Go That Way: Exploring Supplementary Physical Movements by a Stationary Robot When Providing Navigation Instructions

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ABSTRACT
We describe an exploration of how kiosk-type stationary robots might provide navigation instructions for blind people. Inspired by a technique used by Orientation & Mobility experts in which a route is traced out on a person's palm, we developed five methods that supplement verbal instructions with physical movements. We explored the usability, strengths, and limitations of each of our methods in two exploratory studies with blind participants. One method, in which the robot used its entire arm to create path gestures while participants held its gripper, was preferred by 5 out of 8 blind participants and performed comparably on a recall task as a verbal-only instruction method. A closer approximation of the original palm method failed. We analyzed interview data to understand the reasons behind the failures and successes. We discuss the lessons learned from our studies about instruction methods, how robots in public settings can be useful for blind people, and the challenges of deploying such systems in public.

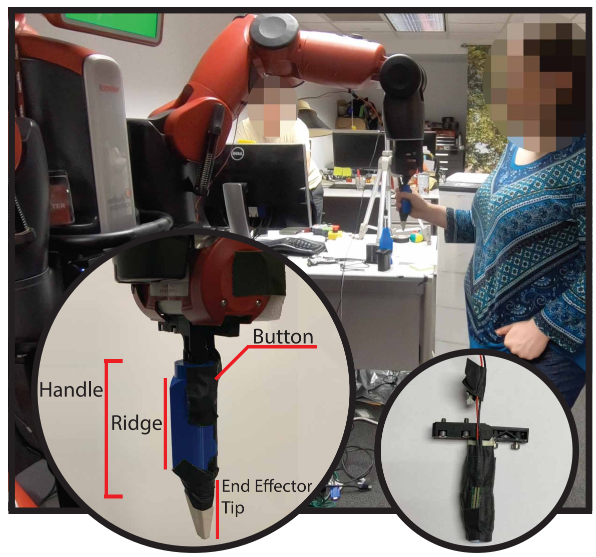

Figure 1. Top: A blind participant receiving navigation directions from our robot using the *Hand* mode. Bottom right: Handle in second exploration study. Bottom left: Handle in feature exploration study.

CCS Concepts
•**Human-centered computing → User centered design;**

Author Keywords
human-robot interaction; assistive robots; blindness; navigation instructions

INTRODUCTION
Robots have started to interact with people in museums [13], guide people in airports [31], deliver food [22], and patrol buildings to provide security [11]. This trend of having service robots that are owned by and situated in specific buildings alleviates some of the need for individuals to purchase expensive robots for themselves, allowing a greater number of people to have access to and benefit from advancements in robotic technologies. As we are still in the early stages of robot deployment in public social spaces, there are opportunities to leverage these technologies in ways that assist people who are blind and foster their independence.

Our work explores new service roles for stationary robots that are designed to be at a fixed location in a building. These robots may act as a kiosk [17, 43] and potentially provide a wide range of services that utilize the computation and manipulation capabilities of the robot. Beyond their original purpose, these service robots have also been identified as having potential to assist people with visual impairments [5]. These robots will likely be tasked with providing navigation directions for visitors to the buildings. While a mobile, nimble robot might sometimes be best suited to help with navigation escort tasks, that may not always be the case. Travel distance may sometimes be too trivial for a mobile robot, and a mobile robot may not always be available or practical to use. As such, we believe there is benefit in exploring how stationary robots can provide navigation directions. This is especially true for stationary robots that already engage building patrons by serving in other roles, such as information kiosks or security guards.

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By equipping these robots with techniques for assisting with navigation, we may add value to their existing roles and interactions. A rudimentary direction-giving navigation system should be able to provide customized verbal directions that do not rely on visual landmarks and cues to users with visual impairments. However, when sighted people give navigation instructions, they often supplement their verbal instructions with gestures to indicate routes and landmarks [9, 41]. This raises a key question: Is it possible to provide supplemental spatial information with verbal instructions for blind users?

We drew inspiration from conversations with Orientation and Mobility (O&M) experts, who demonstrated a technique that combines verbal and tactile signals to provide instructions. After obtaining consent, the O&M expert holds the person's palm up. Then, the expert places their finger on the bottom of the person's palm and starts to give verbal instructions. At the same time, they move their finger along the palm and trace the path the person will take relative to their starting point. This technique attempts to reinforce the verbal instructions with physical touch instead of relying solely on the auditory channel. Additionally, this method provides an opportunity to build upon our earlier question and ask specifically whether a kiosk robot with manipulation capabilities can provide a similar experience and present both verbal and physical route information. The goal of our project was to explore how we might create interactions inspired by this strategy on a physical robotic platform that has some manipulation capabilities.

A direct recreation of the technique of drawing on the user's palm was challenging due to physical and system constraints. Current affordable manipulation systems are unable to make fine movements with dexterity, especially on such an uneven and varied surface as a human palm. While we did attempt to recreate this interaction, we also explored other methods that leverage the idea of reinforcing verbal instructions with physical movements when providing navigation directions.

This paper describes our exploration into designing dexterous robot interactions to provide navigation directions to people who are blind that are inspired by the existing O&M Palm Drawing technique. We iterated on our system through two exploratory studies. As a part of each study, we collected feedback from participants about their experiences as well as general thoughts about how robots might assist people with visual impairments. We showed that while directly emulating the Palm Drawing method may not always be feasible, it is not the only way to apply the concept of supplementing verbal instructions with movement by a stationary manipulator robot. We also found opportunities for continued system improvement and captured general impressions and concerns that users have regarding stationary building service robots.

RELATED WORK

Providing Directions for Indoor Navigation

Assisting people who are blind while navigating indoor spaces remains an active, challenging area of research. Most recent work on this topic has focused on providing turn-by-turn navigation instructions using mobile applications [2, 12, 15]. For example, Guerreiro et al. [21] presented an application, "Virtual Leap", that helped visually impaired users build a mental map of a space using a virtual walk-through of the route. Prior work has also explored how haptics can supplement or replace verbal instructions. Ertan et al. [14] used a haptic array to communicate in which direction to turn. Pielot et al. [35] used a tactile compass to encode different directions with binary haptic signals. Azenkot et al. [6] compared the tactile compass with two new haptic interactions, Wand and ScreenEdge, and found preferences for the compass and ScreenEdge. In Wand, the phone vibrated when the user pointed the phone in the desired direction. In ScreenEdge, the phone vibrated when user touched the edge of the screen corresponding to the desired direction. Similarly, Yatani et al. [44] attached multiple tactile haptic generators onto the back of a smartphone to present directional information about the destination and build spatial awareness of the desired path.

A more traditional navigation technology for new locations is to use tactile maps [16]. Physical tactile maps have long been a useful orientation aid to help people with visual impairments understand the location they are in and the available destinations. Prior work has examined augmenting these maps to make them interactive through audio and haptic signals [1, 23]. Wang et al. [42] described a system where a tactile map was generated from a map image, printed using an automatic process, and placed onto a touchscreen. A blind user could then interact with the map and obtain audio descriptions by pressing tactile symbols for areas of interest. The usefulness of these interactive tactile maps was also validated in prior work [8] where they were shown to be more efficient and have higher user satisfaction. Talking tactile maps have also been deployed in public spaces [20]. Beyond physical tactile maps, prior work explored how users could 3D print their own maps [19], print on large surfaces [38], or use virtual environments to create cognitive maps [30]. Among these improvements, the most relevant work for the current project is research on how blind people may use haptic devices to explore and learn maps [36, 45]. Early exploration by Lahav and Mioduser [29] showed that blind participants were able to learn a room's layout with a haptic device and safely navigate in that space afterwards. Tzovaras et al. [24] demonstrated a system that converts a 2D online street map into a pseudo-3D haptic map with audio cues that could convey to the user the streets, crosswalks and points of interest on the map. While these system have some similarities with our work, we focused more on recreating existing methods used by O&M experts and trying to provide immediate navigation direction to a location instead of exploration and learning of the map.

Assistive Robots for People who are Blind

A wide variety of robots have been explored to improve quality of life for people with visual impairments. Prior work explored how different types of robots, such as stationary robots [7, 39], aerial robots [3, 4], mobile robots [10, 18, 26], and handheld robots [40] could assist blind people. For example, Kulyukin et al. [25] developed a mobile robot to guide blind participants indoors. The robot was able to guide participants to different locations in the building, with some limitations. In terms of stationary robots, Bonani et al. [7] conducted a study where blind people worked together with a manipulator robot to complete a Tangram task. They show that participants were able to complete the task with physical assistance from the robot and perceived the robot to be more warm, competent and useful compared to when the robot only gave voice feedback. Azenkot et al. [5] explored how building service robots could provide useful assistance to blind people through a participatory design approach with an eight-member team. The design team proposed three potential robot roles: Information Kiosk, Escort, and Sighted Guide. While the authors pointed out the Information Kiosk robot may not need a physical embodiment, our work aims to demonstrate that there are benefits to have a physical form and being able to provide physical guidance.

FEATURE EXPLORATION STUDY

The goal of the feature exploration study was to understand the design space of how physical movements can help users while they receive verbal instructions. We restricted our interaction to a single-hand interaction because many users need to hold onto their canes, phones, or guide dogs during these interactions. This restriction also enables our interaction techniques to be executable by a single arm manipulators.

Stationary Robot

For both of our exploratory studies, we used a Rethink Robotics Baxter Research Robot. The Baxter robot is an affordable, human-safe robot designed for interaction with human in close proximity and had a retail price of around \$30,000 USD (but has since been discontinued). It is about 178cm tall and has two 7 degrees-of-freedom arms. Both arms have exchangeable end effectors (the device at the very end of the robot arm) that allow attachment of different tools. In the feature exploration study, we created a prototype handle that we constructed by wrapping foam around the robot's gripper end effector (Figure 1, bottom right). The handle allowed users to hold onto the robot's end effector as it performed the different physical gestures. At the end of the handle is a smooth material to allow the tip to glide on the user's palm. To simplify controls and maximize the constrained workspace of the robot (the space reachable by the robot arm), we constantly pointed the robot's end effector downwards and constrained the movements to translations along the X, Y, Z axes (3 DoF) and rotation around the Z-axis (the spinning of the handle).

Ideation & Approach

Inspired by the Palm Drawing method used by O&M experts and aware of the robot's limitations, we designed multiple physical movement cues that served the same purpose. We attempted to provide sensory feedback regarding both the turns the users would take and the distances of the segments of the path they would follow. In addition to recreating the palm method, we designed four other ways for the robot to provide physical cues. In all modes, the user was initially oriented to face the robot when it started to give the instructions. The five different navigation direction giving modes are as follows:

1. *Rotation* - The robot rotated only the handle based on the turns the user would take with respect to their current orientation in the route. For example, a "right turn" or "3 o'clock turn" involved the robot rotating its handle 90 degrees clockwise. Because Baxter's end effector cannot complete a complete 360-degree revolution (it can only move 350.5 degrees), if it encountered a path that required it to rotate close to the limit, it would have to rotate in the opposite direction (to reset) and continue from there to reach the desired heading. To avoid confusing participants, we avoided using example paths for which this would be a problem.
2. *Rotation + Movement* - In addition to the rotations described in *Rotation* movements, the robot also translated the handle in the direction of travel. For example, a instruction to "turn right and walk 10 steps" involved the robot first turning the handle clockwise 90 degrees and moving the handle along the negative Y-axis (the positive X-axis pointed towards the robot). The distance that the robot's end effector moved was calculated from a logarithmic function that compresses long paths of travel.
3. *Force* - In this mode, instead of rotating the hand, the robot calculated the force to push the handle in a particular direction for a certain duration. The calculation of the force was done by solving the transformation of the forces in the robot's workspace to its jointspace through $F_{joint} = J^T F_{workspace}$, where J is the Jacobian of the current robot joint positions. The force command was then sent to the robot's torque controllers for execution. Compared to the *Rotation*, this command moved every single joint of the robot arm to generate the desired forces. After the forces were executed, a position controller slowly moved the hand back to the original position. In this mode, the instruction "turn right" had the person's hand pushed towards the right for 0.3 seconds, followed by the hand slowly drifting back to the original position.
4. *Force + Movement* - In addition to the *Force* movements described above, after the robot's hand returned to the original position, the robot applied a translation motion to move its hand in the direction that it had told the the user to move. Again, the distance travelled was scaled using a logarithmic function. The direction in which the user's hand was pushed was still relative to the direction they were facing at the current step. For example, with a command of "turn right, walk 10 steps and turn right", the second "turn right" would push the participant's hand towards their body.
5. *Palm* - This method was similar to the *Rotation + Movement* mode in which the robot drew the user's path, but instead of holding on to the robot's hand, the user placed their palm on Baxter's other hand with their palm facing up. The robot then drew the path on their palm. To ensure the robot had the correct configuration, the experimenter first moved the robot's hand to the surface of the user's palm and then starts the *Rotation + Movement* system. The travel for all translation motion was set to a fixed distance of 2cm.

Navigation Directions

The navigation directions were generated by a server that had an annotated map of the building for which the robot was giving instructions. The robot requested information from the map server by providing it with the starting and ending

ID	Gender	Eyesight	Aid	Preference
P1	Male	Blind	Cane	Voice
P2	Female	Blind	Cane	Voice
P3	Male	Blind	Cane	Force + Movement
P4	Male	Blind	Cane	Voice

Table 1. Demographic information for feature exploration study

points. The map server then calculated the shortest path and counted the number of openings and hallways the route passed through to reach the destination. It returned a list of distances, turns, and types of junctions to the robot. The robot converted this list to human-understandable verbal instructions using a rule-based system where each instruction was given as a combination of "turn [left/right/10 o'clock] until [type of junction]". The last instruction before the destination was delivered as, "Walk [X] steps and your destination, [name of destination] is to your [left/right/10 o'clock]."

Procedure

For the feature exploration study, we invited 4 blind participants (Table 1) to experience the different types of physical movements while receiving navigation instructions. After obtaining consent or reaffirming that the participant fully understood the consent form if they pre-signed online, an experimenter introduced the user study and conducted a quick familiarization phase with the robot. The experimenter verbally described the parts of the robot as the user physically touched them. This ensured that the user had a sense of the size and parts of the robot and felt comfortable with it before beginning a procedure in which constant contact with the robot was required.

Each participant experienced 4 of the 5 modes described above in a random order, with only P3 and P4 experiencing the *Palm* mode but not the *Rotation + Movement* mode. In each mode, they received navigation directions to a room in an imaginary office building that consisted mainly of hallways with opening/turns at different lengths. At any time, the participant could rotate the handle to ask the robot to repeat the previous step or, at the end, to repeat all of the instructions. Once each interaction was complete, the experimenter asked the participant to recall the directions and junction types. After trying the different movement modes, the participant interacted with a version of the system that only gave verbal instructions (*Voice*) to serve as our baseline. Upon completion, we asked which physical movement mode they liked the most and how it compared to the baseline, *Voice*. The participant then received instructions in their preferred physical movement mode to navigate to a real room on the same floor of the building and were asked to traverse the path. Finally, semi-structured interview was conducted to examine the participant's experiences.

Findings

Our findings are drawn from participant feedback during the task, observations by the experimenter and the semi-structured interview at the end of the session. The main piece of feedback from the feature exploration study was that the physical movement cues were unhelpful and might also be distracting for users. Three of the four participants preferred the *Voice*-only mode with the remaining participant preferring the *Force + Movement* mode. The participants who preferred the *Voice* over the other modes interpreted the physical movements as unhelpful and distracting and would have preferred to just focus on the verbal instructions. One of the participants pointed out that the main cause of distraction was the rotations.

> P2:"If it could just move your hand, that's fine. If it's rotating at the same time, it just distracts."

A single participant, P3, saw potential in our approach of using the physical movement to supplement verbal instructions, and preferred physical movements over only *Voice*.

> P3: "It added... another level, another layer... of the direction. Along with the verbal... you have a physical action to help cement what was being told."

P2 also felt that the least useful mode was *Rotation*. This aligns with the feedback from other participants who said that movements which only provide rotations are unhelpful.

Participants also provided feedback on improvements to consider. For example, participants requested that we add more landmarks and cues to the path to help them navigate spaces.

> P4: "I heard that [water fountain] on the way out [to the study]. That would have been a really nice clue. So, for instance, when someone is giving me directions, in addition to the left and right and number of paces, if they were to say, um, you maybe hear a fountain on the right."

Reflections

Feedback from participants regarding the methods that utilized movement was largely negative, though there were some bright spots. We interpreted this to mean that the physical movement methods might be more beneficial for some users than others. For the second iteration, we decided to maximize the benefit of movement for users who liked it (e.g., P3) and minimize the distraction for users who did not. We focused on the rotational instructions and noticed that the main difficulty our participants encountered was keeping track of orientation while trying to remember a sequence of instructions. We asked the participants to hold onto a cylindrical object that rotated 90 degrees clockwise when turning right. However, the symbolic relationship between a 90 degree clockwise rotation of the hand and a left or right turn of the entire body is not necessarily intuitive. Even in the *Force + Movement* mode, where turns were communicated by pushing the hand in a desired direction, pushing the hand after the first rotation was not always intuitive because it was not obvious which way the user would have been facing.

An O&M expert pointed out that a potential benefit of our system is that it can give a sense of distance to the users. While the logarithmic function to scale the distance allowed the systems to gesture for large distances without exiting the boundaries of the workspace, it concealed the difference between large and small distances and potentially confused participants. We decided to maximize the benefit of movement by providing a clearer distinction between short and long distances using linear scaling instead of logarithmic scaling.

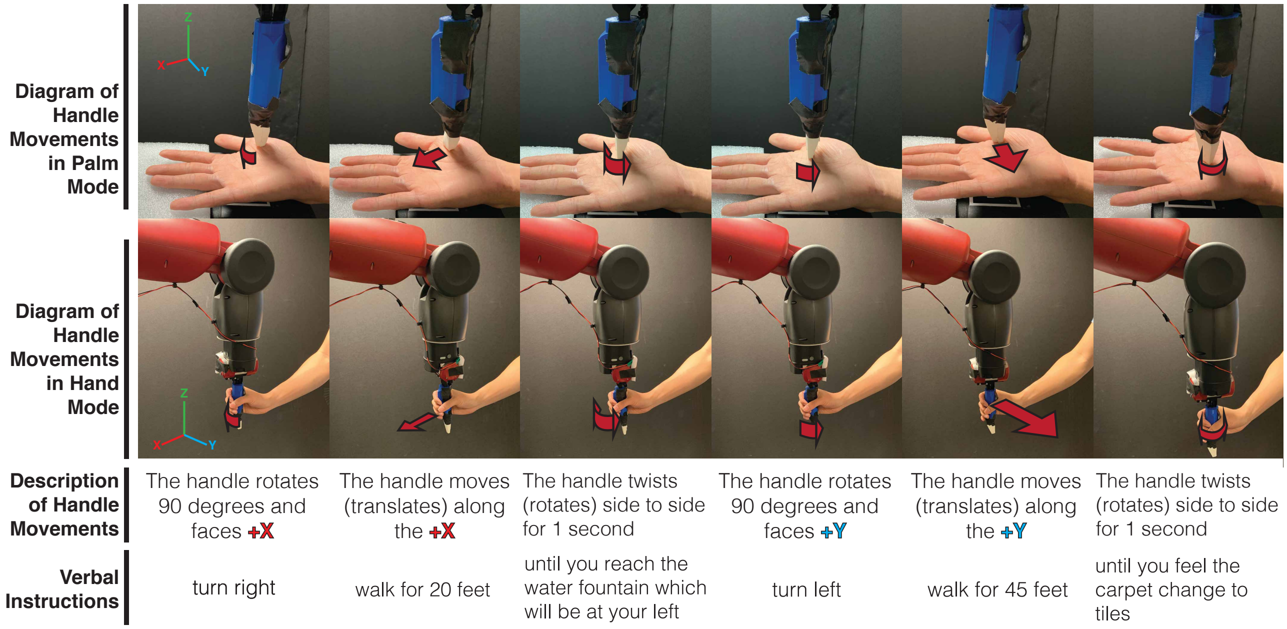

Figure 2. Diagram of the how the robot's handle and tip signal turns and movement for both *Hand* and *Palm* modes.

SECOND EXPLORATION STUDY

Design Improvements

Based on our initial exploration, we dropped all modes where there was no translation motion of the robot end effector (*Force* & *Rotation*). We also focused on addressing three aspects highlighted by participant feedback: *Rotation*, *Distance*, and *Cues*. These changes were further refined during pilot testing with one blind participant and an O&M expert.

Rotation

As mentioned earlier, users have no intuitive way of perceiving their future orientation when the robot provides relative rotational commands like "turn left" or "turn right". Our solution was to add a mechanism to the robot's handle to signify orientation. In our initial exploration, the handle was simply the existing gripper wrapped in foam and gaffer tape to form a cylinder. For our second iteration, we designed a 3D-printed handle that slid onto the gripper. The handle had a cylinder profile with a diameter of about 3cm that was easier to hold compared to the old handle (about 1.5cm diameter at its thickest point). The improved handle also had an extruded, triangular ridge along one side to indicate the orientation for the front of the body (i.e., the nose of the face). At the bottom of the handle was a flat circular surface, which allowed us to attach different types of materials that would make contact with the user's hand in the *Palm* mode. In the second exploration study, a triangular foam tip was attached to the end of the handle. A force-sensitive button was added to the side of the handle cylinder to allow users to provide binary input.

Distance

Based on earlier feedback, we changed the distance conversion function to a linear function. The system first calculated the complete trajectory of the movements and then scaled them to either the maximum x or y length of the expressible workspace, maintaining the aspect ratio of the path. This scaling ensured that the ratios between distances were preserved as the overall route was scaled down to fit the workspace.

Cues and interaction changes

We added additional landmarks/cues to our systems for changes in floor texture (e.g., carpet to wood), different ambient sounds (e.g., ice machines, water fountains, noisy locations), and hallway properties (e.g., narrowing of hallways, ends of hallways). We marked these with both verbal and physical signals. We added the physical movements after learning from the O&M expert after the feature exploration study that an expert will often twist their fingertip on a visually impaired person's palm to mark a landmark along a traced route. We also restricted our landmarks/cues to turning points along the route. If there were cues at the turning point, the robot told the participant about the cue at the end of the distance movement (example: "walk for 10 feet until you feel the carpet change to tiles"). As the robot told the cue (starting from "until"), it twisted 20 degrees from side to side for about 1 second.

Improved Navigation Directions System

The improved system generated a list of navigation directions using a rule-based approach similar to the method used in the initial exploration. We also incorporated a distance metric into the instructions. Each instruction consisted of two or three parts: the rotation ("turn right"), the distance travelled ("walk for 20 feet"), and the cue, if any ("until you reach the end of the hallway"). We used a *Voice* mode as a baseline to compare to the newly improved versions of the *Rotation+Movement* (called *Hand* in second exploration study) and *Palm* modes. We chose to continue to evaluate the *Palm* method despite mixed feedback in the initial study because it was a direct implementation of the technique used by O&M experts. We did not continue to evaluate *Force* based modes. This is because with every motion, the ridge needed to rotate such that it pointed in the correct direction, and we believed that also using forces to communicate the rotation was redundant. The following are descriptions for the three modes in the second iteration:

1. **Voice** – In this mode, only verbal instructions were given. An additional delay of 1 second was added between instructions to address the speed advantage of this method and to give the user a similar amount of time as the other modes to memorize the instructions. Throughout the interactions, the users could press the button on the handle to make the robot repeat the previous step.

2. **Hand** – This mode was an upgraded version of the prior *Rotation + Movement* mode. As before, the robot drew the map while the user held onto the handle. The map was scaled to a 0.2m x 0.2m space around the robot's left hand. The robot first moved its hand to a starting location that supported the scale and space needed for the map. It rotated the handle to signify turns and applied a translation motion that moved the handle the appropriate distance for each step. Again, all rotations were relative to the direction the user's planned orientation. For example, the instruction "turn left and walk 10 feet" would be accompanied by having the robot first rotate its hand 90 degrees counterclockwise so the handle ridge faced the user's left and then moving the handle in the direction the ridge was pointing, scaled according to the total trajectory travelled. Again, pressing the button would repeat the most recent step.

3. **Palm** – This mode was similar to the *Palm* mode in the feature exploration study. This time, the user was asked to place their hand on a pedestal located directly in front of them. The system then slowly lowered the robot's handle tip to the surface of the user's palm with the experimenter providing corrections to the height and position through a controller. As with *Hand* mode, the map was scaled down, but to an even smaller space of 0.06m x 0.04m (slightly smaller than the area of an average palm). Participants could slightly lift their fingers (a detectable gesture for computer vision, given a well-placed camera) to repeat the previous step. In our exploration, this gesture was detected by the experimenter to ensure accuracy. Throughout the experience, the experimenter also provided adjustments to the height of the tip to the palm surface in an attempt to maximize the contact between the handle tip and the palm.

Procedure

The exploration followed a similar initial procedure as before where we obtained or reaffirmed consent, introduced the study, and conducted a familiarization phase with the participant. Afterwards, participants experienced each of the three modes (*Voice*, *Hand*, and *Palm*) in counterbalanced orders (see Table 2). In the *Voice* and *Hand* mode, participants first found the robot's hand independently through an interaction where the robot slowly rotated its wrist to generate audio cues. In the *Palm* mode, participants were asked to search for a pedestal placed in front of them by the experimenter and rest their palm facing up on a foam portion of the pedestal. For each mode, the participant received instructions for three different routes in an imaginary office building. Each route consisted of five different left or right turns and two landmarks/cues. A total of 95 feet was randomly distributed into four distance chunks with the constraint that all distance chunks were at least 10 feet long and one chunk was always greater than or equal to 40 feet. An example of one route is given below:

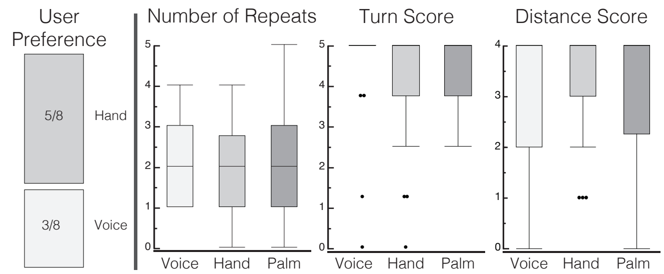

Figure 3. The distribution of participants' preferences, number of repeats, and number of turns and distances recalled correctly.

(1) Turn right, walk for 15 feet.

(2) Turn left, walk for 45 feet until the end of the hallway.

(3) Turn right, walk 20 feet until you reach the water fountain which will be at your left.

(4) Turn left, walk 15 feet.

(5) Your destination, Washington room, is to the right of you.

During the interactions, participants could ask the robot to repeat the previous step. Participants could also use the same method at the end to repeat the navigation directions from the beginning. Participants were allowed to repeat the directions as many times as they wanted. After the participants ended the interaction for each destination, the experimenter asked them to recall all the information they could remember (turns, distances, and landmarks/cues). Upon completion of each mode, we conducted a semi-structured interview with the participant to gain feedback on that specific mode. We conducted another semi-structured interview at the end of the session to reflect on the differences among the modes and obtain participants' general thoughts and feelings about robots.

Results

We recruited 8 blind participants (4 female, 4 male) who had not participated in the feature exploration study using word of mouth and mailing lists. Participants' ages ranged from 34 to 73 years with a mean of 56.13 ($SD: 14.47$) (Table 2).

Objective results

Overall, a majority of the participants preferred the *Hand* mode. Five out of the eight participants most preferred the *Hand* mode, while the remaining three preferred the *Voice* mode. None of the participants preferred the *Palm* method, and it was rated least likable by most of the participants when they reflected back on the different methods they experienced.

In terms of performance, participants were able to recall all of the information in most cases (Figure 3). In the *Voice* mode, participants recalled 4.6 ($SD: 1.0$) of the 5 turns and 3.1 ($SD: 1.2$) of the 4 distances on average. In the *Hand* mode, participants recalled 4.3 ($SD: 1.2$) of the turns and

ID	Age	Gender	Eyesight	Onset Age	Navigation Aid	Method 1	Method 2	Method 3	Preference
P101	70	M	Blind	Since Birth	Cane	Voice	Hand	Palm	Hand
P102	55	M	Blind	Since Birth	Cane	Hand	Palm	Voice	Hand
P103	45	F	Blind	Since Birth	Dog	Palm	Hand	Voice	Hand
P104	43	M	Legally Blind	Since Birth	Dog	Voice	Palm	Hand	Hand
P105	70	F	Blind	Since Birth	Cane	Hand	Voice	Palm	Voice
P106	73	F	Blind	Since Birth	Cane	Palm	Voice	Hand	Voice
P107	59	M	Legally Blind	Later in Life	Cane	Voice	Hand	Palm	Voice
P108	34	F	Blind	Since Birth	Dog	Palm	Hand	Voice	Hand

Table 2. Participant Demographics, Method Order and Preference

3.4 $(SD: 1.1)$ of the distances. Lastly, in the *Palm* method, participants recalled 4.7 $(SD: 0.6)$ of the turns and 3.2 (1.3) of the distances. An exploratory statistical analysis found no significant differences in recall among the modes. However, this could be driven by a small sample size and ceiling effects.

Participants rarely asked the system to repeat a previous instruction during a route. Some participants mentioned that they did not realize that they could ask for repetitions *during* the route despite the instructions or that they chose not to because they were worried it would confuse them. However, in most cases, participants asked the robot to repeat the instructions from the beginning upon reaching the end of the route. In the *Voice* mode, participants asked for repetition 2.0 $(SD: 1.0)$ times on average, with a range of 1 to 4 times. In the *Hand* mode, participants repeated 1.8 $(SD: 1.1)$ times with a range of 0 to 4 times. Participants repeated on average 2.0 $(SD: 1.2)$ times in the *Palm* mode with a range of 0 to 5. These results indicate no obvious difference across modes for repetitions.

We also wanted to know whether participants had prior familiarity with the Palm Drawing technique used by some O&M experts. Among the eight participants, six participants were unfamiliar with the technique. The remaining two had experienced the technique with O&M experts before. Of these, one did not remember it being helpful, and the other said that it was useful when done successfully.

Qualitative findings

To better understand how participants actually perceived our system and why participants preferred the *Hand* mode, we analyzed the interview data from our study. We analyzed our data using Affinity Diagramming [27, 28], in which common themes are drawn out from a set of qualitative data. We used this method instead of a more structured one (e.g., grounded theory) because our work is exploratory and not an attempt to form rigorous theory. We first extracted relevant quotes and key points from the interviews and sorted them into groups using affinity diagrams. These groups were then condensed into higher-level themes, which we discuss in the remainder of this section.

Distractions from verbal instructions

Feedback we received in the initial exploration suggested that the physical movements were distracting and took away some focus from the verbal instructions. We found that this trend continued in the *Palm* mode in the second exploration study but was less of an issue in the *Hand* mode.

Distraction in palm mode – Most participants found the movements by the robot on their palm to be distracting. When we probed why, some participants mentioned they felt the movement of the robot finger did not match the verbal instructions. For exmaple, P108 felt that there was always a delay in the drawing of the path on the palm and that the movement was always “a step behind”. Others made remarks about the motions not aligning with the verbal instructions.

> P105: “Sometimes it felt like the verbal instructions that it was saying, it felt like, the action on my the palm was the opposite of what I should do. Maybe it wasn’t, but that’s what it felt like, I couldn’t seem to reconcile sometimes.”

> P101: “The direction sort of shifts at the hand and you sort of have to pay attention to it much more so than following the arrow [hand mode].”

> P104: “I was kind of expecting her to move her hand somewhat congruently to the measurement... it didn’t feel like she was doing that either.”

Participants also had a hard time visualizing their orientation. Because participants were always facing forward when they received instructions, it was sometimes unclear which direction the robot was referencing. At least one participant noted that when the robot drew out a turn, they were not sure whether it corresponded to left or right. Together, these issues sometimes led participants to ignore the physical movement cues of the interaction and focus only on the verbal instructions.

> P107: “I already decided that I was focusing more on what I was hearing instead of what I was feeling anyway.”

> P104: “I didn’t use the hand cues at all, they confuse me.”

In short, this type of physical movement cue was unhelpful for most participants and did not provide value to the interaction.

Distraction in hand mode – Similar to the initial exploration, there were a few participants who found the physical movements of the hand to be unhelpful. These participants preferred to focus solely on the verbal instructions.

> P106: “I didn’t find, the, the turning around, the turning of the hand. I didn’t find any of the way it, it telling me, it trying to help me with the map helpful. I just needed it to talk. ”

> P105: “I like it [voice] better because I don’t have to concentrate on two things, the voice and the movement of the hand.”

Other issues in palm mode

Beyond the movements being distracting, participants had other issues such as awkward hand position and unclear movements when using the *Palm* mode.

Light touch – One of the complaints about the method was that participants did not always feel the movement of the foam "finger" on their palm. Multiple participants noted that the finger did not always touch their hand, did not apply enough pressure, and sometimes even fell off the edge of their hand. The soft contact and imprecise robot hand positioning could have contributed to the negative experiences in this mode.

> P101: "At times, the turn was not so detectable"

> P103: "I didn't feel her drawing on my hand as much as she... said she was, that could have been the way my hand was positioned. 'Cause I noticed sometimes she was right at the edge of my palm. So, I didn't always feel the drawing."

Awkward position – Participants also found placing their hand in the designated position to be awkward. Some participants tolerated having their hand in the position for a short period of time even though it was an unnatural position.

> P105:"You had to hold so still, that's what, what I didn't like it. And the fact that you have to turn your palm up, it's not the natural way you hold your wrist."

> P107: "It was fine, I won't want to keep it that way long term. You know, for the period of time of the interaction, it was fine."

Participants also brainstormed other positions in which they could place their hand without having to aim their palm upwards. Some suggested having the palm facing down, or holding their hand up sideways like a handshake. We had chosen to face the hand upwards to match how O&M experts did this task and to omit the need for mental rotation.

> P103: "I think your hand should be faced down 'cause it's more natural of a position for the person's arm to lay this way, like on the table than it is to do that."

We attempted to ensure that the pedestal was positioned at a comfortable height for each participant's arm at the beginning of this mode. Even while resting on the pedestal, the requirement to constantly have an arm outstretched with the palm up may still be too uncomfortable.

Potential – We asked participants whether they felt the drawing in the palm mode would have value in the future, if working correctly. Some participants described the potential benefit if the mode worked correctly, while others were skeptical of even an ideal implementation of the method.

> P108: "Because it's kind of trying to draw a primitive map in your head. You know, demonstrating on your palm."

> P106: "It is not going to make any sense if something draws on me. ... Have something touch me and do something, it doesn't work, it doesn't give me any information. It's cool the robot could do that, but it didn't help me in any way."

Value of hand mode

Participants had more praise for the *Hand* mode in the second exploration study than in the feature exploration study.

Enhancing verbal – Multiple participants reflected that the movement and rotation of the hand helped them remember the instructions better.

> P102: "I would think having the tactile direction pointer, it can help reinforce the direction of travel."

When asked about *how* the tactile interaction helped to reinforce the verbal instructions, participants said that they received reinforcement of the direction information from the physical movements of the hand and that the movements helped them form a mental image of the path.

> P101: "You are getting verbal instructions reinforced by the turn of the arrow [the ridge]. So, I think that's what would be most helpful for me."

> P108: "It was easier for me to kind of put a map in my head, as to, okay, I go to the lobby, make a right. I can picture that right."

Difference in distance – One aspect that we identified as a strength of the physical translation motions was that they were able to communicate the differences in distance between different steps (i.e., "go 20 feet" was paired with a larger movement along the horizontal axis than "go 10 feet"). We did not explicitly describe this functionality to the participants, but some participants noticed and found it to be useful.

> P107: "The movement like to signify a long distance versus short distance, I think was helpful."

Participants also used the distance differences to remember the change in number of feet. P105 described using this information as cues to remember which path was longer even if they did not remember the exact number of feet.

> P105: "If I would think like the third movement, saying, then I would think that's longer than the second one, so that's more feet. Even if I don't know the exact number of feet, I would know one is more or less, like the first one was more than the second one or less than the second one or whatever, and try figure out that way too."

Remaining issues in hand mode

Even though many participants liked the *Hand* mode, they pointed to aspects of the interaction that could be removed and to concerns about how this system might be used in real life.

Twisting gesture – In the second iteration, we added a movement in which the robot would slightly twist its hand as it described landmarks and cues. We hoped that the extra twisting movement would be helpful in reinforcing the cues and landmarks. Participants in fact found the twisting gestures to be unhelpful, and one participant forgot that the movement had happened until the interviewer asked about it.

> P107: "I'm not sure the wiggle back and forth ... I don't know, that was necessary, all that helpful from the robot other than just a verbal command."

P108 pointed out in the interview that it was confusing for her because the movement was similar to the rotation that signified the turn. She was confused about whether the twist was meant to communicate additional information about landmarks.

> P108: "If I didn't know it was going to twist like that. I would think why is it twisting like that, is it telling me the landmark is to the right, is it telling me the landmark is to the left, where is this landmark?"

The sentiment was shared by P103, who suggested an alternative movement: instead of extra twisting, the robot could move its hand up and down so that the landmark-identifying rotations would not be confused with turn-identifying rotations.

> P103: "Up and down would be a completely different signal and you couldn't get it confused with the directions."

Familiarization with system – In our study, the experimenter introduced each mode and also provided a detailed explanation about what each mode did. It was particularly important to point out the meaning of the ridge of the handle (orientation of the user along the route), the tip (meant to function like a finger), and that the rotations were always relative to the direction the user would be facing at the current point along the route. Participants appreciated these detailed explanations, but they were concerned that they might not be intuitive for users without an introduction to the system.

> P107: "[The ridge signalling the orientation] would be confusing if someone walking up to it cold did not get that kind of explanation [from the experimenter]."

> P108: "If I have never came across this robot, I wouldn't fully understand why the ridge was facing me. I can see how that could be confusing."

This points towards a need to further explore how the robot should introduce this method when it interacts with people in public. We also saw in the *Palm* mode and the feature exploration study that a system that is confusing to participants can go beyond being unhelpful and actually distract users, making it harder for them to remember the verbal instructions.

Remaining issues in verbal instructions

Instruction clarity – In general, participants found the verbal instructions to be clear and natural. No participant experienced any difficulty in understanding the utterances of the robot. When participants provided their feedback, the only suggestion they had was adding options to customize the speech in future versions of the system. Participants were concerned that if they were using this system in a public space, they might not able to hear the voice and would prefer to be able to change the volume or voice type during the interactions.

> P102: "[The voice] was fine ... Thinking about real life situations, might there be a need to control volumes and voice speed, voice rate?"

Distance – The most common comment we got from participants was about the decision to use feet as a distance measure. Multiple participants expressed that they are unable to distinguish the differences between the different distances in feet.

> P103: "If someone tells me to take 10 feet or 50 feet, I'm not good at measuring that."

However, participants did not universally agree on any alternative. When presented with the option to replace feet with time or steps instead, some said that they do not count steps either, or that such measures depend on individuals' walking speeds, which vary from person to person and from day to day for the same person.

> P106: "Step is useless ... My strides are different lengths depending on how confident I am. The more confident I am, the longer my stride is."

Some participants also suggested grouping the distances, or providing distance measurements only for long hallways.

> P101: "I think in terms of long, short hallways instead of 15, 20 feet."

Others appreciated the use of landmarks for when to turn; this information was an effective supplement to the directions.

> P102: "You covered floor surfaces changes, physical objects, such as drinking fountains, and openings. Giving reference points at the point of turns, I think helps."

Participants also expressed uncertainty, however, when presented with the possibility of directions that only referred to landmarks and did not quantify distances. P104 also noted there might be routes that do not have specific landmarks.

General perceptions of a robot kiosk

We asked participants to reflect on their impressions of robot kiosks in general, and we inquired as to whether they believed they might be able to use them outside the lab in their daily lives. They saw great promise in robotic technologies broadly. Specific factors that contributed to the belief that robots could support independence in daily life were (1) that robots can give very detailed and specific instructions and (2) that robots do not become offended or annoyed by requests for repetition.

> P106: "[The robot] will repeat, it doesn't get impatient with you, it doesn't say 'I told you' such and such. ... It has no sense of frustration with a human."

> P105: "I think they'd be good in buildings because you could get the route, even if you didn't totally remember it all, you might remember enough that you get closer to what you want, and then when you ask somebody, you'll be more likely to get good directions than if you ask somebody at the very beginning when you are further away from your destination."

One of the main concerns of our participants about using robot technology in public places, such as malls and airports, is the need for users to locate the robot upon arrival.

> P105: "How close to the robot do you have to get before it will speak to you?"

To address this, participants suggested using beacons, lights, and mobile apps to help guide people to the robot.

DISCUSSION

Transfer of the Navigation Technique to Robots

The fact that most participants preferred the *Hand* mode in the second exploration study suggests that taking inspiration from techniques used by O&M experts is a viable starting point for designing direction-giving capabilities into stationary robots. While human techniques did not effectively transfer directly given the robot's constraints on small movements, we were able to design new interactions that rely on similar psychological fundamentals (e.g., providing spatial cues to indicate movements and turns). Most of the participants found the physical movements helpful in reinforcing the verbal instructions. A question that remains after both studies is whether an improved implementation of the *Palm* mode would yield better results.

Mechanical and software limitations prevented us from implementing a precise palm-drawing technique. Our robot platform had inaccurate motors and any movement could have an error of $\pm 5mm$, which made it challenging to make fine, dexterous movements on a person's palm. This was further complicated by human palms being uneven surfaces and by the participants placing their hands in different positions and orientations. To be in constant contact with the palm, a robot would need to be able to execute fine movements, sense accurate distances to the palm, and have a control system that is refined enough to execute precise movements. While creating such a system could be feasible with current technology and hardware, it is likely to cost significantly more and be more specialized than general purpose kiosk robots.

Our alternative method, the *Hand* mode, showed that it is possible to modify existing human-human interaction techniques to provide similar benefits using an affordable robot. It is relatively common in human-robot interaction to successfully adapt human skills to accommodate and leverage robot characteristics (e.g., [34]). *Hand* mode appears to be another example, given that many participants preferred this human-inspired design that works around robot limitations while leveraging robot capabilities.

Road to Deployment

Participants were generally positive about idea of deployment of this system in public and looked forward to using the functionality. They noted two key strengths of using a robot to assist blind people with navigation: robots can give precise instructions and will not get impatient. However, we believe there are still two major interaction barriers to overcome: (1) **Introduction & Familiarization** and (2) **Usefulness**.

Introduction & familiarization – Using physical movements to reinforce verbal instructions is not a common practice. This is evidenced by our participants' lack of familiarity with the Palm Drawing method used by O&M experts. Participants were also concerned about the complexity of the *Hand* mode; they were worried about needing to be aware of orientation and understanding the meaning of the ridge on the handle. This type of introduction is probably not challenging since the one we provided at the start of each mode was sufficient. None of the participants were confused or asked questions about the instructions once they started the interaction. Future work is needed to further explore how a robot can self-explain functionality without a human present to answer questions and address issues [33]. Concern about explanations when using the robot in public also surfaced in our interview with P108, who said that she would prefer the *Voice* mode in multi-story buildings, such as a mall, because she was uncertain about the cues robots would use to supplement verbal instructions for going up or down a floor.

Usefulness – Our findings for the *Hand* mode showed no obvious benefit or excessive distraction. Yet, a majority of the participants preferred this mode over the *Voice* mode, thereby demonstrating some value to end users. This aligns with the Principles of Universal Design [37], which emphasize the value of redundant information in perceptible forms. In this regard, our exploration suggests that physical gestures by kiosk robots can provide value to people who are blind.

It is worth commenting on our choice to limit the number of turns to five and not walk the route. Five turns is a realistic approach because it is within the range of what a person can be expected to recall [32]. Longer or more complex routes are probably better served by smartphone apps that can track progress and provide each step as needed or by mobile robots. Likewise, there are questions about the ability of people to recall directions over longer durations. Because this was an initial exploration, we did not have participants travel the paths. We were only interested in the user experience and whether there is benefit in this class of interactions. Future work should explore these memory recall issues in more complex and realistic scenarios. This would allow a more comprehensive and objective assessment of our approach's navigation benefit.

CONCLUSION

This paper documents our explorations of how a robot making physical movements inspired by a Palm Drawing technique used by O&M experts can help blind participants remember navigation directions. Our two exploratory studies illustrate the challenges in implementing such interactions yet show potential promise for this kind of assistance. We developed a technique where a user holds onto a robot hand to feel turn-by-turn gestures concurrent with matching verbal instructions. This technique was preferred by 5 of 8 participants, and appears to be worth pursuing in future robot deployments.

Our work also illustrates that human-robot interactions loosely based on human-human interactions can be more successful than implementing completely faithful recreations. We also show that it is possible to leverage general purpose kiosk robots to support people with disabilities.

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