FingerSight: A Vibrotactile Wearable Ring for Assistance With Locating and Reaching Objects in Peripersonal Space

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***Abstract*—This paper describes a prototype guidance system, "FingerSight," to help people without vision locate and reach to objects in peripersonal space. It consists of four evenly spaced tactors embedded into a ring worn on the index finger, with a small camera mounted on top. Computer-vision analysis of the camera image controls vibrotactile feedback, leading users to move their hand to near targets. Two experiments tested the functionality of the prototype system. The first found that participants could discriminate between five different vibrotactile sites (four individual tactors and all simultaneously) with a mean accuracy of 88.8% after initial training. In the second experiment, participants were blindfolded and instructed to move their hand wearing the device to one of four locations within arm's reach, while hand trajectories were tracked. The tactors were controlled using two different strategies: (1) repeatedly signal axis with largest error, and (2) signal both axes in alternation. Participants demonstrated essentially straight-line trajectories toward the target under both instructions, but the temporal parameters (rate of approach, duration) showed an advantage for correction on both axes in sequence.**

***Index Terms*—Assistive technology, blind, guidance, peripersonal space.**

I. Introduction

It is estimated that 1 million Americans were legally blind in the year 2015. According to a recent study by the National Eye Institute, given an aging population, it is estimated that these numbers will skyrocket to 8 million in 2050 [1]. Given this prevalence, it is not surprising that engineers have developed a variety of advanced technologies to improve the lives of visually impaired people. Some, such as magnification and optical character recognitions systems, have focused on assistance in reading the printed page. Assistance in reading diagrams was provided by a system that converted a color representation to haptic textures, using a piezoelectric actuator mounted around the finger [2]. The problem of object identification more generally has been addressed with devices reading information from head-mounted cameras [3]–[5].

A number of systems have been implemented to address the problem of guiding those with low vision or blindness in navigating pedestrian environments (see review in [6]). These locomotor guidance systems rely on location monitoring by means of devices like infrared transceivers or GPS, and often use vibration as a means of signaling. Vibrotactile information has been found sufficient to guide navigators to designated targets across a range of form factors. Tactors may be mounted on the body. For example, an early system took the form of a vest embedded with a 4 x 4 tactor array to convey cardinal directions [7]; another system was in the form of a harness [8]. Vibrators in belts around the waist are another approach that allows more variability in angular orientation guidance [9], [10]. Vibrators worn on the wrist are a further variant [11]. A single tactor that signaled correctness of the pointing direction of the arm was one such approach [12]; another used an 8-tactor array on a wrist band [13]. The shoe has been a further site of tactile direction cues [14]. Recent reviews of these devices include [15], [16].

Relatively few applications, however, have focused on assistance with accessing locations in peripersonal space, i.e., within reach of the body. In one such effort, Lenay [17], [18] attached a single photocell to the tip of a finger and used it to activate a vibrator held in the other hand to locate light sources in 3D space. The result is that vibratory feedback was contingent on pointing to the target, and the location of the target was cued by the user's joint angles (i.e., by kinesthetic cues).

The present paper describes a novel approach to the problem of near-space localization, called FingerSight [19]. Vibratory signals are used to guide a user to a desired target object detected by a finger-mounted camera. The device adheres to recommendations for sensory substitution via touch [20], in that the vibrotactile cues are well suited to the sensory bandwidth of the skin; in particular, no attempt is made to portray an image of the target on the skin. A series of prototypes developed over the past decade began with a finger-mounted device incorporating an active laser system that physically vibrated across optical boundaries using regenerative feedback [21]. A separate fingertip stimulator was added as small inexpensive cameras became available. At this point, computer vision techniques were implemented to recognize and manipulate graphical

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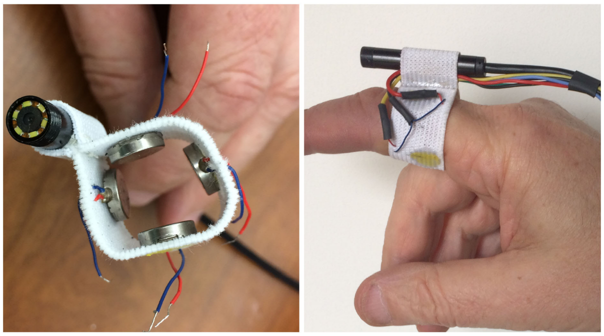

Fig. 1. Initial prototype device with Velcro ring and camera holder.

controls on a computer screen, such as virtual slide-pots and knobs, with linear and rotational gestures [22]. In a subsequent version, two tactors presented stereo stimulation to the fingertip. Testing confirmed the ability of a blindfolded user to determine the angle of an edge at a distance [23]. Another version consisted of binocular cameras mounted on the user's hand along with five vibrators attached to the back of the hand. Computer vision methods were used to generate a depth map and then identify and locate the target object in 3D space, activating the tactors to help the user grasp an object [24]. However, the difficulty of reliably mounting the camera and tactors in this configuration was a barrier to deployment.

In this paper we present a new version of FingerSight with a single camera and a new approach to tactile feedback, which takes the form of a ring at the base of the index finger with small tactors mounted along the two perpendicular axes across the finger (left-right, up-down). The compact form has the virtue of being easier to mount than predecessors, and interpretation of the directions relative to the finger axes is cognitively accessible and easily trained. An initial issue was whether the relatively bony structure of the finger has sufficient mechanoreceptive density to sense the vibrotactile input. Our candidate receptor population in this regard is the Pacinian corpuscles, which respond to vibration or low amplitude, high frequency stimuli [25]. In support of the idea that locations around the finger can be discriminated, success was previously demonstrated with a finger-surrounding haptic stimulator using electroactive polymer and soft actuators [26]. Here we report success in sensing and discriminating this form of stimulation, and we provide detailed quantitative measures of its efficacy in steering the finger to a target (a need that has been emphasized in [27]). We next describe our new device in detail.

II. Device Design

A. Hardware

The prototype device, shown in Fig. 1, consists of a ring worn around the index finger, on which is mounted a small cylindrical camera commercially available for inspecting plumbing systems (Walmart / Okeba HD 2M/7 mm). Within the ring are embedded four 10-mm diameter tactors commonly found in cell phones (Adafruit product# 1201). For purposes of stimulus control, these are interfaced with an Arduino Uno board. Camera and Arduino are USB-connected to a computer. The camera provides a video frame with a resolution of 480 x 640 x 3 to the computer with a viewing angle of 66°. As explained below, frames were passed for analysis at a rate of 2/sec., at which point feedback was provided to the user.

Additional hardware used in evaluation experiments described below incorporated an optical tracking system capable of determining the 3D location and orientation of an array of 10 infrared (IR) light emitting diodes (LEDs) mounted on the ring, thus permitting continuous tracking of the FingerSight device during the experiments.

The ring was iteratively developed. Problems that were addressed by successive versions included the following: The initial approach, an inflexible ring with small gaps between tactors, allowed vibrations to be transmitted from one site to another, confounding tactor localization. In addition, the variability in individuals' finger sizes precluded a one-size-fits-all approach and made mis-fit a salient factor. An elasticized fabric ring solved this problem and reduced the vibrotactile transmission between tactors but suffered from an unfortunate tendency to reduce blood flow, especially in users with larger fingers.

The ultimate prototype consisted of a Velcro strap of width .75 inch (19 mm) and a custom camera holder. Under the strap, the four tactors were individually attached to the finger using double-sided tape with a width of 0.5 inch (12.7 mm). The camera holder was 3D printed, such that the Velcro passed through a notch in its base. At the top of the camera holder was attached a curved housing for an array of ten infrared diodes for tracking during the experiment, though this would be removed for normal usage of the device.

A custom circuit was built for the Arduino Uno to drive the four tactors, with current amplification to provide the required 75 mA, and surge suppression to protect the Arduino from the inductive load of the tactors.

B. Computer Vision Algorithm

As stated earlier, frames from the camera were captured for analysis every 0.5 sec. To detect the target object, a computer vision algorithm was implemented using the open-source computer vision library, OpenCV. For each frame, a binary mask is applied using a pre-determined range of color and intensity for the pixels, to match the spectrum of the white LEDs used as targets (described in the Experimental Methods section below). After a series of erosions and dilations to remove noise, connected pixels are analyzed to detect circular blobs. The result is an effective segmentation differentiating a white LED from the black background in a lit room, from which the (x,y) coordinates and radius of the circular cluster are extracted to inform the vibrotactile instruction delivered to the user. The goal is to direct hand motion to bring the LED target to the center of the video image. Since the target becomes larger as the camera moves towards it, the radius of the circle indicates how far the user is from the target. If there is no blob detected in a given frame, no instruction is delivered.

C. Finger Stimulation

The ring was worn on the index finger of the dominant hand. Tactors mounted on the dorsal, medial, lateral, and

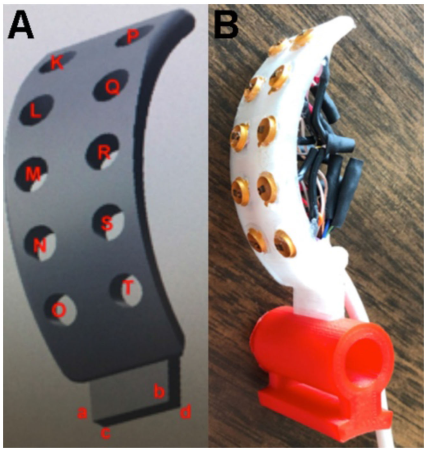

Fig. 2. Array of ten markers embedded in a custom curved frame attached to the FingerSight camera holder.

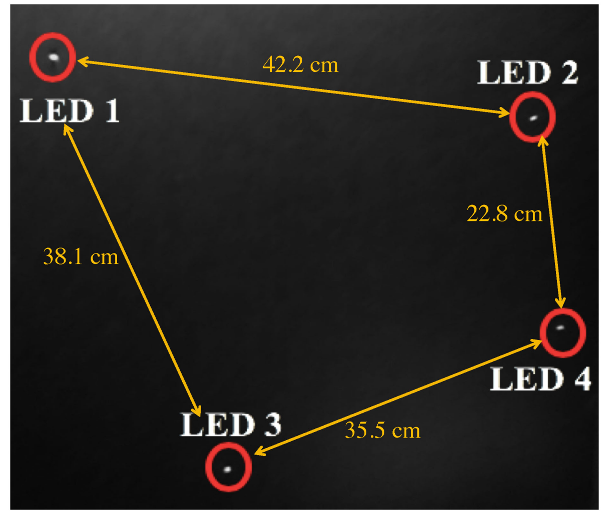

Fig. 3. LED Placement on black cardboard poster.

ventral surfaces represent up, right, left, and down relative to the camera frame, whose orientation was thus aligned with the natural coordinate system of the hand. Participants found this mapping easy to interpret in terms of hand motion. An optimal voltage level of 4 V to be applied to individual tactors was determined by pretesting, providing sufficient vibration intensity for detectability while avoiding unwanted transmission around the ring if intensity was too high. When activating all four tactors simultaneously to indicate success, an optimal level of 3.3 V was determined to keep the total intensity from being excessive.

An optimal rate of delivery for the haptic instruction was also established by pretest, to balance between the need for timely information update and unwelcome redundancy relative to the speed of the user's motion. An update rate of 2/sec was determined to meet these goals, at least for unpracticed users. Users accustomed to the system might eventually move more quickly and benefit from a faster update.

D. Motion Tracking

Additional hardware was used in experiments to evaluate the FingerSight device. The location of the device while performing a search task was tracked in 3D with an Optotrack Certus (Northern Digital, Inc.), an optical tracker with high precision and speed [28]. The system consists of a control unit, a set of markers, a strober that activates the markers, and a 3-camera position sensor that determines marker locations and sends them to the computer, where they are stored. These processes were implemented with the First Principles software (also from Northern Digital). Markers used in the experiment were special infrared (IR) LEDs, each containing four independent light-emitting elements in a small square to improve accuracy.

To allow tracking of the FingerSight device over an acceptable range of orientations, we designed a curved frame to contain ten of the IR-LED markers, which was rigidly attached to the ring. A minimum of three markers must be properly oriented in the field of view of the 3- camera position sensor of the optical tracker to correctly determine the pose (orientation and location) of the rigid body. To ensure this minimum over the expected range of hand orientations resulting from 90° wrist rotation, we 3-D printed the curved frame shown in Fig. 2, into which the markers were embedded. Identifying the relative locations of the ten IR-LED markers (labeled K-T in Fig. 2A), along with the corners of the rectangular surface (labeled a-d) that pressed up against the camera housing, allowed the location and orientation of the camera to be computed, as long as three or more markers were visible to the 3-camera position sensor. These data were tracked at a frequency of 20 Hz. Participants were asked to move their hand in response to particular tactor vibrations, with these haptic instructions being delivered at a frequency of 2 Hz. The tracker was synchronized with the FingerSight system, so that exactly 10 locations were recorded for every haptic instruction.

We next present the experimental evaluation of the system described above.

III. Experimental Methods

A. Participants

With IRB approval at Carnegie Mellon University, experiments were conducted using volunteer undergraduates recruited from the Psychology Department participant pool. The participants consisted of 19 males and 11 females. All were sighted with no known visual impairments and had the ability to feel vibration in their hand and control hand movement normally, by self-assessment and observation. All participants were right-handed. All participants signed a consent form before the experiment, which lasted less than 1 hr.

B. Stimuli

Four white Light Emitting Diodes (LEDs) inserted into a black cardboard poster acted as the target objects. The four LEDs were placed in arbitrary locations to form a quadrilateral with no sides parallel or equal, as shown in Fig. 3, to ensure that the participant could not easily predict target location. (Only one configuration was tested for all participants.)

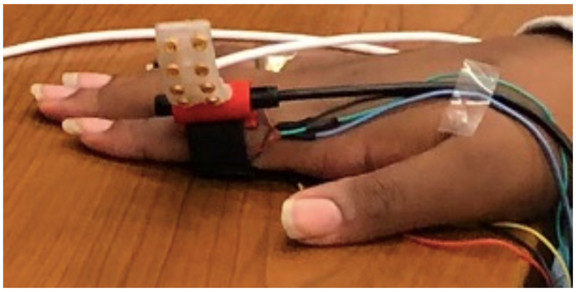

Fig. 4. Full finger mounted system used in experiments.

Fig. 5. Numeric Keypad to report the vibrating tactor(s).

C. Design and Procedure

Participants were seated at a table (91 x 60 cm) facing the poster containing the LED targets, which was oriented in the frontal plane with the bottom edge resting on the table. They wore the ring of tactors, camera, and tracking array as described above, shown in final form in Fig. 4.

IV. Experiments

A. Experiment 1: Tactor Localization

In the first experiment, we assessed how well the participants could identify which tactors(s) were activated. Initially, the particular tactors used as haptic instructions (left, top, right, bottom, and all four) were activated with the correct answer given verbally, to familiarize the participant. Then, over a series of 15 trials, each haptic instruction was tested three times, in random order. For each test, the participant held their hand steady while the tactor(s) vibrated for 90 msec, after which they reported what they felt by means of a numeric keypad. As shown in Fig. 5, keys with arrows pointing in the four cardinal directions were used to report single pulses, and the central key (number 5) corresponded to all four tactors being activated. The participant's responses were recorded by a computer along with the correct signals. If a participant made more than 3 errors, the 5 possible stimuli were again presented with the correct answer. The experiment was then repeated for these participants.

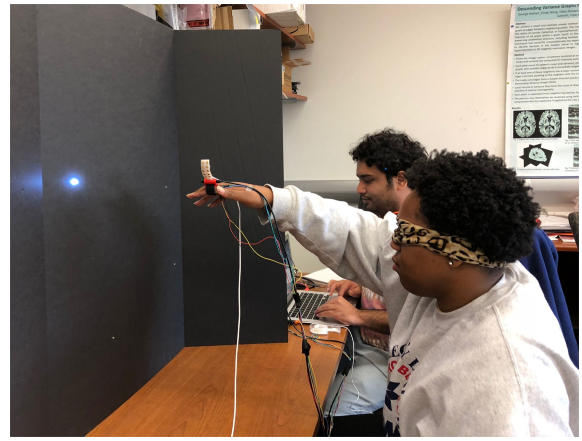

Fig. 6. Layout of experiment for guidance to target.

B. Experiment 2: Guidance to Target

In this experiment, illustrated in Fig. 6, the participant attempted to move the hand wearing the FingerSight device in the direction of the perceived vibration in order to reach the target. For example, if they felt the left tactor vibrating, they moved their hand in the left direction, and so on. Activation of all four tactors simultaneously indicated that their finger was aligned with the target object, in which case they were supposed to move straight forward, closer to the target object. Before the first target approach, each of the five haptic instructions was manually executed three times and described, to re-familiarize participants.

The participants were blindfolded, and a curtain that had covered the four target objects during the initial part of the study was removed. To begin each trial, the participant sat with their palm resting on the edge of the table, approximately centered relative to the poster's width dimension. The target LEDs were at an average Euclidean distance of 76 cm from this starting point. One of the four target LEDs was turned on. At this point, participants had to first search for the target by sweeping their hand so that the target object would become visible to the cameras. As soon as the target object was in the frame of the camera, participants received a vibration indicating the direction of the target object. They should then move the arm toward the target with minimal wrist rotation. As previously described, the participants received instructions at the rate of 2/sec. When participants were properly aligned and within approximately 10 cm of the target, all the tactors were activated for 3 sec, instructing the participant to move their finger forward to touch the target. There was no time limit.

We initially considered four different guidance strategies to lead the participant's hand to the target: (1) Worst-Axis-First, (2) Adjacent-Pair, (3) Two-Tactor-Vector, and (4) Warmer-Cooler. These were defined in terms of coordinates aligned

TABLE I
CONFUSION MATRIX OF ERROR FOR FIRST ATTEMPT

Activated \ Reported	1	2	3	4	5	Total Errors	Error Proportion
1		0	7	3	2	12	0.13
2	4		9	10	2	25	0.28
3	15	5		0	0	20	0.22
4	5	6	0		0	11	0.12
5	10	0	3	4		17	0.19

TABLE II
CONFUSION MATRIX OF ERRORS FOR BEST ATTEMPT

Activated \ Reported	1	2	3	4	5	Total Errors	Error Proportion
1		0	0	1	0	4	0.04
2	1		9	4	2	16	0.18
3	4	2		0	2	8	0.09
4	7	5	0		1	13	0.14
5	5	0	1	1		7	0.08

with the horizontal and vertical axes of the camera frame and the depth axis orthogonal to the frame.

(1) Worst Axis First, as the name suggests, is based on an algorithm that determines if the participant is further away from the target in the horizontal or vertical direction and indicates the user to correct in the worst direction first. For example, if the Cartesian coordinates of the target object relative to the center of the camera frame (where the target is desired to be) were (20,50) the user would receive a signal to move their hand upward first, in turn minimizing the distance (error) in the up direction. Once the vertical distance fell below a certain threshold (described below), the participant would be directed to move towards the right. Thus, with each new frame received from the camera, the algorithm determined the worst axis and corrected it first. The threshold was the radius of the target object, i.e., if an axis fell within the contours of the blob, the algorithm considered the participant to be aligned in that direction.

(2) The Adjacent-Pair strategy is based on signaling the participant to move in both the horizontal and vertical directions in a given 1-second interval, by alternating signals. Thus, instead of first correcting one of the directions completely, participants were guided in both directions, if appropriate, over a sequence of two instructions. From the earlier example, if the Cartesian co-ordinates of the target object were (20,50), the signal would guide them to move right and up relative to the camera frame with the next two instructions. Once the finger was correctly aligned in one of the directions, the participants would get the same directional indication twice or more in succession, which in turn also informed them that they were aligned in the other direction. Subsequent mis-alignment would reinstate the alternation of both instructions.

(3) The Two-Tactor-Vector strategy was designed to test if two adjacent tactors could be activated at the same time to stimulate a vibration in the intermediate direction. Thus, if the target object was located at (20,50), the system would simultaneously activate both the top and the right tactor. It was hypothesized that this would indicate the participant to move in a direction corresponding to a vector in between the two signaled components, reducing errors in both x and y simultaneously. If the participant was already aligned in one of the axes, using the same threshold as above, only one tactor was activated.

(4) The Warmer-Cooler strategy was based on determining if the participant had just moved into closer alignment with the target object or further away. The tactor was only activated if they were moving in the correct direction. Thus, the proper direction of motion had to be actively interrogated by the participant. This is similar to the approach used by Lenay [18], in that it activates only under correct behavior.

In pilot testing all four of the hand guidance strategies, we found that the Two-Tactor-Vector and Warmer-Cooler strategies were ineffective. The problem with the Two-Tactor-Vector strategy was that it was difficult to determine which two tactors were activated; the likely problem was cross-talk due to transmission of vibration through bone and soft tissue. The Warmer-Cooler strategy failed because the lack of directional feedback led to an unsystematic search for improvement. Thus, it was evident that these two strategies could not effectively guide users and would lead to arm and hand fatigue in any reasonable experiment searching for the target.

Following the pilot study, the formal experiment was conducted with the two remaining guidance strategies, Worst-Axis-First and Adjacent-Pair. Note that both of these strategies give the user feedback to correct errors, in contrast to signaling only when the target has been acquired, as in [18]. This experiment consisted of four trials performed by participants, two trials per guidance strategy. To ensure that participants could not predict the location of target, a different target was used in each trial. For a particular guidance strategy, the target objects were LED 1 and LED 4 (diagonal pair), while for the other strategy the target objects were LED 2 and LED 3 (see Fig. 3). The sequence of strategy and targets was counterbalanced across participants, to ensure there was no bias in the experiment.

V. RESULTS

A. Tactor Localization Results

All 30 participants completed Experiment 1. Eighteen participants repeated the task because they initially reported three or more signals incorrectly. Tables I and II show the confusion matrix of errors after the first and best (last) test periods. The numbers 1 through 5 each represent a particular haptic instruction: (1) top, (2) right, (3) bottom, (4) left, and (5) all tactors activated. Only incorrect responses are shown, in which case the reported instruction does not correspond to the activated tactor; thus, the diagonals of the matrices are left blank.

It is evident that the mean number of errors was generally reduced with additional training, especially for instructions 2 (right), 3 (bottom) and (5) all, for which errors were larger initially. Overall the total proportion of errors was reduced from 18.8% to 11.2% with the repeated testing.

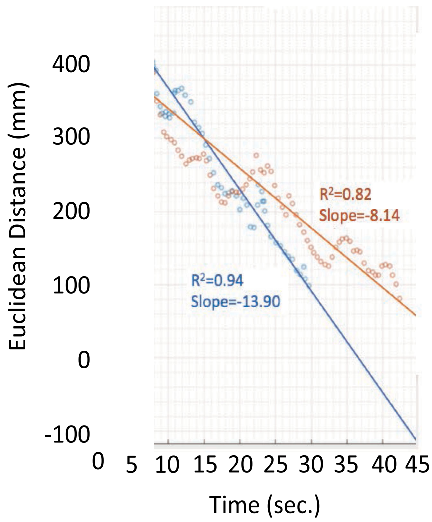

Fig. 7. Sample regression of Euclidean distance against time for two trials from a single participant, one for each of the two strategies implemented.

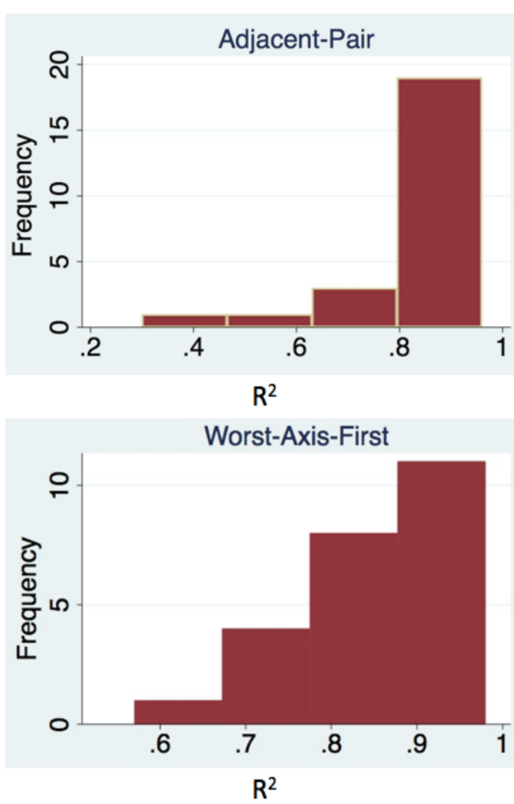

Fig. 8. Histogram of R^2 for linear fit to the approach to the initial stopping point, for each of the two strategies implemented.

B. Guidance to Target Results

The same thirty participants who had completed Experiment 1 performed Experiment 2. During each trial, with a specific guidance strategy and a specific target, the vibratory instructions delivered to the participant and the corresponding tracked locations of the markers were recorded. In order to analyze guidance to the target, we considered the distance of the participant's finger from the target in the x, y, and z

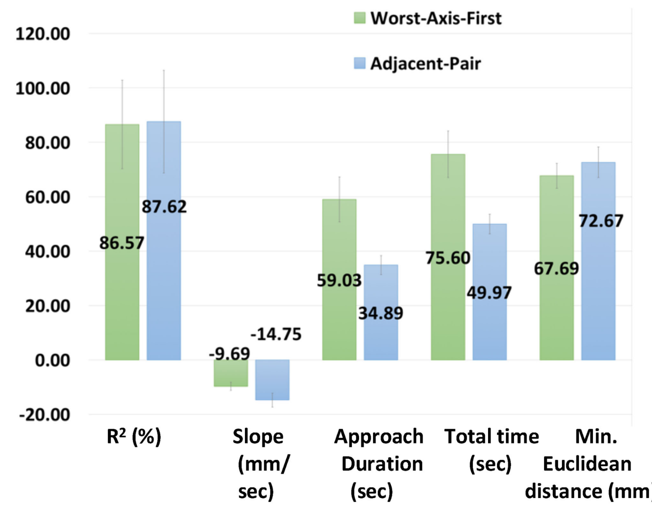

Fig. 9. Means of the five measures for each strategy. The error bar is 1 s.e.m.

directions, as well as the Euclidean distance of the finger from the target, in tracker-designated space.

Participants completed all trials within the 10-cm constraint. From the data it was evident that participants generally approached the target linearly with respect to time in terms of the Euclidean distance from the moment they received the first haptic instruction until they were 10 cm from the target. A regression line was fit to the Euclidean distance vs. time during these periods. Fig. 7 shows a representative example of the slopes and goodness of fit (R^2) of the regression line for the two different strategies as used by one participant. Regressions with $R^2 > 0.6$ were considered acceptable. While it appears that an exponential function might be a better fit for the Worst-Axis-First strategy, the linear fit meets our acceptability criterion, and it is clear that the regressions reflect the slower approach to the target for Worst- Axis-First.

Fig. 8 shows the distribution of R^2 of this linear regression as a histogram for the participant population, separately for each guidance strategy. Out of the 30 participants, data collected from 22 could be analyzed. Data collected from the remaining 8 participants had to be discarded, because six participants had missing data from the tracker for both trials with a guidance strategy, and two had an unacceptable linear fit ($R^2 < 0.6$). For one of the participants, who apparently had difficulty at the beginning of a trial responding correctly to the tactors, we kept the overall results after adjusting the period of descent to begin only when he started moving correctly in response to the haptic instruction.

Considering data from the 22 participants retained, the graphs in Fig. 9 show, for each guidance strategy, the mean R^2 and the slope of the linear regression on Euclidean distance to the initial stopping point at below 10 cm, along with the duration of that approach. Also shown is mean total time for the trial and the mean minimum Euclidean distance reached relative to the LED target when the trial ceased.

From Fig. 9 it appears that the mean slope, duration, and total time are all lower for the Adjacent-Pair strategy, as compared to the Worst-Axis-First strategy. The correlation of

TABLE III
STATISTICAL COMPARISONS OF EXPERIMENTAL VARIABLES USING STUDENT'S T-TEST

Mean difference: Worst-Axis-First minus Adjacent-Pair	Test Statistic (t)	p
R^2 for linear approach	-0.57	0.57 (ns)
Slope of approach	-2.24	0.04*
Duration of approach	3.24	0.004**
Total trial time	3.28	0.004**
Minimum Euclidean distance	-0.62	0.54 (ns)

linear fit to the approach to target (R^2) and minimum Euclidean distance at the end of the trial, in contrast, are very similar for the two guidance strategies, indicating comparable regularity in approach toward the final stopping point and the final distance from the target.

A paired t-test was performed on each of the five variables to test for differences between the two strategies. The results are summarized in Table III and confirm the descriptions above. Specifically, the differences in slope and duration of approach to reach the target location, as well as total trial time, are significantly different for the two guidance strategies, with an advantage for the Adjacent-Pair guidance over Worst-Axis-First. In contrast, the R^2 and minimum Euclidean distance were not reliably different.

An explanation for the disadvantage of the Worst-Axis-First is that while correcting the more distant direction from the target, participants could not adequately monitor the other, causing them to drift, with the results of decreasing overall accuracy and increasing time. This trend is visible in the sample in Fig. 10, showing a participant's trajectory on the x and y axes for each strategy. Corrections tend to trade off in Worst-Axis-First, as opposed to the more regular approach on both axes for Adjacent-Pair.

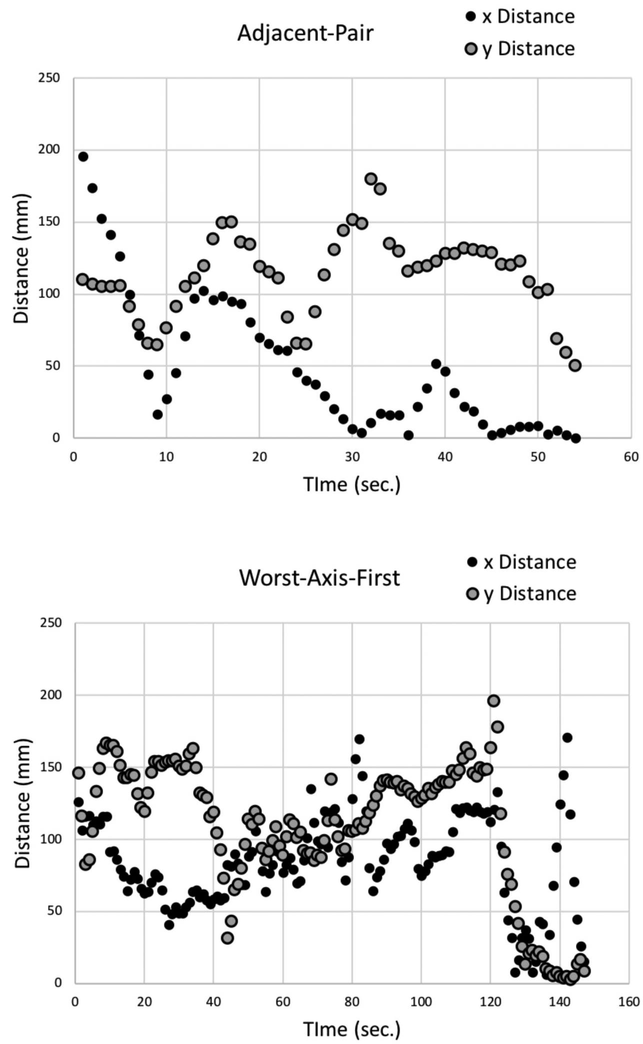

Fig. 10. Sample trajectories of tracked distance from the target over time in x and y directions, by each guidance strategy for a single participant.

VI. DISCUSSION

The present experiments demonstrate promise for a finger-mounted display to be used by visually impaired people to locate and reach objects in peripersonal space. The experiments demonstrated that minimal training was needed to allow users to discriminate haptic feedback in four cardinal directions by means of a compact ring stimulator, and that this feedback could be used for accurate guidance to target objects.

As currently designed, FingerSight is intended to support motions directed toward a target, in the form of initial search and subsequent homing. It does not support rapid ballistic reaching, as occurs during visually directed action. Still, the mean duration of approach in our experiments, approximately a half minute with the optimal guidance, is admittedly slow relative to normal reaching. However, speed could likely be increased by several factors: Experienced users would benefit from practice, for example, by learning to do strategic search (e.g., do not revisit regions already scanned) and achieving more consistent control of the arm (thus avoiding target loss). Practice could also allow use of a faster refresh rate in communication from the system. In addition, approach to targets would be faster if users had a mental model of the searched space (e.g., an expectation of where they had last touched an object like a coffee mug). The size of the current targets, small LEDs, is another aspect of the task that would slow performance. Most objects used in everyday interactions are scaled to the hand and would thus be considerably larger. It is also possible to develop other strategies for guidance, although the current tests with the warmer-cooler approach suggest that feedback signaling only correct behavior (as in [18]), would not facilitate performance.

Other features of FingerSight enhance its prospects for use. Because it does not rely on audio/sonic feedback, nor does it generate high-dB sound, use of the device should minimally if at all interfere with environmental sounds that blind people rely on for performing other tasks. Cost is unlikely to be a consideration if the device becomes commercially viable, because the required components are inexpensive (in our current device, approximately \$60). The tracker is intended to be used only for our experimental data acquisition and adds no cost to the system. However, in order for a trackerless system to provide adequate guidance for homing, the camera data must be effectively processed to recognize when a targeted object is in view, which is a challenging task. The requirement of a local computer to process camera data could be eliminated by offloading the required computation to a cloud-based agent or a smartphone application. New developments are making the latencies of such systems feasible [29]. Such accessible enabling technologies are critical in addressing the known linkage between poverty and vision loss [30].

The system could further be improved by adapting its features to the individual user. In this regard, we have conducted preliminary research on using control systems analysis to create a model of the user's behavior based on the experimental data from that individual. The goal of such an approach would be not only to optimize the control system to find the best strategy for tactor activation in a future generation of FingerSight, but also tune that strategy to the individual.

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