Enabling Building Service Robots to Guide Blind People

A Participatory Design Approach

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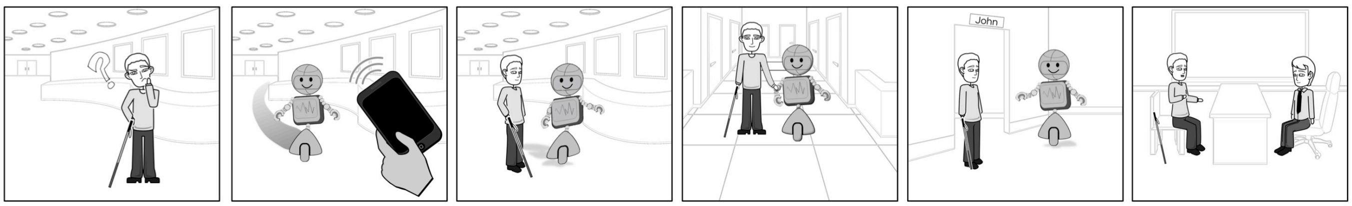

Fig. 1. A sample interaction between a user and a building service robot according to our design. (a) A user enters a building. (b) The user summons the robot with a mobile application. (c) The robot approaches and the user says he would like assistance finding John's office. (d) After the user selects an assistance mode, the robot guides the user through the building in the Sighted Guide mode. (e) The user and the robot reach the user's destination. The robot describes the room ("there is a large desk in the center with an empty chair straight ahead"), and the user dismisses the robot. (f) The user finds a chair and meets with John.

Building service robots—robots that perform various services in buildings—are becoming more common in large buildings such as hotels and stores. We aim to leverage such robots to serve as guides for blind people. In this paper, we sought to design specifications that detail *how* a building service robot could interact with and guide a blind person through a building in an effective and socially acceptable way. We conducted participatory design sessions with three designers and five non-designers. Two of the designers and all of the non-designers had a vision disability. Primary features of the design include allowing the user to (1) summon the robot after entering the building, (2) choose from three modes of assistance (Sighted Guide, Escort, and Information Kiosk), and (3) receive information about the building's layout from the robot. We conclude with a discussion of themes and a reflection about our design process that can benefit robot design for blind people in general.

Keywords—Robots, accessibility, blind, participatory design.

I. Introduction

Robots that provide various services in large buildings, or *building service robots* (BSRs), are becoming increasingly popular. Commercially available robots are fetching and delivering items in hospitals [1, 32] and hotels [20, 37], and greeting and guiding people in large stores [19, 27] or shopping malls [35]. These robots share certain features: they are autonomous, mobile, and at least three feet tall; they know how to find their way to specified locations in their buildings and can navigate through crowded spaces to get there. Given these features and the increasing popularity of BSRs, we wondered whether we could leverage such a technology to address the important open problem of indoor navigation for blind people.

Many researchers have attempted to address the challenge of indoor navigation, but no solutions have been widely adopted. Researchers have focused on the technical challenges of localizing the user and routing her down hallways and around obstacles. Most researchers attempted to address these challenges by adding infrastructure to an indoor environment, such as RFID tags [9, 43, 44] or other technologies [10, 31, 34]. It seems unlikely that such techniques will be adopted broadly to solve accessibility problems. Adding infrastructure requires an investment in resources that without legal intervention, will probably not be adopted broadly to support a relatively small and marginalized group of people with disabilities. Blind people currently resort to finding their way in unfamiliar buildings by asking sighted people for assistance.

To leverage BSRs effectively for indoor navigation, we sought to understand blind people's needs and preferences, and together design interactions and behavior for a BSR guide. While BSRs are technically sophisticated enough to interact with a blind person and guide her to a specified location, there are no known design specifications that detail *how* a robot should do this in a helpful and socially-acceptable way. For example, how should a BSR approach a blind person? What kind of feedback should a BSR provide while guiding a blind person through a building? How should a BSR interact with bystanders when guiding a blind person? In this paper, we aim to answer these questions.

We used *participatory design* [21, 36], a method where a system is designed collaboratively by designers and target users. Our design team consisted of three designers and five non-designers. Two of the designers had vision impairments, so members of our team had overlapping experiences. We created the design over multiple sessions: an interview between a designer and each non-designer, a group workshop, and an individual session with each non-designer and a robot.

Throughout the sessions, we specified how the robot should initiate contact with a blind user, guide the user to her destination, and conclude its interaction with the user (see Fig. 1). The design team specified three modes of guidance to a destination: *Sighted Guide*, where the user holds the robot as the robot leads the way; *Escort*, where the user and robot walk side-by-side; and *Information Kiosk,* where the robot provides specific directions without accompanying the user.

In summary, this paper contributes a design for a BSR that can help blind people navigate indoors [1]. The design is expressed through a discussion of needs, concerns, and recommendations. Our work will enable robot designers and developers to leverage mainstream robots to solve an important accessibility problem.

II. RELATED WORK

We draw on two areas of related work: research on indoor navigation technology and research on robots that serve blind people. While there has been a lot of research in both areas, our work differs in two key ways. First, we are the first to conduct *participatory design* of robot interaction with blind people, presenting bind people's needs and preferences. Prior work has merely evaluated technology with (a limited set) of blind people and has focused largely on addressing technical challenges in navigation. Second, we are the first to present a design for a BSR, instead of a personal robot. BSRs usually have certain features and constraints that personal robots do not.

Indoor navigation for people with and without disabilities has been an active area of research over the past two decades. This research has focused on identifying the user's location, and detecting and avoiding obstacles. Most researchers have attempted to address this problem by adding some infrastructure to the indoor environment. Long *et al*. [26], Butz *et al.* [8], and Mulloni *et al.* [31] presented examples of systems for the general population that instrumented the environment. Long *et al.* and Butz *et al.* presented systems where users' handheld devices communicated with beacons placed in the environment. Mullen presented a system where users captured images of fiducial markings with off-the-shelf cameras.

A large body of work has focused on indoor navigation systems for blind people. These systems determined the user's location and provided audio wayfinding instructions to guide a user to a destination. Kulyukin [22, 23] presented a robot guide that helped blind people wayfind indoors with RFID tags in the environment. The user of Kulyukin's robot guide system held the robot with a dog leash in addition to their mobility aid, receiving audio and tactile feedback. This work motivates ours: researchers believe that robots would be effective tools for indoor navigation, but they paid little to no attention to the design of the human-robot interaction. While Kulyukin *et al*. evaluated their system with five blind participants, blind people were not involved in early stages of the design process and there was little discussion of how the robot behaved and interacted with users. In 2004, Ran *et al.* presented Drishti [34], an indoor and outdoor navigation system that used an ultrasound positioning system to enable precise indoor navigation. The user wore sensors that communicated with beacons that were placed around a building. Drishti provided walking directions to a destination and alerted users to obstacles in their path. Many subsequent projects developed systems where the environment was marked with RFID tags [9, 11, 22, 43, 44]. Unlike prior work, our work leverages BSRs instead of augmenting an environment to solve an accessibility problem.

Golding *et al.* [15] proposed an indoor navigation system for blind people that, like our approach, did not require changes to the environment. Their system included a variety of wearable sensors, such as temperature sensors and florescent light sensors. They used data from the sensors to build a model of the indoor environment and localize the user. This system thus required users to train the system by walking around a building. A robot guide may need training as well, but we focus on designing the robot's behavior and interaction with the user rather than the technical challenge of learning an indoor environment.

In addition to providing routing instructions, researchers have attempted to replace a standard mobility aid with an electronic device. Shoval *et al.* described GuideCane [40, 42], a handheld device that, attempting to replace a white cane, used robotic obstacle detection and avoidance methods. Faria *et al.* [13], Hub *et al.* [18], and Aigner and McCarragher [2] also proposed electronic devices designed to detect obstacles and replace a white cane or guide dog. Lacey and Dawson-Howe [24, 25] developed PAM-AID, a smart walker for older adults with vision loss. The walker automatically avoided obstacles and moved along walls but did not provide wayfinding instructions. In contrast, we design a robot guide that walks with the user, replacing a sighted guide but not a cane or a guide dog.

Informing our work, several projects explored user requirements and techniques for gaining information about their environment [3, 4, 6, 29]. Montague discussed a mobile interface for an indoor wayfinding application for people with different disabilities [29]. He found that people give three types of feedback when giving routing instructions: preparation, decision, and confirmation. Montague's work complements ours, but we go into much more detail about the kinds of directions blind people prefer. Hersh *et al.* [16, 17] conducted an extensive survey to explore blind and low-vision people's attitudes and preferences towards having a personal robotic mobility aid. Unlike our design, they proposed a portable personal system that people would own and travel with in their daily lives. They found that people were receptive to the idea, motivating our work.

[1] We presented a brief summary of this work in a late breaking report [14].

Table 1. Descriptions of non-designers in our design team.

ID	Age/Sex	Vision	Mobility Aid	Occupation
ND1	38/m	Legally blind, no central vision, peripheral vision intact, reads large print	None	Administrative assistant
ND2	36/m	No functional vision	Cane	Rehabilitation teacher for blind people
ND3	53/f	Legally blind, sees "about 10 percent," doesn't read large print	Cane	Accessibility manager
ND4	32/m	No functional vision, light perception.	Cane	Assistive technology specialist
ND5	36/f	No functional vision	Cane	Tax collection call representative

Table 2. Descriptions of designers in our design team.

ID	Age/Sex	Vision	Mobility Aid	Occupation
D1	30/f	Low-vision, can read large print	None	Human-computer interaction researcher
D2	24/f	No functional vision	Cane	Human-computer interaction researcher
D3	31/f	Sighted	None	Human-robot interaction researcher

III. METHOD

We used participatory design (PD) [36] to design the behavior of a robot guide. In PD, all stakeholders (*e.g.*, employees, customers) are involved in the design of a system. The goal of PD has traditionally been to improve the user or worker experience rather than advance technology. Over the last two decades, PD has evolved into a practice where designers and non-designers of different backgrounds and interests collaborate on design activities throughout the design process [36]. It has been used by HCI researchers with a variety of non-designer populations, including children [30], older adults [12], and people with disabilities [28]. In our work, two of the three designers had disabilities as well, so there was diversity and overlap of perspectives among members of the design team.

A. Design Team

We created a design team made up of three designers (Ds) and five non-designers (NDs) with varying visual abilities (see Table 1 and Table 2). A "designer" was someone with a background in technology research and design (i.e., one of the researchers on this project), and a "non-designer" was a target user who did not have a background in technology research or design. Two of the designers were also target users: one had no functional vision and the other had low-vision. The designers' expertise were human-computer interaction and human-robot interaction.

We recruited the five non-designers (2 females, 3 males), with an average age of 39 (age range: 32–53) through word-of-mouth. They were all legally blind professionals who used mobile devices, desktop computers, and various specialized assistive technologies on a regular basis. None of them had experience designing or developing technology. All but one used a cane. Unfortunately, we were unable to recruit a non-designer who had a guide dog.

B. Procedure

We conducted three kinds of sessions to formulate our design: (1) a 30-minute one-on-one interview conducted by a designer with each non-designer, (2) a group brainstorm and discussion session with all non-designers and two designers, and (3) individual design sessions with a robot, performed by a designer and each of the non-designers. Interviews were conducted remotely and all other sessions were conducted in a university lab containing the robot.

In the 30-minute interview, our goals were to (1) describe the structure of the project, (2) describe the robot's assumed capabilities and our design space, and (3) probe the non-designer for ideas. It was important to probe the non-designers individually before coming together in the group session where they were likely to converge on ideas [36]. We also asked the non-designers to describe the challenges they experienced when navigating indoors and strategies used to address these challenges.

The goal of the group session was to develop a conceptual storyboard that described the interactions between the robot guide and the user, from the time they met to the time they separated. In the beginning of the session, the team felt the robot to understand its form and reviewed its capabilities and the project's assumptions. The team then sat around a table to formulate the storyboard. Because most members of the team were blind, it was not possible to create a visual storyboard, as is common in group design sessions. Instead, the designers took notes and guided the discussion with high level questions. For example, the designers asked, how will the robot and the blind person connect? How should the robot guide the person? What kind of feedback should the robot provide while it's guiding the person? What should the robot do when reaching a destination?

The goal of the third session was to develop low-level specifications for how the robot should behave when guiding the user. We wanted to answer questions such as: How should the robot move when guiding the user through a doorway? What should the robot do when approaching and passing a turn or an obstacle in the path? When exactly should the robot give feedback when approaching a turn or obstacle in a hallway?

When walking with a sighted guide, these low-level behaviors would probably feel natural to the blind members of our team. We thought they would likely leave out such details that would be important specifications. We therefore used a method inspired by contextual inquiry, which aims to elicit a user's tacit knowledge. We asked each non-designer to walk with a human who acted as a naïve sighted guide. The human guided the non-designer down a hallway, around a corner, past an obstacle, past a group of people, to an elevator, up an elevator, and through a doorway. Throughout this process, we asked and noted the non-designer's preferences and instructions to the sighted guide, asking probing and clarifying questions.

We concluded each session by prototyping the robot's navigation method with Wizard-of-Oz, where a designer controlled the robot with a joystick and spoke for it. Throughout this process, we sought the non-designer's feedback about how to design the interaction effectively.

C. Apparatus

We used a PR2 [33].in our study. We chose to use the PR2 because it shared features with current BSRs (and we did not have access to a more appropriate robot). Like the TUG [1] and Savioke [37], the PR2 was mobile, it could rotate, and it was more than three feet tall. Like Japanese hotel and department store robots [19, 20], the PR2 spoke and had arms. We asked the team to focus on these features and assume that the robot knew the building's layout and could navigate around obstacles. We also instructed the team to assume that the robot could perform tasks like reading signs and engaging in simple dialog, which were technically possible and likely to be implemented in at least some BSRs.

D. Analysis

We audio-recorded all sessions and took notes, then transcribed the recordings, coded the transcripts, and organized the codes by common themes.

IV. RESULTS

A. Use Cases for a Robot Guide

The blind members of our design team used sighted guides mostly when walking in unfamiliar buildings and in groups. One non-designer mentioned using a sighted guide to walk to meetings in unfamiliar rooms in the office building he worked in. Most team members used a sighted guide to keep up when walking with a group. Team members felt that the robot would be most useful in office buildings, shopping malls, airports, and conference centers. We focused our discussion on robots in office buildings, such as the Computer Science building at our university.

B. Robot Aesthetics

There was some concern over the robot's aesthetics but members of the design team agreed that "function" was more important than "form." ND5 showed some concern about how others perceived the robot, wondering whether the robot looked "attractive." Some team members felt strongly that it was more important for the robot to be able to navigate through narrow passages and walk up stairs than be attractive. The rest of the team eventually agreed with this sentiment. ND4 said the robot needs to be versatile, and he didn't mind whether "it looks like a fridge or a person."

C. Initiating Contact

The team discussed how the robot and the user would find each other when the user entered a building. One of the designers proposed that the robot detect and approach people who entered the building with a mobility aid to see whether they needed assistance. The rest of the team dismissed this design for two reasons. First, not all blind and low vision people use a mobility aid (ND1 and D1 are examples) and, second, a person with a mobility aid may not require assistance. A robot that singled out a person with a mobility aid may be perceived as paternalistic or simply annoying.

The team decided that the user should be able to (1) find out whether there was a robot in the building, and (2) summon the robot to her current location. It was important that the design enabled users to be spontaneous—that it would not require them, for example, to reserve the robot in advance. Since many blind people are avid smartphone users, the team decided that the user and robot could make contact through a smartphone application. When the user entered a building, she would launch the application on her smartphone, check whether a guide robot was available, and summon the robot to her location. More generally, the robot should enable a user to summon it through a mainstream device, without having to plan in advance.

I don't plan my life around appointments too well, so I'm probably not going to call a day ahead for the robot—I just won't use the robot. So I need to know if I get to the building and I pop the app and, oh awesome, they have an Assistance2000, I can push a button and it'll show up... come right over or somehow find me and try and get my signal from my phone. (ND4, male, 32 years old)

After the robot approaches the user, it should engage the user in a dialog (similar to the Lowe's robot [41]). Members of the team said the robot should be "friendly" and act "like a receptionist." It should ask the user, "how can I help you? I can do the following things…" ND2 felt that the user should be in control of the interaction; the robot should describe the different kinds of assistance it can offer, allowing the user to customize her experience.

When it says, "how can I help you?" then I think it's up to us [the users] to say I'm blind and I need, you know, assistance in finding a certain place. Or I'm blind and need some information about... (ND2, m, 36)

D. Mode of Assistance

Team members designed three modes of assistance that would address people with different levels of vision and familiarity with the building. They noted that blind people have a wide range of vision abilities and mobility skills.

Information Kiosk. In this mode of assistance, the robot would only provide information and routing instructions, without accompanying the user to a destination. The information kiosk would be especially useful for people who were somewhat familiar with the environment or people who were trying to learn more about a building's layout. This mode does not require a robot, but it leverages the robot's knowledge of the environment and ability to make contact with a person who needs assistance.

Escort. In this mode, the robot would guide the user to a destination by walking next to or slightly ahead of the user, without direct contact. This mode is likely to be more appealing to people with low vision than the sighted guide mode. ND2 and D1, who have functional vision, found this mode especially useful. While half of our design team had no functional vision, low vision is much more common than lack of functional vision, so this mode is important.

Sighted guide. This mode emulates a human sighted guide [7]. The robot guides the user to her destination by walking next to and slightly in front of the user. The user lightly touches the robot, like she would touch the back of a person's elbow. This mode would be useful in situations where a sighted guide is useful: for people who have little to no functional vision, in crowded environments, and in unfamiliar places.

E. Holding the Robot

The design team explored ways in which the user could hold the robot in Sighted Guide Mode. When interacting with the PR2, members of the design team had difficulty finding the robot's elbow and holding onto it while walking. Unlike a human elbow, the PR2's arms were in front of its torso instead of beside it. Moreover, the robot's arms were thick and difficult to grasp. While we were not designing specifically for the PR2, these challenges could also arise when working with other robots.

Team members tried holding other parts of the robot's body and decided that its shoulder would be best, but not ideal. The shoulder was appropriately located on the side of the robot but was still difficult to find. How would a blind user find the robot's shoulder when she was not familiar with the robot's build? Several of the team members suggested that the robot take the user's hand and guide it to a convenient contact point. Sometimes, they pointed out, a sighted guide would direct a blind person's hand to her elbow by lightly touching the blind person's hand with her own hand to provide a point of reference. ND5 suggested adding tactile markers to the robot that would converge on the elbow's shoulder. However, this would require custom modifications to the robot. If the robot did not have arms or shoulders (*e.g.*, a TUG robot [1]), it could describe its shape and suggest a contact point.

While walking with a user in Sighted Guide Mode, the robot should adjust its pace according to the user. At the very least, the robot should respond to the user's requests to slow down or speed up. If the robot can sense the user's touch, it should stop moving if the user lets go of it. Moreover, the robot should also sense whether the user was pushing or pulling against the robot at the contact point, adjusting its pace according to this feedback, if possible.

F. Routing Instructions

In the Information Kiosk mode, the design team said that the robot should give the user directions that were specific and "quantitative." For example, "walk down the hall, and the room you're looking for will be the third door on your right." If the route involved stairs, participants wanted to know how many flights of stairs but not how many stairs. The robot should use landmarks that are accessible to blind people, such as audible or tactile cues (a water fountain, coffee bar, or the edge of a carpet).

D2 and ND3 wanted the robot to give cardinal directions as well. Other team members said that many blind people (and many people in general) find it difficult to navigate with cardinal directions, but they agreed it should be an option. D2 said that cardinal directions would be especially useful if the robot gave a point of reference, such as "you just walked in the East door."

The robot should verbally direct the user when walking in Sighted Guide and Escort mode. These directions should be brief, and refer to upcoming turns or obstacles in the path. We discuss these directions further in subsequent sections.

When giving verbal feedback throughout the user's interaction with the robot, the robot should speak in an appropriate volume (as in "natural conversation") so as not to disrupt others or attract extra attention. ND4 suggested the robot should project its speech towards the user, even when walking beside and slightly in front of the user.

G. Choosing a Path

The robot should ask the user, if relevant, whether she prefers to use the stairs or the elevator in all assistance modes. People often assume that blind people can't walk up and down stairs, so they lead them to an elevator. ND4 felt this assumption was demeaning.

[Taking the stairs or elevator] should be presented as an option. Sometimes nowadays, like we were talking about human guides, an automatic assumption is made that you would want an elevator. Like if you go to the airport, you have a cane, you're being helped... they're not going to lead you to the top of the escalator. Next thing you know, you're going around a corner, down a hallway by an elevator because there's this engrained assumption that we can't [walk down stairs]. (ND4, m, 32)

ND4 explained that he wanted the robot to be able to guide him along "mainstream traffic" routes, instead of going down "weird elevators." Other team members agreed with ND4's sentiment. Current BSRs do not climb stairs and would have to guide participants to elevators, but this is likely to change in the future.

H. Approaching Turns and Obstacles

In both the Sighted Guide mode and the Escort mode, the robot should alert the user when approaching obstacles, narrow passages (*e.g.,* doorways), changes in direction (*e.g.*, turns), or changes in the surface level (*e.g.*, stairs or ramps). The robot should tell the user what they are approaching and indicate which direction they will turn, if needed. For example, when approaching a turn, the robot should say, "approaching a left turn." When approaching an obstacle, the robot should say, "veering right to avoid an obstacle." This verbal feedback should be given about four steps before the obstacle or landmark is reached. The blind members of the team said they do not want the robot to slow down or stop.

Since the user is walking next to and slightly behind the robot in Sighted Guide and Escort modes, the robot should ensure that there is enough space for the user when traveling. When walking through narrow passages in Sighted Guide mode, the robot should position the point of contact with the user so that it is facing backwards, just like a sighted guide would move her elbow behind her. This signals the user to walk behind the robot in a single file. When prototyping the design with the PR2, we rotated the robot 90 degrees so that its shoulder was pointing backwards when walking through narrow passages.

When approaching an elevator, the robot should guide the user so that he or she is standing in front of the elevator button panel. The robot should tell the user which buttons to push.

The design team felt that the robot should behave differently when encountering people than inanimate objects. The team insisted that the robot behave in a socially appropriate manner, speaking softly but audibly and politely to the user and the people ahead. D2 wanted the robot to allow her to say, "excuse me," to the group of people herself. When discussing this design decision, the blind members of the team recalled the experience of being driven on a cart in an airport. They said the cart was loud and disruptive to other people, making the experience "embarrassing" and "demeaning."

I. Options for More Information

Team members agreed that the robot should give the user an option to receive detailed descriptions of the building in all assistance modes. For example, team members wanted the robot to tell users which rooms they were walking by: "On the right is room 120, a computer lab for undergraduate students;" "on the left are the restrooms;" "On the left is a drinking fountain." Pointing out the location of bathrooms was most important. ND3 said that descriptions of the building's layout would also be helpful, including the location of stairs or elevators.

The design team wanted the robot to ask the user whether she wants to hear extra information. The descriptions of the building and various rooms would be useful when users wanted to learn how to navigate independently in the building. If users were in a hurry or were not planning to return to the building, they would not need this information.

J. Ending Contact

In the Sighted Guide and Escort modes, the guidance session must end in some way once the user reaches her destination. At this point, the robot should guide the user to the door of the destination room, describe what the user's options are, and wait for further instructions. The user can, for instance, ask the robot to leave, or guide her to another destination.

I would like, maybe if it stopped at the door and I would initiate knocking on the door or leaning in the door and then I could say, either like "I'm good," or let's say [the person I'm visiting] is not in his office, "oh he's not here, I actually need you to show me something else." I would like the robot to not up and disappear as soon as [we get to the door]. (D2, f, 24)

Another option team members suggested was the ability to tell the robot to return to the current location in a specified amount of time. For example, if the user is attending a one-hour meeting, she would tell the robot to return in one hour to guide her back to her office.

The team members said that the robot should also be able to guide users to a seat in the destination room. When going to a conference room, ND5 wanted the robot to lead her to an empty seat and tell her where the front of the room was. Other team members said the robot should lead them to an empty or specific seat in an auditorium. If the robot was unable to lead them to a seat because, for example, it could not fit in narrow aisles or walk down stairs, team members wanted directions to their seat instead. ND3 thought directions to a seat would be more useful than guidance so she could stay within the "flow of traffic" rather than be an "obstruction."

In addition to guidance, team members wanted the robot to describe the room and point out tables with snacks or drinks. They were enthusiastic about having the robot fetch a drink or a snack for the user at the user's request, if possible. ND3 explained that these sorts of tasks can be stressful for blind people to do on their own in crowded or unfamiliar environments. D2 explained that as long as the user was *asking* the robot to complete such tasks, the interaction would support the user's sense of independence.

It is independent because you're asking the robot like what you want. You want them to do it…to me, I don't think if you ask... obviously if the robot went over there and just assumed that I wanted whatever that's different. But if I ask then I think I wouldn't feel like it was [taking away my independence] at all. (D2, f, 24)

V. DISCUSSION

In general, using a robot for indoor navigation has two main advantages. First, interacting with the robot requires minimal training from the user, who can converse with the robot and touch its elbow (or shoulder) as she would with a helpful receptionist. Second, we assume the robots will be in buildings to perform a variety of other tasks, so no special hardware or infrastructure would be needed to solve this accessibility problem. This approach requires minimal additional resources and is more likely to be broadly adopted than, for example, a system that requires adding RFID tags around a building. One limitation of our approach, on the other hand, is that it only works in cases where the robot knows the building's layout. Otherwise, the robot may offer little advantage to using a mobility aid and a smartphone.

One dominant theme in our design was having the robot provide options for the user. Initially, we expected the robot to act merely as a sighted guide (as in the Sighted Guide Mode). We didn't anticipate the different assistance modes, options to use the elevator or stairs, varying levels of detail required about the building, *etc*. The non-designers raised these issues drawing from their different visual abilities and experiences in indoor navigation scenarios.

Another important and related theme that emerged in the design was user control of the robot. The robot would not make assumptions about the user's needs. For example, the robot would not approach people with mobility aids on its own initiative and it would not assume the user needed to make contact when being guided. As long as the user was *asking* the robot to do things, the design team felt the experience was respectful and supported the user's independence. In prior work on accessible travel, Azenkot *et al.* [5] found that enhancing independence during travel was critical for making travel accessible.

The design touched on a third theme: avoiding actions that were disruptive or attracted extra attention. The team discussed the volume and tone of the robot's voice, which should be conversational and projected at the user. The design team wanted the robot to flow with traffic along hallways and in large spaces. Team members wanted to be perceived as (and felt they were) social, considerate, and competent people. As found in prior work [38, 39], they did not want to attract negative attention because of their disability.

One surprising finding was the design team's lack of concern for the robot's aesthetics. This somewhat contradicts prior research [39] that found that people with disabilities preferred assistive technology that was attractive and felt self-conscious when using unattractive technology that did not look mainstream. Our design team may have felt differently because, unlike the devices studied in prior work, our robot guide is not a personal device; it is a robot that resides in a building and is familiar to the building's inhabitants. Also, the design team was excited by the novelty of the robot, which may have overcome feelings of self-consciousness or stigma.

In our work, we used a novel PD process that we believe other researchers can adapt for different accessibility scenarios, especially those involving blind people. In retrospect, the three sessions in our process (interview, accessible group design session, and individual Wizard-of-Oz sessions with the robot) were successful in producing actionable design recommendations that were grounded by participants' experiences and concerns. Every team member contributed insights with a unique perspective, which is important since people with disabilities have diverse abilities and skills. Although there was a small number of participants, two of the non-designers were assistive technology specialists (ND2 and ND4) who represented the views of the blind community more generally. Conducting the initial individual interviews was key for generating a broad set of design ideas and discussing team members' challenges and strategies with indoor navigation. However, we recommend that researchers introduce participants to the design of several robots at the early stages of the process, to spur creativity while providing some necessary constraints.

In addition to a small number of participants, our process was also limited by the use of the PR2. There are different kinds of BSRs and the PR2 was not an ideal model for one. PR2s were designed mainly for manipulating objects and were not optimized for moving around buildings to perform various tasks, which we expect of BSRs. We tried to counter this by asking team members to focus their design on PR2 features that *were* likely to be incorporated in BSRs (such as mobility; see *Methods*). We also tried to specify designs that could work for BSRs with different levels of sophistication.

VI. CONCLUSION AND FUTURE WORK

In this paper, we have explored one approach for solving the challenge of indoor navigation for blind people: using build service robots (BSRs) as guides. We used a novel participatory design process to elicit design recommendations from a group of designers and target users who had a range of visual abilities. In the future, we will develop a prototype robot guide with a commercially available BSR (*e.g.*, [1]). We will conduct a formal evaluation of the prototype to measure its effectiveness for finding a destination, teaching the user about her environment, and supporting feelings of independence and social acceptance. We hope our work will inform and inspire robotics researchers and developers to develop BSRs that can also solve accessibility challenges.

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REFERENCES

[1] Aethon: Autonomous Mobile Robots and Tracking Solutions: *http://www.aethon.com/*. Accessed: 2015-10-05.

[2] Aigner, P. and McCarragher, B. 1999. Shared control framework applied to a robotic aid for the blind. *IEEE Control Systems Magazine*. 19, 2 (Apr. 1999), 40–46.

[3] Alkhanifer, A. and Ludi, S. 2014. Towards a situation awareness design to improve visually impaired orientation in unfamiliar buildings: Requirements elicitation study. *2014 IEEE 22nd International Requirements Engineering Conference (RE)* (Aug. 2014), 23–32.

[4] Alkhanifer, A.A. and Ludi, S. 2014. Visually impaired orientation techniques in unfamiliar indoor environments. *Proceedings of the 16th international ACM SIGACCESS conference on Computers & accessibility - ASSETS '14* (New York, New York, USA, Oct. 2014), 283–284.

[5] Azenkot, S. et al. 2011. Enhancing Independence and Safety for Blind and Deaf-Blind Public Transit Riders. *Proceedings of the 2011 annual conference on Human factors in computing systems - CHI '11* (New York, New York, USA, May 2011), 3247–3256.

[6] Banovic, N. et al. 2013. Uncovering information needs for independent spatial learning for users who are visually impaired. *Proceedings of the 15th International ACM SIGACCESS Conference on Computers and Accessibility - ASSETS '13* (New York, New York, USA, Oct. 2013), 1–8.

[7] Being a Sighted Guide: *http://www.afb.org/info/friends-and-family/etiquette/being-a-sighted-guide/235*. Accessed: 2014-09-07.

[8] Butz, A. et al. 2001. A hybrid indoor navigation system. *Proceedings of the 6th international conference on Intelligent user interfaces - IUI '01* (2001), 25–32.

[9] Chumkamon, S. et al. 2008. A blind navigation system using RFID for indoor environments. *2008 5th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology* (May 2008), 765–768.

[10] Coroama, V. 2003. The Chatty Environment - A World Explorer for the Visually Impaired. *Adjunct Proceedings of Ubicomp 2003*. (2003).

[11] D'Atri, E. et al. 2007. A system to aid blind people in the mobility: A usability test and its results. *2nd International Conference on Systems, ICONS 2007* (Apr. 2007), 35–35.

[12] Ellis, R.D. and Kurniawan, S.H. 2000. Increasing the Usability of Online Information for Older Users: A Case Study in Participatory Design. *International Journal of Human-Computer Interaction*. 12, 2 (2000), 263–276.

[13] Faria, J. et al. 2010. Electronic white cane for blind people navigation assistance. *World Automation Congress (WAC), 2010*.

[14] Feng, C. et al. 2015. Designing a Robot Guide for Blind People in Indoor Environments. *Proceedings of the Tenth Annual ACM/IEEE International Conference on Human-Robot Interaction Extended Abstracts - HRI'15 Extended Abstracts* (New York, New York, USA, Mar. 2015), 107–108.

[15] Golding, A.R. and Lesh, N. 1999. Indoor navigation using a diverse set of cheap, wearable sensors. *Digest of Papers. Third International Symposium on Wearable Computers* (1999), 29–36.

[16] Hersh, M.A. and Johnson, M.A. 2010. A robotic guide for blind people part 1: a multi-national survey of the attitudes, requirements and preferences of potential end-users. *Applied Bionics and Biomechanics*. (2010).

[17] Hersh, M.A. and Johnson, M.A. 2012. A robotic guide for blind people Part 2: Gender and national analysis of a multi-national survey and the application of the survey results and the CAT model to framing robot design specifications. *Applied Bionics and Biomechanics*. 9, 1 (2012), 29–43.

[18] Hub, A. et al. 2003. Design and development of an indoor navigation and object identification system for the blind. *ACM SIGACCESS Accessibility and Computing*. 77-78 (Sep. 2003), 147.

[19] Humanoid Robot Starts Work at Japanese Department Store - NBC News: *http://www.nbcnews.com/tech/innovation/humanoid-robot-starts-work-japanese-department-store-n345526*. Accessed: 2015-10-05.

[20] Japan's robot hotel: a dinosaur at reception, a machine for room service | World news | The Guardian: *http://www.theguardian.com/world/2015/jul/16/japans-robot-hotel-a-dinosaur-at-reception-a-machine-for-room-service*. Accessed: 2015-07-18.

[21] Kensing, F. and Blomberg, J. 1998. Participatory Design : Issues and Concerns. *Computer Supported Cooperative Work: 7*. 1993 (1998), 167–185.

[22] Kulyukin, V. et al. 2004. RFID in robot-assisted indoor navigation for the visually impaired. *2004 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (IEEE Cat. No.04CH37566)*. 2, (2004), 1979–1984.

[23] Kulyukin, V. and Nicholson, J. 2002. A Robotic Wayfinding System for the Visually Impaired. *In Proceedings of the National Conference on Artificial Intelligence* (2002), 864–869.

[24] Lacey, G. 2000. Context-Aware Shared Control of a Robot Mobility Aid for the Elderly Blind. *The International Journal of Robotics Research*. 19, 11 (Nov. 2000), 1054–1065.

[25] Lacey, G. and Dawson-Howe, K.M. 1998. The application of robotics to a mobility aid for the elderly blind. *Robotics and Autonomous Systems*. 23, 4 (1998), 245–252.

[26] Long, S. et al. 1996. Rapid prototyping of mobile context-aware applications: The cyberguide case study. *Mobicom* (1996), 97–107.

[27] Meet Lowe's New Robot Retail Workers: 2015. *http://www.businessinsider.com/lowes-new-robot-retail-worker-2014-10*. Accessed: 2015-05-08.

[28] Moffatt, K. et al. 2004. The participatory design of a sound and image enhanced daily planner for people with aphasia. *Proceedings of the SIGCHI conference on Human factors in computing systems*. (2004), 407–414.

[29] Montague, K. 2010. Accessible indoor navigation. *Proceedings of the 12th international ACM SIGACCESS conference on Computers and accessibility - ASSETS '10* (New York, New York, USA, Oct. 2010), 305.

[30] Moraveji, N. et al. 2007. Comicboarding: using comics as proxies for participatory design with children. *Proceedings of the SIGCHI …*. (2007).

[31] Mulloni, A. et al. 2009. Indoor positioning and navigation with camera phones. *IEEE Pervasive Computing* (2009), 22–31.

[32] On-Demand Delivery: *http://www.vecna.com/on-demand-delivery*. Accessed: 2014-09-22.

[33] PR2: *https://www.willowgarage.com/pages/pr2/overview*.

[34] Ran, L. et al. 2004. Drishti: An integrated indoor/outdoor blind navigation system and service. *Proceedings - Second IEEE Annual Conference on Pervasive Computing and Communications, PerCom* (2004), 23–30.

[35] Robot Guide Premiers in Shopping Mall in Spain (video) - Singularity HUB: *http://singularityhub.com/2010/08/05/robot-guide-premiers-in-shopping-mall-in-spain-video/*. Accessed: 2015-10-05.

[36] Sanders, E.B.-N. et al. 2010. A Framework for Organizing the Tools and Techniques of Participatory Design. *PDC 2010 - Proceedings of the 11th Biennial Participatory Design Conference* (New York, New York, USA, Nov. 2010), 195–198.

[37] Savioke: *http://www.savioke.com/*. Accessed: 2014-09-22.

[38] Shinohara, K. and Tenenberg, J. 2009. A blind person's interactions with technology. *Communications of the ACM*. 52, 8 (Aug. 2009), 58.

[39] Shinohara, K. and Wobbrock, J.O. 2011. In the shadow of misperception. *Proceedings of the 2011 annual conference on Human factors in computing systems - CHI '11* (New York, New York, USA, May 2011), 705.

[40] Shoval, S. et al. 2003. NavBelt and the GuideCane. *IEEE Robotics and Automation Magazine*. 10, 1 (Mar. 2003), 9–20.

[41] The Lowe's Robot and the Future of Service Work - The New Yorker: *http://www.newyorker.com/business/currency/lowes-robot-future-service-work*. Accessed: 2015-10-05.

[42] Ulrich, I. and Borenstein, J. 2001. The GuideCane-applying mobile robot technologies to assist the visually impaired. *IEEE Transactions on Systems, Man, and Cybernetics Part A:Systems and Humans.* 31, 2 (Mar. 2001), 131–136.

[43] Willis, S. and Helal, S. 2005. RFID information grid for blind navigation and wayfinding. *Proceedings - International Symposium on Wearable Computers, ISWC*. 2005, (2005), 34–37.

[44] Yelamarthi, K. et al. 2010. RFID and GPS integrated navigation system for the visually impaired. *Midwest Symposium on Circuits and Systems* (Aug. 2010), 1149–1152.