional cues. For instance, Jiang et al. extended this approach by designing a system where ten electrodes were mounted on the fingertips to achieve directional mapping across eight directions [22]. Unlike directly adjusting stimulus positions, this method relied on specific pairing configurations of electrodes to represent each direction, guided by participants' reported perception quality. Additionally, an interval time was introduced between consecutive stimulations to prevent masking effects, ensuring the clarity and accuracy of the perceived directional cues.

Building on previous directional guidance methods, Mulot et al. proposed and compared four mapping strategies combining direction and distance cues. Direction was encoded via spatially offset haptic circles (at target or palm border along the direction) or palm-relative directional lines, while distance was conveyed by dynamically adjusting circle radii or line lengths proportional to hand-target distance [15]. In the context of ultrasonic mid-air haptic feedback for the dorsal hand, different mapping strategies present varying challenges. Relative motion-based tactile feedback, while effective on continuous surfaces, faces limitations when applied to the knuckles as the gaps between fingers interrupt the continuous motion path, potentially compromising the clarity of directional cues. The approach of combining fundamental tactile units requires generating multiple focal points simultaneously, which demands significantly higher power in ultrasonic systems. In contrast, direct spatial mapping between stimuli positions and intended directions offers a straightforward and efficient solution, particularly suitable for the dorsal hand structure, as it can effectively convey directional information through discrete stimulation points while maintaining power efficiency.

III. System Setup

The KnuckleGuide system employs focused ultrasound beams to generate mid-air haptic feedback at strategically defined positions on the dorsal hand surface, creating a novel directional guidance mechanism. By implementing two mapping strategies with varying levels of complexity—a simplified approach and a comprehensive mapping—the research explores how different spatial configurations influence user perception and navigation. The system meticulously maps specific hand locations to represent distinct directional cues, allowing precise tactile guidance during surface exploration. Through careful design of ultrasound emitter positioning and feedback intensity, KnuckleGuide aims to develop an intuitive haptic interface that can effectively communicate directional information to users through dorsal hand-focused sensory stimulation. In this section, system setup and mapping strategies will be elaborated.

A. System Setup

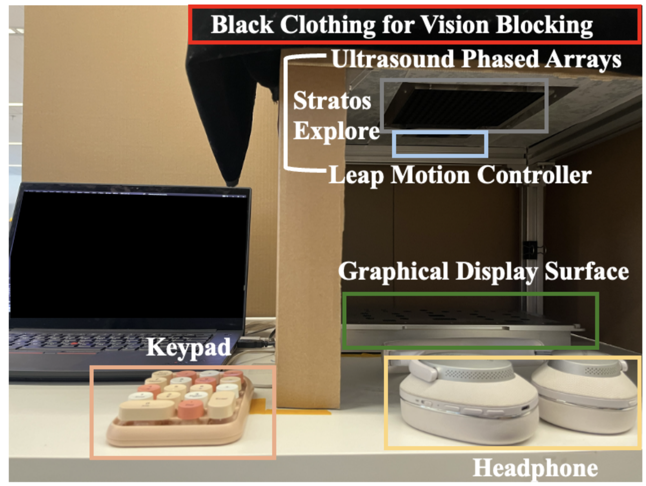


Fig. 2: Experimental setup of KnuckleGUide: Ultrasound Phased Array in the grey box emit focused ultrasound beams at predefined positions captured real-time by Leap Motion Controller in the blue box. Users explore targets on the Graphical Display Surface in the green box and input commands with the keypad in the orange box. The black clothing in the red box blocks user's vision during experiments. Users wear the headphone in the yellow box playing white noise.

The KnuckleGuide system consists of (i) a Stratos Explore (Ultrahaptics, now Ultraleap) platform for generating mid-air haptic sensation, (ii) Leap Motion Controller from Ultraleap (formerly Ultrahaptics), which utilizes infrared optical technology to detect precise hand and finger positions, and (iii) a stand that holds Stratos Explore and Leap Motion Controller (Fig. 2). The Stratos Explore device is mounted on an aluminum frame using an acrylic plate in an inverted configuration including ultrasound phased arrays and the Leap Motion Controller. The device is positioned 25cm above the graphical tactile display surface of which the positioning was carefully calibrated to ensure optimal hand tracking reliability and consistent haptic feedback transmission. The entire setup is enclosed within a custom-designed cover constructed from cardboard and black fabric. This enclosure serves the dual purpose of ensuring robust hand tracking performance and creating a controlled environment for subsequent non-visual experimental trials.

The Stratos Explore platform generates ultrasound mid-air haptic sensation with arrays of ultrasonic transducers that emit precisely phase-shifted acoustic waves. The device consists of a 16cm × 16cm square array with 256 ultrasound transducers at a 40 kHz operating frequency. The acoustic waves are controlled to constructively interfere at focal points in space. When these focal points interact with the skin, they generate acoustic radiation pressure that produces localized tactile sensations, which users typically describe as feeling similar to gentle air pressure, breeze, or wind [40] [41]. Through dynamic phase modulation of the transducer array, these focal points can be rapidly repositioned with high spatial precision in the interaction volume above the device, enabling precise control over the haptic feedback location. In the study, the modulation is designed to generate focal point of 1 cm diameter circular patterns.

The Leap Motion Controller is placed next to the Stratos Explore platform for hand and finger tracking. The controller utilizes infrared optical technology to detect precise hand and finger positions, poses and movements with a low latency of 10-20 milliseconds, facilitating responsive real-time data collection. During operation, the system processes spatial data from the hand-tracking module while simultaneously calculating phase delays for the ultrasonic transducer array. This enables dynamic positioning of the focal point at designated locations on the user's hand. The focal point updates at 40 kHz, enabling seamless haptic feedback that provides fluid navigational assistance to users exploring surfaces.

Establishing on the device configurations, we employ the spatiotemporal modulation method with the point density is consistently set to maximum to ensure optimal tactile sensation. Each emission manifests as a small circular modulation pattern with a diameter of 1 cm, providing a well-defined focal point of stimulation at the designated locations.

For the experiment, we placed a tactile display—originally designed for visually impaired users—below the Stratos Explore and Leap Motion Controller. The display consists of a 120 × 60 matrix of dynamically controllable dots that can be elevated or lowered through precise electronic actuation. An embedded computing system processes visual information and converts it into tactile patterns by selectively raising specific dots, enabling users to perceive tactile representations of images through touch exploration. In this experiment, we used the display surface to present static tactile contents for the experiments without providing dynamic guidance information.

B. Mapping Strategy

To design an effective and optimized mapping strategy, we conducted a pilot study to investigate stimuli-sensitive regions on the dorsal hand. The study revealed that metacarpophalangeal (MCP) joints and proximal phalanges and especially spacing between the joints exhibit pronounced sensitivity, whereas direct stimulation on the dorsal finger surfaces is considerably more difficult to perceive and a continuous motion across fingers could lead to ambiguous directional perceptions. The stimuli-sensitive regions align with previous researcher by Montano et al. [3] , who demonstrated both the knuckle joints (metacarpophalangeal joints) and the finger segments

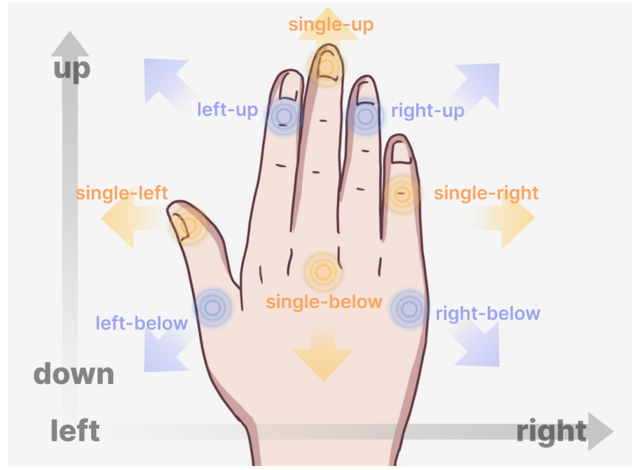


Fig. 3: Illustration of Mapping Knuckles to Directions. The four cardinal direction approach used left, right, up, and down to present directional cue to user's hand. The eight cardinal direction approach added diagonal directions, left-up, left-down, right-up, and right-down to the four cardinal direction approach.

closest to the palm (proximal phalanges) showed heightened sensitivity to stimuli [3].

Based on the insights, we proposed two distinct spatial mapping strategies for ultrasonic haptic navigation shown in Fig.3. We tried to assign each direction to a discrete single location on the hand, ensuring clearer and more precise directional feedback. The first strategy implemented a four-cardinal-direction system (left, right, up and below in yellow arrows) with intuitive simplicity and reduced cognitive demand. The second strategy expanded to an eight-direction paradigm incorporating diagonal vectors in blue arrows provided with enhanced spatial granularity at the cost of increased complexity. The two mapping strategies were motivated to evaluate the trade-off between system complexity and user performance, and to assess the cognitive load associated with different spatial mapping configurations.

IV. User Experience Survey and Analysis

We designed three experimental tasks with progressively increasing complexity to evaluate the feasibility and performance of guiding a user's hand on a flat surface using KnuckleGuide. The flow of the user study is shown in Fig.4.

- **Directional Perception with Static Hand.** Participants placed their hands on the display surface without movement during this task. We applied tactile sensations using four-cardinal and eight-cardinal direction approaches and asked participants to indicate the perceived direction of the applied force.
- **Directional Perception with Hand Movement.** We asked participants to move their hands to acquire targets (extruded pins on the tactile display) placed in the direction indicated by the system. As participants moved their hands, the system continuously applied force in the

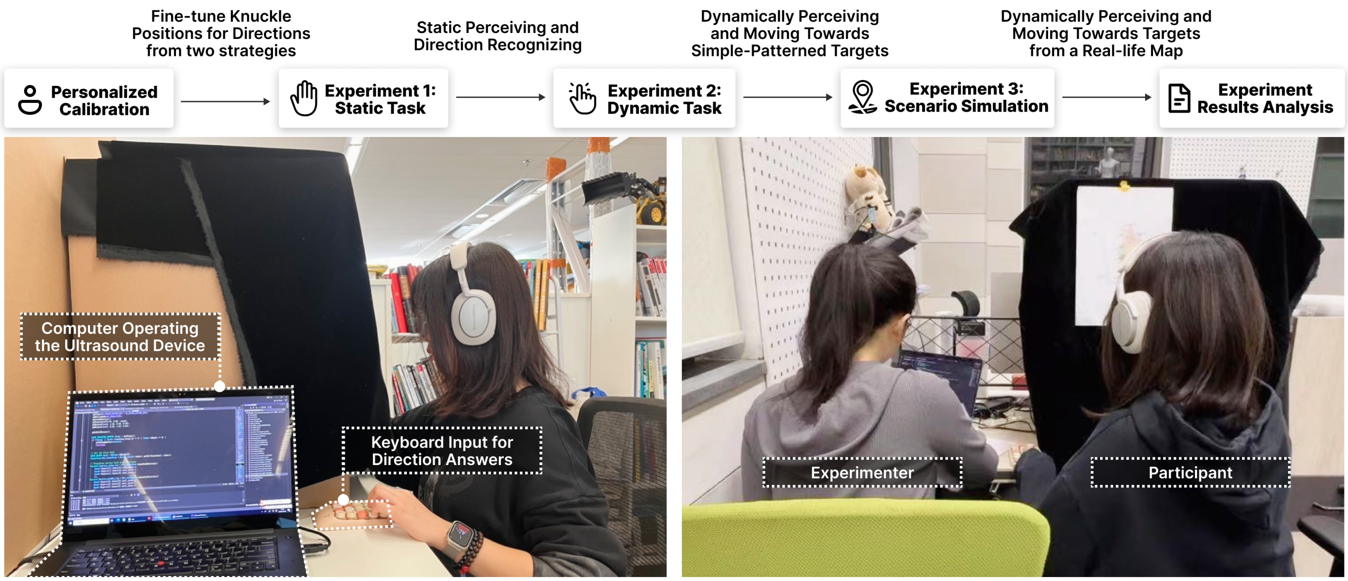


Fig. 4: Flow of evaluation user study.

target direction, and participants followed this signal to reach the target.

- **Target Acquisition on a Map.** This task simulated a real-world scenario where users navigate their hands on a map eyes-free. We designed this task to assess the system's usability in a more complex, realistic situation.

We recruited eighteen participants for the study. All of them performed the three experimental tasks. However, two participants among them could not focus on the experiment while performing the third tasks and yielded data that noticeably deviated from the data that we obtained from other participants. We decided to exclude the data from them. Therefore, the final user performance was evaluated with responses from 16 participants (5 males and 11 females, within the age range between 21 and 34). All participants gave written consent for their participation. Participants were recruited from social media and did not require previous experience with mid-air haptics and overall haptic navigation technology. During the whole experiment procedure, participants wore headphones playing white noise to mask ambient sounds with the noise-cancelling function turned off. Additionally, devices including Stratos Explore and the graphical display surface were visually blocked, ensuring that the participants solely relied on the haptic stimuli rather than visual or auditory information when discerning directional cues.

A. Personalized Calibration

Despite that we have designed the mapping strategy of directional information to specific knuckle locations based on the pilot study, inherent anatomical variations among participants, including differences in knuckle morphology and skin thickness, can introduce subtle misalignment between predefined ultrasound focal points and optimal perceptual regions. These variations potentially compromise the final resolution and perception of haptic feedback. To mitigate this challenge, we implemented a personalized calibration prior to the formal experiment, allowing each participant to fine-tune the specific feedback positions. For each direction, we initialized the ultrasound focal point at the corresponding joint position as illustrated in Fig.2. Participants adjusted the focal point position along both vertical and horizontal axes while receiving real-time haptic feedback for comparisons. Calibration was conducted comprehensively across all intended feedback directions. This individualized adjustment process ensures that the haptic stimulation is optimized for maximum perceptual distinctiveness and tactile sensitivity across different hand anatomies, thereby enhancing the reliability and accuracy of our directional guidance system.

B. Experiment 1: Directional Perception with Static Hand

1) Experiment Procedure: We instructed each participant to place their right hand relaxed, resting statically at the center of the tactile display. We asked them to keep the fingers neither deliberately extended nor constricted and make sure that the dorsal surface faced towards the ultrasonic phased array transducer. For each strategy (four and eight cardinal directions), 48 ultrasound stimuli were randomly emitted towards predefined directional positions, with an equal number of emissions for each direction. Specifically, in the four-direction strategy, KnuckleGuide delivered 12 emissions to each of the four cardinal directions (up, down, left, and right). In the 8-direction strategy, six emissions were delivered for each direction. Participants used a keypad to input their perceived direction of each stimulus, which we recorded for analysis.

2) Result Analysis: The performance of Experiment 1 is evaluated and visualized in Fig. 5 and Fig. 6 for the four-direction and eight-direction strategies respectively, including

(a) a bar plot of accuracy across directions and (b) the overall confusion matrix.

The four-direction strategy demonstrated exceptional reliability, with consistently high mean accuracies across all directions: up (97.9%, 95% CI [95.3%, 100%]), right (99.0%, 95% CI [97.4%, 100%]), below (92.7%, 95% CI [88.0%, 96.9%]), and left (97.9%, 95% CI [94.3%, 100%]). This robust performance is further validated by confusion matrix analysis revealing minimal misclassifications, with off-diagonal cells accounting for only 3.12% of responses. These results establish a strong baseline for ultrasound-based tactile directional discrimination in stationary conditions.

When increasing the directions to eight_direction strategy, performance remained viable but with expected decreases in accuracy. Direction accuracies ranged from 74.0% for left-below (95% CI [60.4%, 85.4%]) to 94.8% for right (95% CI [87.5%, 100%]). A clear pattern emerged where right-side directions (right: 94.8%, right-below: 93.8%, right-up: 87.5%) consistently have higher accuracies over left-side directions (left: 84.4%, left-below: 74.0%, left-up: 87.5%) and vertical directions (up: 81.2%, below: 76.0%). This hemispheric advantage suggests potential perceptual asymmetry that should inform design considerations.

To understand the perceptual challenges of the eight-direction system, we analyzed adjacent direction confusion patterns—cases where participants mistook a direction for one of its neighboring positions. Of the 116 total errors, 44 (37.9%) were classified as adjacent direction confusions. The highest adjacent confusion rates occurred for left-below (76%), right-below (66.7%), and right (60%) directions, while left-up, right-up, and left directions showed substantially lower adjacent confusion rates (25%, 25%, and 20% respectively). The below direction showed moderate adjacent confusion (39.1%) across 23 total errors.

Four-direction strategy demonstrated robust performance, proving participants can identify directional instructions from ultrasound stimuli focused at corresponding pre-defined positions in a stationary state with high accuracies across all directions. Despite its increased complexity, eight-direction strategy maintains acceptable performance levels that exceed chance expectations. Notably, the right-sided directions consistently outperformed other positions, with right-below significantly more accurately identified than below (adjusted p = 0.0192). These findings demonstrate that directional guidance can be perceived in a static status at multiple levels of direction complexity. The four-direction system offers exceptional reliability for applications prioritizing accuracy, while the eight-direction system provides viable performance for scenarios requiring finer directional resolution.

C. Experiment 2: directional perception with hand movement

1) Experiment Procedure: In Experiment 2, we extended our investigation of the dorsal hand's perception of ultrasound stimuli as directional cues during active movements. The experimental setup utilized the graphical display surface configured with constant eight raised dots arranged on a 12 cm radius circular configuration in Fig.7. Each dot circle measured 2.5 cm in diameter and comprised five adjacent pins, strategically placed to align with directions from eight-directions strategy and did not provide guidance cues during the experiment.

At the trial's onset, participants positioned their hand at the graphical display surface center. Upon stimulus presentation, participants were instructed to move their hand in the perceived direction, terminating the movement by stopping at the corresponding dot using their middle fingertip. Stimulus

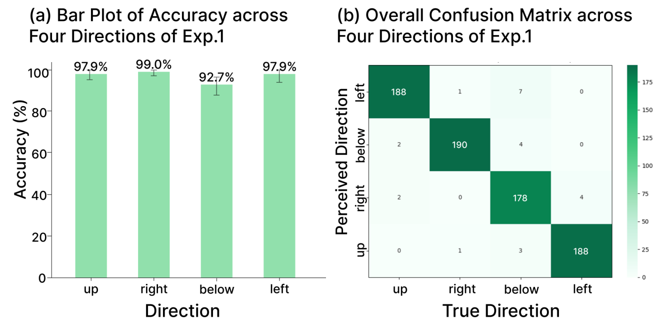


Fig. 5: Performance evaluation of applying four-direction strategy in experiment 1:(a)Bar plot of accuracies across directions with error bars representing 95% confidence intervals; (b) Confusion matrix of perceived directions relative to the true directions aggregated across all participants.

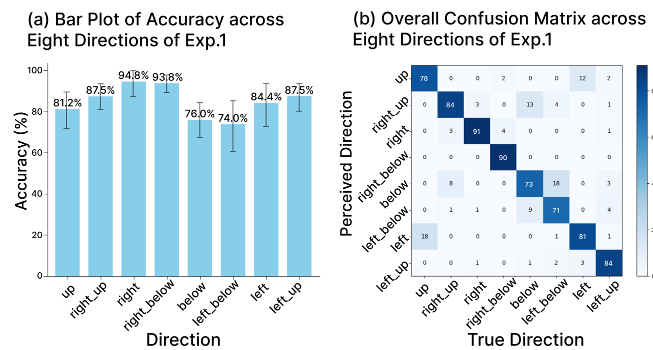


Fig. 6: Performance evaluation of applying eight-direction strategy in experiment 1: (a) Accuracy for each direction with with 95% CI; (b) Confusion matrix of perceived vs. true directions.

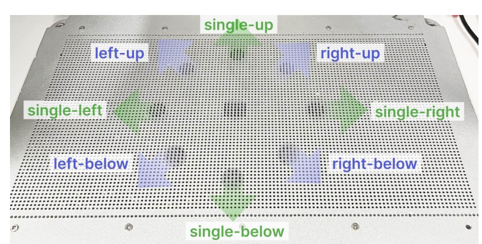


Fig. 7: Target setting on the graphical display surface in experiment 2

presentation was controlled, with 48 ultrasound cues per strategy distributed equally across directions and randomized to minimize systematic bias. The experimental design deliberately diverged from Experiment 1 by introducing movement as a critical variable, enabling a more comprehensive exploration of directional cue perception. Participants would record their finger position via keypad after each movement and return to the center, preparing for the subsequent trial.

2) Result Analysis: Experiment 2 also demonstrated high overall accuracies for the four-direction strategy (Fig.8(a)). Mean accuracies were 95.8% [95% CI: 91.1%, 99.0%] for the up direction, 95.3% [95% CI: 89.6%, 99.0%] for the right direction, 97.4% [95% CI: 94.8%, 99.5%] for the left direction, and 85.4% [95% CI: 76.6%, 92.2%] for the below direction. The below direction exhibited both the lowest accuracy and the largest variance, as indicated by its wider confidence interval, suggesting less consistent performance among participants. In contrast, the left direction achieved the highest accuracy with the smallest variance, indicating more uniform performance across participants.

A closer examination of error patterns in the confusion matrix (Fig.8(b)) indicated a directional asymmetry: below cues were frequently misidentified as left cues (21 of 192 trials), while up cues were rarely mistaken for below cues (3 instances). Despite no statistically significant differences emerging from pairwise comparisons using Bonferroni-corrected t-tests, this directional confusion suggests improvements to the mapping for the below direction to enhance the robustness of the four-direction strategy. The average accuracy for the four-direction strategy decreased slightly from 96.9% in static recognition condition to 93.5% here, indicating a modest overall decline in recognition performance when users need to recognize directions in a dynamic condition.

For the eight-direction recognition strategy, the overall accuracy rates demonstrate promising feasibility with a mean accuracy of 79.7% across all directions. The data reveal accuracy rates ranging from 60.4% to 90.6%, with six directions exceeding 74% accuracy. Specifically, the up and right_up directions achieved the highest accuracy at 90.6% (95% CI [83.1%, 95%]), followed by left at 86.5% (95% CI [78.2%, 91.9%]), below at 84.4% (95% CI [75.8%, 90.3%]), and left_up at 83.3% (95% CI [74.6%, 89.5%]).

The 95% confidence interval analysis reveals substantial heterogeneity in users' recognizing directions from haptic stimulus across the eight directional categories. High-performing directions such as up and right_up demonstrate robust recognition with lower confidence bounds of 83.1%, indicating reliability even under conservative estimates. In contrast, the horizontal right direction's performance was significantly lower at 60.4% (95% CI [50.4%, 69.6%]), with an upper confidence bound that falls below the lower confidence bounds of most other directions. This statistical evidence reinforces the substantial performance disparities across different directional categories.

Analysis of the error patterns revealed that adjacent direction confusion emerged as a significant challenge in the eight-

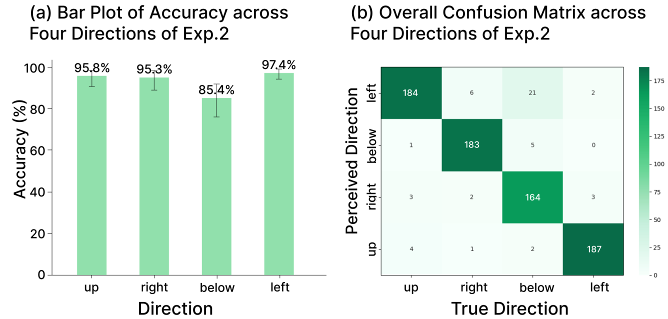


Fig. 8: Performance evaluation of applying four-direction strategy in experiment 2: (a) Accuracy for each direction with with 95% CI; (b) Confusion matrix of perceived vs. true directions.

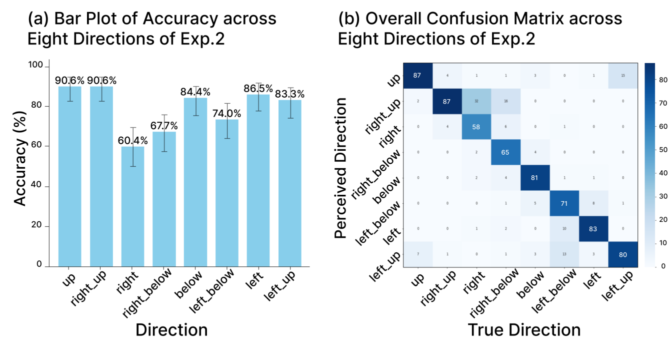


Fig. 9: Performance evaluation of applying eight-direction strategy in experiment 2: (a) Accuracy for each direction with with 95% CI; (b) Confusion matrix of perceived vs. true directions.

direction tactile feedback strategy. Among all recorded errors across directions (156 total errors), approximately 69% (107 errors) were specifically attributed to confusion with adjacent directions. The adjacent confusion rates were particularly high for certain directions: up (100%), left-up (93.75%), right (89.47%), right-up (88.89%), and left (84.62%). The lower quadrant directions (below, left-below, and right-below) exhibited more diversified error patterns with substantially lower adjacent confusion rates (60%, 44%, and 32.26% respectively).

Overall, both the four-direction and eight-direction strategies demonstrate reduced accuracies in discerning directions compared to Experiment 1, yet they continue to show strong potential for conveying directional cues in a moving task.

D. Experiment 3: Target Acquisition on a Map

1) Experiment Procedure: In Experiment 3, we aimed to assess the practicality of using ultrasound-based haptic feedback guiding in a realistic "target-approach" task on a map. We chose the Forbidden City as our layout, since its symmetrical arrangement along a central axis and diverse building clusters provided a structured yet varied visual map seen in Fig.10(1). Fig.10(2) displays that six clusters are formed by grouping dots based on their spatial proximity and

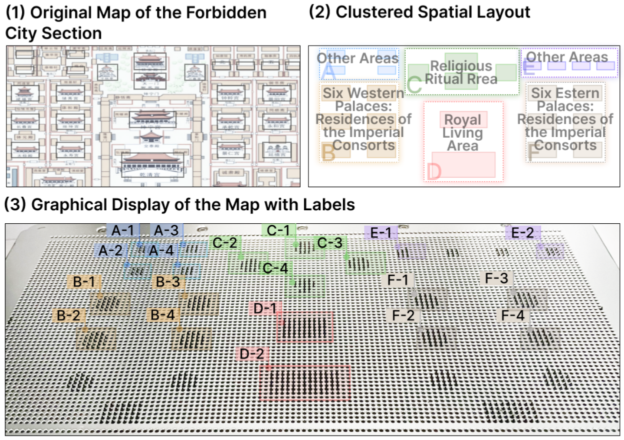


Fig. 10: Design and display the map of Forbidden City for experiment 3. (a) Original map of the Forbidden City section. (b) Clustered layout of the map, partitioned into six distinct architectural clusters (color-coded by structural features). (c) Interactive graphical display of the map, integrating cluster visualization and annotated labels.

architectural structures, reflecting the natural arrangement of the original building groups. Fig.10(3) shows the graphical display surface which aims to reproduce the structural distribution of the architectural groups with 26 points—each representing a building cluster of differing sizes and 20 of these selected and sequenced randomly as target locations.

At the start of each trial, participants placed their right hand freely over the graphical display surface. Leap Motion Controller tracked the direction vector from the participant's middle fingertip to the active target in real time, and ultrasound stimuli guided the user toward that point. When participants perceived the ultrasound focal point to be centered on the second knuckle of the middle finger, indicating reaching the target, they pressed a key to advance to the next trial.

Similarly, we tested two strategies for navigating this map. Under the four-direction strategy, participants first adjusted their horizontal position (left/right) and then made vertical movements (up/below). With the eight-direction strategy, participants could move in two dimensions simultaneously.

2) Result Analysis: Fig.11 presents the success rates achieved at each point with results from Four-direction strategy shown in green bars while results from Eight-direction strategy shown in blue bars. For four-direction strategy, with an average of 51.8% in the success rate, the results range from 31.2% (A_2) to 93.8% (C_4). Meanwhile for results from eight-direction strategy, the results vary from 18.8% (B_2) to 68.8% (C_1) with an average success rate of 48.4% (SD = 13.4%). The data suggests that mid-range points tended to yield higher success rates. By contrast, points located farther to the both sides (e.g., B_2 and E_4) showed comparatively lower success rates, potentially reflecting users' difficulty in perceiving directional cues for peripheral areas with the given ultrasound feedback.

To analyze the spatial accuracy of target point navigation, we examined the distribution of normalized errors between perceived fingertip positions and actual target coordinates. The errors were normalized relative to the display surface dimensions to ensure standardized measurements. For each group, we constructed distribution plots centered at the respective group positions means, analyzing both vertical and horizontal error components separately. This analysis was performed independently for the four-direction strategy (Fig. 12) and eight-direction strategy (Fig.13), enabling comparison of targeting accuracies across different directional strategies.

In examining the horizontal error distributions of four-direction strategy (Fig.12a (a), Group A, B, C, and D, whose target points lie primarily in the left and middle regions of the graphical display surface, exhibit distributions with relatively small error ratios and narrow spreads. Distributions for these four groups are mostly separated which indicate successfully reaching the groups. In contrast, Group E and F show broader distributions. Notably, when navigating to target points in Group E (located on the right side of the surface), participants exhibited failure trials that deviated towards the middle region. For Group F's target points, these trial errors extended even further, reaching into the left region of the graphical display surface. From the accompanying bar plot, Group A and B—both located on the left side—show comparatively low success rates. This performance suggests that a substantial portion of their failures might be due to confusion within the group or confusion between the groups with larger vertical-axis errors. Turning to vertical error distributions under the four-direction strategy seen in Fig.12b(b), a similar pattern across all groups emerges. Although each group's target locations differ vertically, the observed error distributions exhibit considerable overlap among multiple groups. This overlap implies that participants may have encountered difficulty in perceiving up/down cues, causing what should be distinctly separated vertical error ranges to blend together.

For horizontal error distributions of eight-direction strategy visualized in Fig.13(a), certain groups that previously had broader error distributions—particularly Group C, D, E, and F—show a marked tightening of their distributions and a shift toward smaller error ranges. This improvement suggests that participants found it easier to orient themselves along diagonal or off-axis horizontal directions. By contrast, the distributions for Group A and B under the eight-direction strategy remain relatively broad and exhibit lower density, pointing to a weaker performance when trying to align horizontally in the leftmost regions of the display surface with eight-direction strategy. In respect to vertical-axis errors in Fig.13(b), the performance under four-direction and eight-direction strategies is broadly similar. In some groups, the four-direction strategy even yields a slightly higher peak density and narrower spread, suggesting that both strategies are comparably effective at guiding vertical alignment on the graphical display surface.

V. Discussion

Overall, our study proposes a novel system for conveying directional information on the dorsal hand which is a rarely

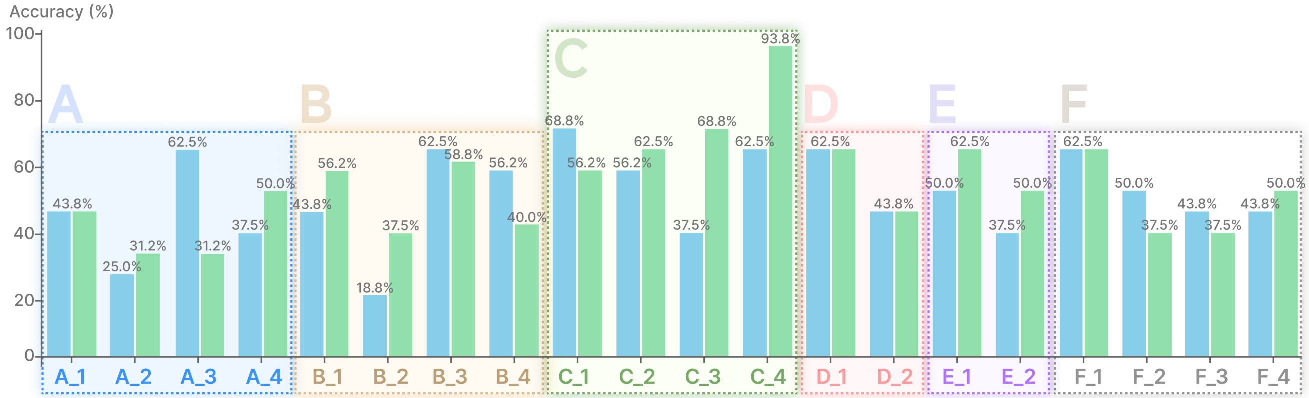
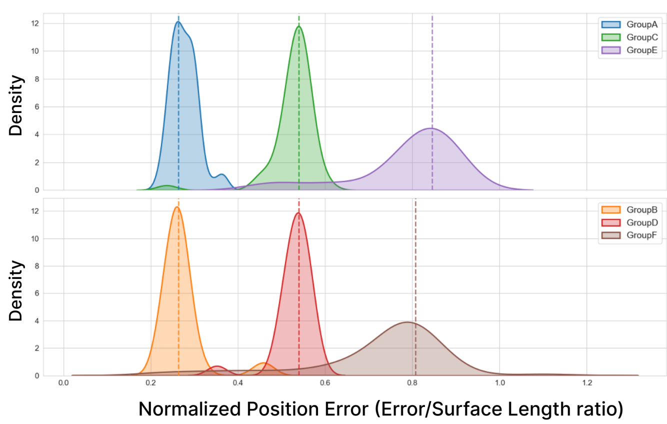
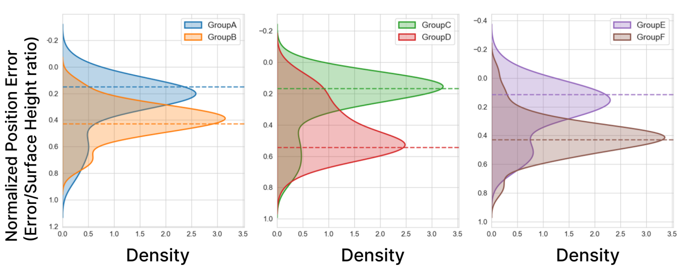


Fig. 11: Accuracy bar plot of users achieving target points using both strategies (four-direction strategy shown in green and eight-direction strategy in blue)

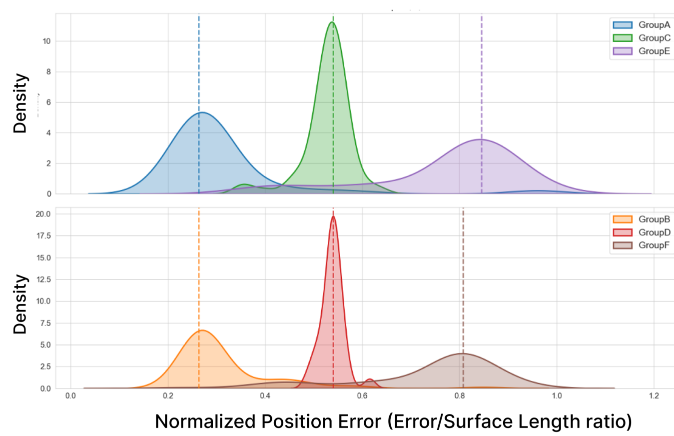


(a) Distribution of middle fingertip coordinates along the horizontal axis applying four-direction strategy in experiment 3

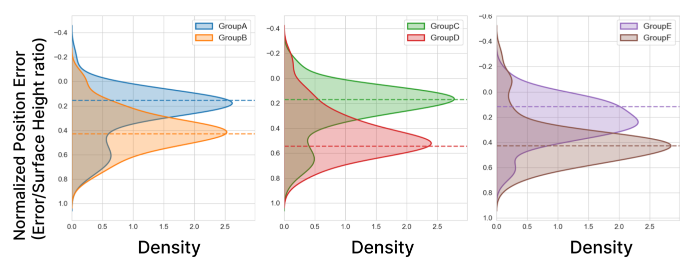


(b) Distribution of middle fingertip coordinates along the vertical axis applying four-direction strategy in experiment 3

Fig. 12: Overall distribution of middle fingertip coordinates in experiment 3: (a) horizontal axis; (b) vertical axis



(a) Distribution of middle fingertip coordinates along the horizontal axis applying eight-direction strategy in experiment 3



(b) Distribution of middle fingertip coordinates along the vertical axis applying eight-direction strategy in experiment 3

Fig. 13: Overall distribution of middle fingertip coordinates in experiment 3: (a) horizontal axis; (b) vertical axis

investigated area for haptic feedback created with ultrasound. First, we showed that mid-air haptic feedback can be clearly felt on the dorsal hand, especially space between knuckles, at natural pose while the palmar side is occupied in other tasks. We conducted three experiments to evaluate the performance of the proposed system in various conditions and scenarios. Across all three experiments, our findings highlight both the promise and the challenges of using ultrasound-based cues for directional guidance.

In Experiment 1, the four-direction strategy demonstrated generally high accuracy. Although the "below" direction exhibited a lower accuracy, pairwise z-tests confirmed that its performance was not significantly different from the other three directions. In the eight-direction strategy with more directional cues, while results of most directions are still positive, there were mutually misperceived directional cues—such as "below" and "right_up", "left" and "up", "below" and "left_below". These errors may arise partly from the limited resolution in discerning haptic stimulation across the limited dorsal hand area which leads to inappropriate mapping positions on knuckles. While Montano et al. have noted the importance of maintaining a separation of at least 2 cm between stimuli to prevent them from merging into a single percept [3], controlling for this distance alone for a complicated pattern including 8 stimulus positions may be insufficient when using ultrasound-based haptic feedback. Ultrasound sensations often feel like gentle air pressure or a breeze-like stimulus rather than distinct point contacts [40] [41]. With a 1 cm diameter circular modulation pattern in our study, this challenge is further compounded to the area constraints of the dorsal hand regions. Consequently, certain directions may require more targeted investigation and introduce more parameters to design more diversified stimuli. Additionally, some participants did not thoroughly compare simulation positions both horizontally and vertically during the fine-tuning process to adjust focal positions, leading to suboptimal positioning of stimulation loci and underscoring the importance of systematic calibrations.

Adjacent direction confusion emerged as a more significant challenge in the eight-direction tactile feedback strategy in Experiment 2 as 69% of errors were specifically attributed to confusion with adjacent directions. Besides the factors discussed above, body movement appears to adversely affect directional perception of ultrasound stimulating knuckles in our study. This is evidenced by the notable decrease in accuracy observed in Experiment 2 compared to the static conditions of Experiment 1, as perception pathway in moving conditions differs from pure cutaneous perception in static conditions. Moreover, some others state that when moving continuously and rapidly to perceive ultrasound stimulation under the eight-direction strategy, they feel that the haptic sensations are similar to wind blowing across the hand which perceived as connecting mapping knuckles and lead to confusing perceptions and need to pause for a static and stable perception.

Furthermore, feedback from user surveys reveal that hand conditions significantly influence the perception of ultrasound stimuli. We observed that participants exhibited enhanced tactile sensitivity when their hands were in a relaxed state compared to rigid status, suggesting that muscle tension may interfere with mechanoreceptor sensitivity. Furthermore, maintaining the hand in a natural posture without excessive finger extension appeared to optimize the recognition of ultrasound stimuli, even across all eight directional cues. Another situation emerged regarding hand orientation: participants reported perceiving stimulation from not-defined positions when the hand is moving under certain poses. We attribute the situation to the limitations of noncontact haptic stimulations from a single device. When participants tilted their hands, finger overlap from the perspective of the ultrasound phased arrays potentially disrupted the precise focusing of the focal point. This spatial misalignment could lead to decreased stimulus intensity or imprecise targeting of the intended stimulation points. A more overall layout of ultrasound phased array covering the whole hand of various poses should be constructed for further improvement and real applications. Additionally, our winter-season experiments unveiled an important environmental factor affecting tactile perception. Participants who began the experiments with cold hands initially reported diminished or absent perception of the ultrasound stimuli, highlighting the significance of maintaining adequate hand temperature for optimal tactile sensitivity. This temperature-dependent variation in perception suggests that future experimental protocols should incorporate a hand-warming period before commencing trials to ensure consistent conditions across participants.

In Experiment 3, we assessed the applicability of these directional cues in a map-like "target approach" task. With an average success rate of roughly 51.8% for four-direction strategy and 48.4% for eight-direction strategy among the 20 tested points, participants reliably used the ultrasound feedback to navigate in two dimensions. Further analyses revealed certain spatial biases: points located centrally ("middle" side) and "below"tended to yield higher success rates, whereas targets on the left side and in "upper" regions were more prone to misinterpretation. According to user feedback, weaker haptic sensations occurred near the surface marginal areas compared to the center, potentially contributing to these discrepancies across groups. Additionally, error distributions indicated that the vertical axis tended to exhibit broader and less concentrated inaccuracies than the horizontal axis. One underlying factor may be the dense placement of multiple relevant stimuli (e.g., "up," "below," and success confirmation cues) on the middle finger, which could introduce perceptual interference and increase misinterpretations for closely spaced targets.

Overall, the three experiments suggest that while the proposed ultrasound-based direction cues can effectively guide finger movements, specific directions need stronger or more distinctive tactile feedback. Additionally, the lower accuracy in some configurations highlights the importance of improved training protocols, user adaptation, and potentially personalized mapping to accommodate individual differences in hand orientation or spatial perception. Future work will investigate more refined cue designs (e.g., varying amplitude or focal sizes), explore adaptive algorithms that adjust cue intensity based on user performance, and incorporate other modules for more applications and example scenarios could be seen in Fig14.

One limitation of the current user study is the absence of interaction time analysis. While we focused on the success rate of understanding haptic directions, we did not measure and analyze how interaction time might affect task accuracy. Future research will be done to investigate the potential trade-off between accuracy and time and provide a more comprehensive evaluation of the system's efficacy in real-world applications and help establish optimal thresholds for both accuracy and speed in various implementation contexts.

Second, we plan to investigate more refined cue designs that go beyond the current uniform stimulation by Stratos Ex-

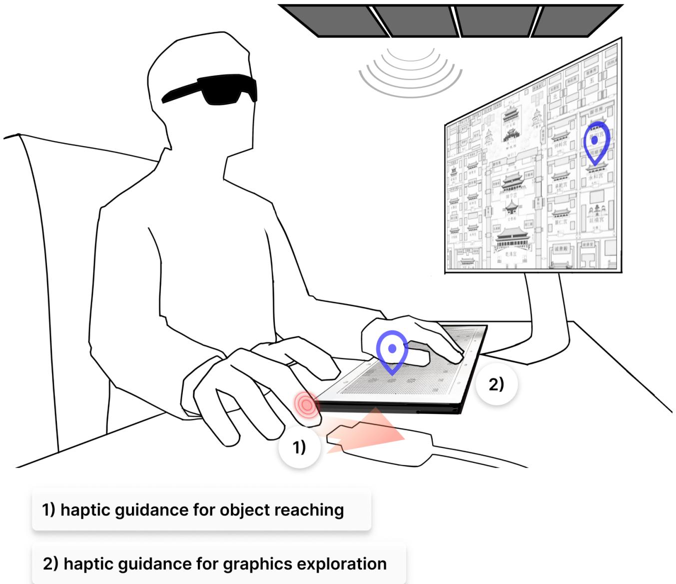


Fig. 14: Potential Future Applications of Proposed Haptic Guidance System

plore. Considering the anatomical structure and neurological characteristics of different knuckles, we can design direction-specific patterns that vary in frequency, intensity, and focal diameter. Biomechanically-informed investigations are to be done to enhance the distinctiveness of directional cues while maintaining comfort and clarity.

Third, adaptive algorithms can be further developed to optimize cue intensity based on user performance. The current requirement for personal calibration is time-consuming, and users often struggle to comprehensively compare and determine optimal positions during the tuning process. By collecting data from a larger user base, we can establish an adaptive algorithm that provides a better initial baseline and enables faster user onboarding while maintaining personalization capabilities.

Furthermore, more work is demanded to integrate this technology with other modules for broader applications. The unique combination of haptic feedback and dorsal-hand targeting presents distinctive advantages for various scenarios. In assistive technology, this system could aid visually impaired individuals in reading tasks and environmental exploration. The technology shows promise in challenging visual environments, such as valve localization in darkened pipelines to eliminate reliance on error-prone head-mounted illumination. It could also serve in attention-demanding situations where visual focus must be maintained elsewhere - from surgical navigation in operating rooms to accuracy manufacturing tasks, from military tactical operations to space exploration activities where visual attention is often saturated. In transportation, it could provide subtle navigational cues for drivers, pilots, or maritime operators without adding to visual cognitive load. The system could also enhance mixed reality experiences by providing precise spatial guidance in virtual or augmented reality environments, particularly in professional training scenarios or remote collaboration tasks where precise hand guidance is crucial.

VI. Conclusion

We introduced KnuckleGuide, a novel system to convey ultrasound-based directional cues on users' dorsal hands, focusing on space between knuckles. A pilot study explored strongly perceived and appropriate areas to map as directions, leading to the design of two mapping strategies with varying complexity. Through a user evaluation comprising 3 experiments, we demonstrated the feasibility of KnuckleGuide for mid-air haptic guidance, testing both static and dynamic movement conditions while users' exploring a graphical surface. While certain cues require refinement for better clarity, the overall results confirm the system's potential. Specifically, in the current single device setup and mapping method, the four-direction strategy overall surpassed the eight-direction strategy across all three experiments in the dimension of recognition accuracies, which indicates that simpler directional mappings of four-directions may be more effective for novice users in ultrasound-based haptic guidance systems. Future work will focus on strengthening cue distinguishability through optimized vibration patterns and developing a more generalizable algorithm for determining optimal mapping positions for each direction to enhance accuracy and clarification. We also target at extending KnuckleGuide's applicability to everyday tasks such as navigation assistance and virtual environment interaction.

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