CARNEGIE MELLON UNIVERSITY

School of Architecture

College of Fine Arts

Thesis

Submitted in Partial Fulfillment of the requirements for the degree of

Master of Science in Computational Design

TITLE:

Designing For Accessible Sidewalk Robots – Insights From People With Motor Disabilities

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Designing for accessible sidewalk robots

– Insights from people with motor impairments

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Abstract:

Sidewalk robots, such as delivery robots, are becoming increasingly common worldwide, as they offer companies a more sustainable and affordable last-mile delivery service. Despite their advantages, the use of sidewalks by these robots for their operations presents challenges for other co-present sidewalk users of the shared space, especially vulnerable road users like people with motor disabilities (PWMD). These individuals have already proven to encounter more obstacles while navigating sidewalks, and the presence of sidewalk robots may exacerbate these difficulties. Therefore, there is a pressing need to investigate how the various design factors related to sidewalk robots might impact the daily navigation of people with motor disabilities. Also, as a new form of Human-robot interaction(HRI) is happening in public spaces, there is also a lack of evaluation tools to replicate the behavior of the robots and test how they alter the navigation experience of PWMD.

I approached this problem through two distinct but interrelated inquiries. Firstly, a Wizard-of-Oz (WoZ) virtual simulation tool was developed to emulate and examine HRI

between sidewalk users and delivery robots in street environments. Preliminary studies using this tool, both through video interviews and immersive virtual reality experiences, demonstrated its potential to foster meaningful design conversations. Subsequently, I conducted semi-structured interviews with ten PWMD to gain insights into their perceptions, interaction preferences, and attitudes towards the emerging presence of sidewalk robots. The qualitative analysis of these interviews led to the identification of 23 themes, clustered into three categories. These encompassed potential influences of sidewalk robots on PWMD, scenarios of interaction between PWMD and these robots, and emerging opportunities for design enhancement.

As public spaces become increasingly populated with robots, my findings argue for the necessity of more robust evaluation tools to facilitate the design of accessible sidewalk robots that align with established social norms. Virtual simulation tools can play a pivotal role in this process, complementing real-world tests and providing crucial data to inform design decisions. The insights gleaned from my research can contribute to the development of equitable deployment guidelines for sidewalk robots and inspire further investigation into the impact of emerging public robots on vulnerable populations.

Key words: Sidewalk robot, Human-robot interaction, people with motor disabilities, Design research, Virtual simulation

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1. Introduction

As service robots become more prevalent [1,2], sidewalk robots are among the newest innovations to be introduced into public sidewalks. International Federation of Robotics projecting a 40% annual growth in the use of mobile robots in public environments[1]. Several companies(e.g., FedEx, Starship(Fig 1), Uber Eats) are in the process of piloting or deploying delivery robots that traverse public sidewalks to deliver food, medicines, and other small cargo. Delivery robots are, blocking common in universities in North America. Starship already collaborates with more than 25 universities across the country to deliver food from dining halls and on-campus restaurants. At the time of writing, Starship has reached 4 million autonomous deliveries[2] . Worldwide, Japan, South Korea, China, and British are all testing and integrating sidewalk robots like delivery robots. However, when sidewalk robots like delivery robots are navigating, most people will, in fact, not be users of them but will just “happen to be there”[1]. Among the co-presenters, there will also be vulnerable road users like wheelchair users and others with motor impairments who already face more difficulties than able-bodied people. Their adaptations to understand better sharing sidewalks with robots are still unclear. In

[1] Data resource: https://ifr.org/ifr-press-releases/news/mobile-robots-revolutionize-industry
[2] Data resource: Starship Technologies (https://www.starship.xyz/company/)

2020, the Pennsylvania General Assembly enacted legislation aimed at regulating delivery robots on a state level, defining them as pedestrians[3]. Other states, like

Previous studies and pilot deployment, have implied potential conflicts between people with motor disabilities (PWMD) and micro-mobility devices[4]. Bennet et al., utilizing interviews and archival traces, found that micro-mobility deployments may underpin the development of yet more inaccessible infrastructure[5]. Additionally, the second author of the paper, a wheelchair user, experienced a life-threatening encounter with a sidewalk robot. The robot stopped on the curb cut and this blocked a safe path to cross and clear to the other side of the road. After she posted an influential tweet[6] about her experience, the company promptly removed the robot in response to the public accountability crisis. However, after that, she received backlash for "*whining,*" given that she "was not hit by a car." Commenters on her tweet argued that "*[halting rollout of delivery robots] is ruining the good thing for us*." Despite the negative tone of these comments, they implied a lack of knowledge of the robots' influence on PWMD and a need for a more harmonious relationship instead of sacrificing one side for another.



Fig 1: The delivery robot from Starship opens the lid so that the user receives their cargo. Image Credit: Starship Technologies

1.1 Research Questions

This thesis seeks to explore the complex interplay between sidewalk robots and PWMD to understand better how these robots can be designed and operated in a manner that is both safe and socially acceptable. To achieve this objective, four key research questions (RQs) have been formulated:

RQ1: What are the design factors of sidewalk robots that influence navigation from the perspective of people with mobility disabilities, and how do people with mobility disabilities perceive these factors? This research question aims to identify the specific design elements of sidewalk robots that have a direct or indirect impact on the navigation experiences of PWMD. Furthermore, it seeks to understand how these individuals perceive and evaluate these factors in the context of their daily lives and mobility needs.

RQ2: Taking these design factors into consideration, how should a delivery robot interact with PWMD on the sidewalk? Building on the insights derived from RQ1, this question focuses on developing interaction models and strategies for sidewalk robots that are sensitive to the needs and preferences of PWMD. This may include aspects such as communication modalities, robot behavior, and physical positioning during encounters on the sidewalk.

RQ3: How can sidewalk robots be more acceptable to people with motor disabilities, and how can designers approach this? This research question explores the broader social and psychological aspects of sidewalk robot design, with an emphasis on understanding how these machines can be made more acceptable and inclusive for PWMD. This may involve considerations related to robot aesthetics, user-centered design principles, and the integration of feedback from the target user group.

RQ4：How can I *design virtual simulation tools* to respond to public robots? Recognizing the importance of simulation tools in the design and evaluation process, this research question investigates how such tools can be tailored to the specific context of public robot development. This includes exploring various simulation modalities,

identifying the most relevant performance metrics, and establishing best practices for integrating virtual simulation tools into the broader design workflow.

1.2 Approach

To begin addressing these questions, I first explored virtual simulation tool development using Unity, a game engine. This Wizard-of-OZ style tool is used to create immersive interaction between different pedestrians and sidewalk robots. I did 4 user tests to reveal the usability of the tool as well as the implication of studying HRI in public spaces. This tool was also used to produce material corresponding to different HRI design factors which I used in the following interview. In the interview, I interviewed 10 people with motor impairments. I first aimed to collect and examine key Human-robot interaction(HRI) design factors to reveal the mechanisms of robot design influencing PWMD. I then explored the interaction preferences of PWMD in different HRI scenarios and social conditions. Finally, I highlighted the potential prerequisites before deploying and the ways sidewalk robots benefit back to the disabled community.

1.3 Contributions

Through developing tools for studying HRI in public spaces and in-depth interviews with PWMD, this thesis depicts the intricacies between sidewalk robots and vulnerable road users. Our work contributes to the following:

- ***Accessible sidewalk robot design:*** Our study scaffolded designers to create a universal sidewalk robot design that can benefit disabled communities. By systematically examining how HRI design factors influenced PWMD, I identified key design principles that prioritized the safety and social acceptance of PWMD in developing inclusive HRI design. By considering the specific challenges of different environments, I also provided insights into designing more robust and reliable robots to suit different sidewalk settings.
- ***Interaction preferences for PWMD:*** **I** explored PWMD's interaction preferences and choices, including interaction modalities, relative proxemics, and scenarios in which both the robot and human initiated interactions. As there were few

precedents for how PWMD interacted with sidewalk robots, our study's findings served as a reference for future sidewalk robot design. I also highlighted clear and concise communication when there were conflicts between PWMD and sidewalk robots.

- ***Advancing benefits for disabled communities:*** Our study continued ethical discussions for the design and deployment of sidewalk robots by identifying how sidewalk robots can be acceptable for PWMD. I collected the prerequisites before deployments, and sidewalk robots' data, functionalities, and mechanisms can benefit PWMD. Our insights into the benefits of sidewalk robots for disabled communities also hold the potential to contribute to a more holistic approach to HRI design that prioritizes community members' needs and well-being.

1.4 Structure of this Thesis

The thesis begins with a Background section, where relevant literature in the domain is reviewed. This section emphasizes the relationship between sidewalk robots and PWMD, along with the exploration of existing tools for studying HRI in public spaces. It provides the theoretical foundation upon which the subsequent studies are built. In the third section, the development, evaluation, and findings of the virtual simulation tool are presented. This section provides an in-depth account of the background, development process, and findings from the virtual simulation tool, showcasing how it can be utilized to replicate and analyze HRI in street settings. The fourth section of the thesis is dedicated to the semi-structured interview study with 10 PWMD. It elaborates on the procedure followed, the method of data analysis, and the key findings from these interviews. This section provides valuable insights into the perceptions, attitudes, and interaction preferences of PWMD towards sidewalk robots. In the Discussion section, the implications of the findings from both studies are explored. It delves into how these findings can contribute to the HRI community and how they can facilitate the design of more accessible robots. The Conclusion section provides a summary of the two studies, highlighting the synergies between them and their collective contributions to the field. The Limitations section primarily discusses the challenges encountered during the studies, focusing on the usability of the virtual simulation tool and the limitations of the

interview study. The Future Work section outlines potential avenues for overcoming these limitations and for further expanding this research. This includes the involvement of more stakeholders and the exploration of additional facets of this emerging problem.

2. Background

This work is situated at the intersection of sidewalk accessibility and HRI studies. I first examine the current sidewalk navigation situations of PWMD in Section 2.1, providing insights into how the robots could affect sidewalk accessibility. In Section 2.2, I report current ethnographic observations, discussions, and experiments on sidewalk robots in public spaces. Section 2.3 reviews previous human-robot interaction design guidelines to inform our study, with a focus on universal design principles that can enhance accessibility and inclusivity for people with motor disabilities.

2.1 Sidewalks: an indispensable public resource for people with disabilities

In the United States, regulations require that sidewalks be accessible to all individuals, including those using mobility devices such as wheelchairs [16]. Unfortunately, for people with disabilities (PWD), using sidewalks can present challenges that impact their quality of life [11, 17], independence [10], physical activity levels [12], and ability to participate fully in society [17]. These challenges are often due to barriers created by poor sidewalk design or construction, insufficient maintenance, or natural terrain features [17, 18].

Studies on sidewalk accessibility have identified the challenges experienced by people with disabilities (PWMD) on a daily basis. Gharebaghi and Amin categorized these barriers into spatial (e.g., surface quality, slopes) and social (e.g., political systems) factors [26]. Vanderschuren's research also revealed that physical obstacles, such as stairs or narrow passages, significantly restrict PWMD's mobility on sidewalks [27]. While Mehmet et al. identified various physical barriers, including uneven surfaces, obstructions, and insufficient width, that impair sidewalk accessibility for PWMD [28].

Rolland et al. also noted that the availability of assistive devices, such as ramps and handrails, is often inadequate, leading to difficulties for PWMD in navigating sidewalks [29]. Social factors such as transport policy and sidewalk maintenance rules also play a critical role in PWMD's navigation experience.

The deployment of sidewalk robots can affect both spatial and social factors. The sidewalk robot can be considered a moving physical object that can reach the maximum height of the wheelchair user. The manner in which sidewalk robots are being deployed also constitutes a transport policy that has not been clearly understood. In addition to physical harm, PWMD also faces psychological harm from these obstacles, which can be implicit in nature. Ripat et al. [6] revealed that the lack of accessibility to sidewalks could cause frustration and isolation for people with disabilities. Thus, even though sidewalk robots may not directly harm PWMD, their co-presence on sidewalks may elicit negative feelings such as anxiety or discomfort. People with hearing or visual impairments are also at risk, as the robot may not effectively communicate necessary information, and a PWD may struggle to respond to sudden, or unpredictable, changes in the robot's behavior.

2.2 Emerging Robots in Public Spaces

As there is limited research on direct interactions between disabled individuals and sidewalk robots, recent studies have focused on the impact of sidewalk robots on public spaces. Bennett and colleagues [13] highlight the safety concerns of people with motor-related disabilities when encountering delivery robots on sidewalks. Bhat and Zhao [2022] explore the experiences of individuals with visual impairments who directly interact with different mobile service robots, describing these robots as "dangerous" and "unfamiliar moving obstacles" due to their lack of predictable behavior and clear intent. Similarly, Gehrke and colleagues [2] found that deployed delivery robots in schools provided convenient last-mile delivery, but also caused conflicts in walking paths and potentially unsafe travel conditions. Salvini et al. [1] discussed the psychological and physical safety risks that arise when robots and pedestrians interact with sidewalk robots in highly-crowded street environments, recommending government regulation of

robot deployment in public areas. Thomasen et al. [3], however, argued that regulating sidewalk robots would create inequities and affect public environments. Finally, Sara et al. [7] collected user-generated videos to explore unguided interactions between people and service robots in public spaces, identifying various circumstances in which these interactions can break down, such as when robots fail to detect individuals who want to interact with them or interrupt other people's interactions.

In addition to these studies, there is tension between service robot companies and advocates for people with disabilities regarding the deployment of sidewalk robots in public spaces [14, 21, 22]. San Francisco City Supervisor, Norman Yee, has expressed concerns that robots pose a threat to seniors, children, and people with disabilities who may not be able to maneuver quickly [14]. However, robot companies claim that they take measures to ensure safe deployment and that most people do not mind the presence of these robots.

2.3 Accessible design factors in Human-robot interaction

Both HRI and HCI communities have proposed design frameworks for robot designers to follow, but the scalability and usability of these frameworks remain controversial. For example, some frameworks were built on the findings from domestic environments which makes it hard to be adopted in public spaces. Among the existing accessibility design frameworks, I found only one proposal, evaluated by Qbilat [8], that specifically addressed accessibility in social robots. Qbilat incorporated six other accessibility guidelines (WCAG 2.0, BBC, Funka Nu, IBM, WAI-ARIA, and PUX), primarily addressing desktop accessibility challenges such as readability, modalities, and colors. From Qbilat's work, I adopted the following guidelines for our case:

- **Color and contrast:** This is directly adopted from WCAG 2.0
- **Alternatives for non-text elements:** For social robots, information should be conveyed in multimodalities like sounds.
- **Displays:** This is also adopted from multiple desktop accessibility guilds.

- **Predictable interactions:** As explained by the author, Predictable interactions refer to using a simple and familiar interaction and navigation mechanism.
- **Errors and feedback:** The user can review and correct interaction information before submitting, this can avoid errors.
- **Reachable human support:** Users can easily ask for human help or support.

However, as our study focused on co-presenters rather than end users, I found that some guidelines were less relevant since they were more applicable for direct interaction or operations, such as input devices and hardware-related items. Moreover, due to the specificity of the sidewalk robot and PWMD, I found that some guidelines were broad and hard to understand directly with participants. For example, "predictable interactions" can have numerous meanings in different contexts, which could lead to enormous robot behaviors. I adopted the aforementioned guidelines to address these issues and defined them more explicitly in our final design factors.

Aside from the forenamed guidelines, there are other essential factors to consider for people's perception of safety and trust in robots. Previous experiments in HRI have shown that approaching behaviors, such as speeds and sizes, can alter people's trust in robots in indoor environments [8, 9]. Based on human-human proxemics, HRI has extensively explored interpersonal distances between humans and robots and proxemic robot behavior by tackling several behavioral factors like posture and approaching direction. After reviewing design factors from prior studies, Table 1 served as a source of inspiration for developing the interview protocol.
I:

Name	Levels	How I adopt them
Numbers on the Road	● Single ● A robot fleet formed by 3 robots	I provided images showing a single robot and a robot fleet.
Sizes	● Small size (Height: 21.8” | 55.4 cm|124.8 cm (with	I provide images of different robot size comparing to

	flagpole); Width:22.4” | 56.9 cm; Length:26.7” | 67.8 cm) ● Large size (Height: 40” | 100 cm (Estimated)|180 cm (with flagpole); Width: 28” | 71.1 cm (Estimated) Length: 36” | 91.4 cm (Estimated))	wheelchair users and people walking on feet (Fig x)
Color Contrast	● Low color contrast ● High color contrast	I provide images of robots in different color contrasts.
Approaching Strategy	● Implicit approach (The robot turns at an early stage) ● Explicit approach (The robot turns at a late stage)	I provide two videos generated by the virtual simulation tools.

Table 1. Design factors from previous literature

In an early study conducted by Meyers et al. in 2002[11], 28 adult wheelchair users were interviewed. It was found that the barriers frequently reported included narrow sidewalks, no ramps or steep ramps, no sidewalk curb cuts, poor sidewalk surfaces, and sidewalk obstructions. Following researchers incorporated different sets of other factors to tackle and evaluate navigation questions in different settings. For example, Kulakov et al.[12] collected 9 obstacles, including unregulated pedestrian crossing, sidewalk width, and curb cut, to build a model measuring road safety for PWMD. Among those factors, sidewalk width[13], slop[14], route congestion[15], and weather[15] are commonly recognized as potential barriers. I also asked participants to rank those factors and brainstorm the other factors.

3. A Wizard-of-OZ Virtual Simulation Tool

3.1 Introduction

However, there is currently a lack of tools for studying the interactions between sidewalk robots and sidewalk users in public spaces. To address this gap, I developed a virtual simulation tool that utilizes WoZ techniques to simulate these interactions. The tool is a two-player platform that involves one experimenter who operates the sidewalk robot using a joystick and another who controls a virtual human agent. They coordinate to

create different interaction scenarios. In the first experiment, I interviewed two participants using videos created by our tool that show different robot navigation strategies and speeds. In the second experiment, two participants took part in a shared virtual reality experience of a conflict scenario when the robot blocked their way.

3.2 Implementation and creation process

My main objective was to develop a tool that can offer a contextual experience of the interactions between sidewalk users and delivery robots in a street environment. To accomplish this, I utilized Unity 2021.3.6f[3], a game engine widely adopted for AR/VR prototyping. The prototype comprised three key assets: a high-fidelity street model downloaded from the Unity Assets Store (See Fig 2b), a delivery robot model developed based on Starship's layouts while incorporating Kiwibot's facial expressions (See Fig 2c), and human agent models that included a male wheelchair user and a male person walking on foot[4]. The model of the person walking on foot was downloaded from Ready Player Me (https://readyplayer.me/) (See Fig 2d).

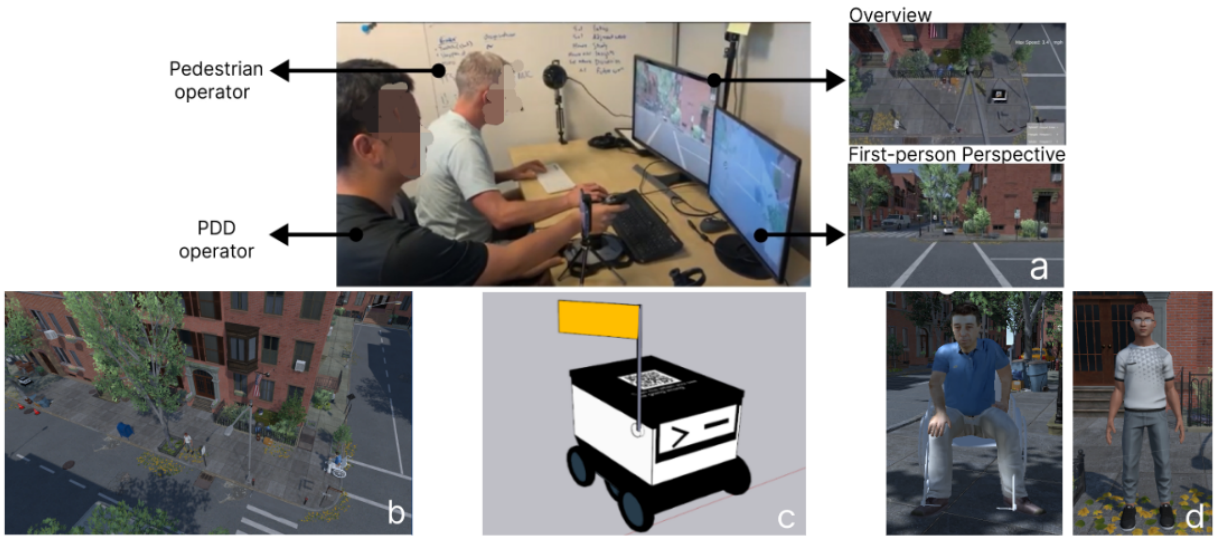


Fig. 2. (a) Settings of the prototype: on the left is the human operator, and on the right is the operator in charge of robots. Two monitors display two views: first-person perspective and overview. (b) The street environment of the prototype: modeled after a commercial street in New York City. (c) Delivery robot

[3] Unity 2021.3.6f(https://unity.com/releases/editor/whats-new/2021.3.6)}
[4] The wheelchair user was adopted from models downloaded from Sketch fab (https://sketchfab.com/

models used in the prototype. (d) Existing avatars include a wheelchair user(left) and a male person walking on foot(right).

The prototype relied on WoZ methods, with two operators required to create scenarios involving a delivery robot and a human agent. WoZ scenarios could be captured with a one-button recording feature. This was implemented to support invocations and future fine-tuning as necessary. While recording, one operator controlled the virtual robot agent using a Logitech joystick[5], while the other controlled the virtual human agent using WASD hotkeys on a keyboard. Each scenario required two operators to synchronously manipulate the two agents and record their movements. In the human view, the first-person perspective was positioned at the avatar's eye height for a more immersive experience (See Fig 2a). The prototype also includes a VR mode where participants can move around by using VR joysticks.

Figure 3 illustrates how I started from a scenario script to different showcases. I followed three steps to implement an interaction scenario:

- ***Setting up scenes****:* Two operators choose a place corresponding to the depiction and plan out the scenario. For example, for a scene where the robot would cross paths with a person walking on foot, operators would select a section of the sidewalk, set up start points, and adjust the size and speed of the robots and the human avatars.
- ***Recording WoZ interactions****:* First, an operator can press the recording key to capture the scenario settings and other parameters of the human and the robot. The robot operator utilizes a joystick to control the robot and can replicate the trajectory discussed before. The human agent operator uses hotkeys to move synchronously. After pressing the recording key again, the scenario data is captured. When finished, they can decide to save this interaction, delete it, or record it again.
- ***Preparing scenarios for end-user encounters****:* A recorded interaction can be transferred to two modes: video or VR. To convert to video, operators can replay the interactions in Unity and record the screen. For VR, I use the Quest 2 VR

[5] Logitech Extreme 3D Pro (https://www.logitechg.com/en-us/products/space/extreme-3d-pro-joystick.963290-0403.html)

headset to replay and experience interactions. Videos can be used, for example, as prompts in interviews or surveys, while VR demonstrations could be used in in-person design activities, such as workshops.

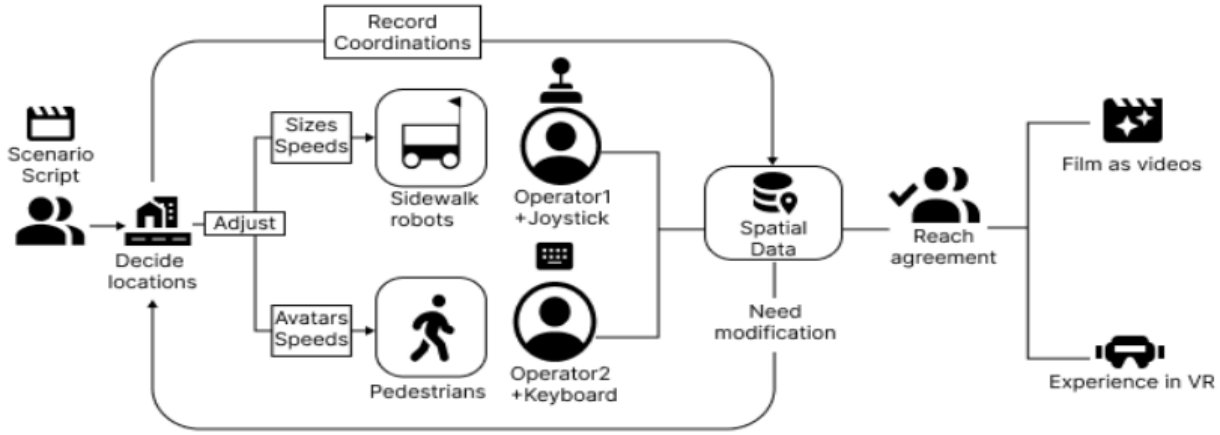


Fig. 3. The process of the prototype from receiving a scenario script to the showcases.

3.3 Evaluation: How might virtual simulation tools help public robot studies

I evaluated the potential of our prototype through two preliminary explorations: interviews and VR demonstrations. In the first experiment, I conducted interviews with two participants who were wheelchair users. I used videos built from our tool as prompts. One scenario video depicted two social navigations, where the robot and a male person walking on feet approached each other from opposite ends of a sidewalk. In one video, the robot bypassed the human agent by turning and maintaining a safe distance (See Fig 4b), while in another video, the robot stopped 2 meters away from the human agent (See Fig 4a,c), allowing him to pass first. I did not use the wheelchair user model directly because I could not accurately model their turning actions at the time of the interview. Another scenario video depicted speed testing, where a male wheelchair user was stationary, and the robot moved at different speeds between 3.4 mph and 10 mph, bypassing the wheelchair user at a safe distance (See Fig 4d). After showing the videos, I encouraged participants to express how the speed and social navigation strategies would affect their experience on the sidewalk should they encounter a sidewalk robot.

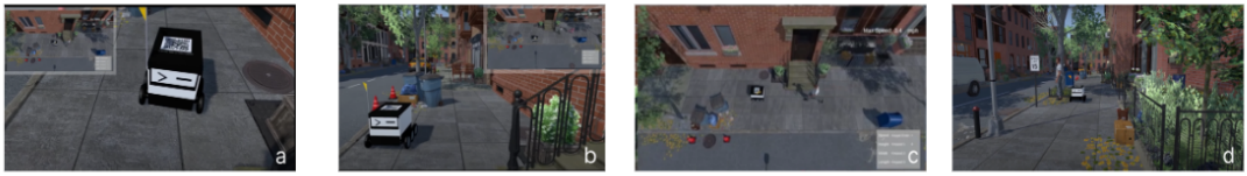


Figure 4. (a) Illustration of Social Navigation Strategy A, where the robot demonstrates yielding behavior by coming to a stop. (b) An overview of the scene captured at the moment when the robot initiated a halt. (c) Depiction of Social Navigation Strategy B, in which the robot maneuvers around the human agent by executing a turn. (d) Configuration settings are used for conducting the speed testing trials.

The second experiment involved a VR experience in which I replicated a real-world accident where a robot blocked the path of a wheelchair user by stopping on the curb cut. To carry out this experiment, I recruited two able-bodied participants (P3-4) as pilot testers, who were trained to use joysticks to move forward in the VR environment (See Fig 5a). Participants were instructed to cross a crosswalk from the opposite side of the road and observe a delivery robot moving forward and stopping at the curb cut. Upon arriving at the other side, the delivery robot remained stationary (See Fig 5b). I encouraged participants to express their thoughts during the interaction. This method is referred to as a going-along interview[16], which has been shown to be effective for participants to demonstrate interactions spontaneously. I also encouraged participants to summarize their thoughts on the overall experience.



Fig. 5. (a) Participants wear headsets and use joysticks to move in VR. (b) The view of VR when participants arrive on the other side

3.4 Findings from the user testing

Both the video and VR-based experiments showed that high immersion prompted participants to notice and relate to the environment in more detail than images and

texts, given that all the participants mentioned street objects during the experiments. P2, when seeing the navigation videos, noticed that there were outside tables and commented, "*I hope it (the robot) won't get stuck when passing the chairs*" The first-person perspective also enabled them to notice details they may have missed compared to online videos shot by others. For instance, during the VR experience, P3 noticed that the robot's stop position prevented him from passing the road corner due to his wheelchair's width. This dynamic interaction introduced unexpected conflicts. The ability to be "*in-person*" in the virtual simulation also allowed participants to evaluate their capacities based on their attributes when interacting with the robot. For example, in response to the fast-moving robot video, P1, a wheelchair user, commented that she would fail to adjust in time when robots ran fast because of her lack of proficiency in maneuvering the wheelchair.

Another advantage of virtual simulations is the ability to capture detailed interaction moments. For example, while playing the social navigation videos, P2 requested that the interviewer stop and scroll to a moment when the robot stopped to wait for her to pass, stating, "*I probably can not accept the robot being that close to me*." Similarly, P3, during the VR test, had a think-aloud moment when he approached the robot, saying, "*I really want to yell for the robot to go away.*" Although feedback can also be collected through other materials, the moments in which the feedback is captured are crucial.

However, there were also limitations encountered when using the virtual simulation tool. One of the primary concerns was that the virtual simulations lacked the physical, sensory feedback that participants experience in the real world, such as tactile feedback when navigating different types of surfaces. Additionally, the tool relied heavily on the assumptions made by the researchers, which may not have reflected sidewalk users' diverse range of experiences and perspectives. The pre-fixed interactions in virtual simulations may have also prevented participants from thinking outside the box compared to open-ended questions, potentially limiting the insights gained from the study.

3.5 Discussion of virtual simulation tools in public robot studies

Regarding future public robot deployment, virtual simulation has the potential to be an auxiliary tool to test different robot behaviors and collect user feedback. It also showed its capacity to replicate failure situations, which can contribute to design responses in emergent conditions. Based on our preliminary findings, I argue that real-world deployments would benefit from at least virtual testing of crucial robot design factors such as social navigation and speeds, particularly in scenarios involving people with disabilities, children, and other sensitive groups, to mitigate potential harm. The simulations could also support evaluating a broader range of human and non-human agents, like cyclists and animals, which might be hard to achieve in physical tests. Moreover, I proposed that virtual simulation could be effectively combined with other design research methods such as body storming, speed dating, and co-design to explore deeper HRI issues. For instance, by integrating physical prototyping with current virtual reality experiences, I could map out the embodied interaction process of future sidewalks.

Our work presents a preliminary exploration of building virtual simulation tools for public robots. Through two preliminary experiments, I demonstrate the capacity of virtual simulation to replicate hazardous situations and compare different robot behaviors with controlled variables. I reviewed our design decisions for building this tool and discussed its potential role in robot evaluations. Leveraging virtual simulation's immersion, safety, and flexibility, our tool holds promise to guide and inform the design and deployment of how future generations of robots appropriately meet sidewalk users. As mobile robots become increasingly common and their adaptations to public space are still being explored, I hope our findings will inform future developments in virtual evaluation tools and encourage more designers and researchers to shape a harmonious relationship between sidewalk robots and sidewalk users.

4. Understanding PWMD's perception of accessible sidewalk robots

4.1 Introduction

After developing and testing the tool, I got a platform to produce material to inquiry about PWMD using more immersive and intuitive prompts. In this interview, I systematically examined PWMD's perception, interaction preferences, and future expectations toward emerging sidewalk robots.

4.2 Method

I recruited 10 PWMD through online platforms (e.g., Reddit, Twitter, Facebook) and they were snowball sampling (Table 2). 7were female, and 3were male. They had an average age of 30(SD=10.0). To participate in our study, they must be 18 years or older, have a motor disability, and be able to communicate in English. They were not required to have experience with the delivery robot or other kinds of sidewalk robots. [Describe their disability type]. The interview took around 60–80 minutes per participant. Participants were compensated with $20, sent how they designated(e.g., cash, Venmo). The recruitment and study procedure was approved by the Institutional Review Board(IRB).

Number	Age	Motor Impairments	Additional Context
P1	25	T5 complete Spinal Cord injury	Uses manual chairs.
P2	52	Idiopathic Brown Sequard Syndrome	Has difficulty walking; used to be but not in a wheelchair anymore.
P3	34	L1 paraplegic.	Wheelchair user; two years post-injury.

P4	36	Quadriplegic	Uses a power wheelchair.
P6	21	spastic diplegic CP.	Uses two loft strand canes when out and about in daily life.
P7	25	T5 complete Spinal Cord injury	Use manual wheelchairs.
P8	29	C-5/6 quadriplegic	Use manual wheelchairs.
P9	19	Physical disability from a disease called TK2D	Uses a power wheelchair.
P10	35	spinal cord injury	Has difficulties walking.

Table 2. Participants' information

4.2.1 Study Procedure

In this section, I will discuss

Demographic Background

In our semi-structured interviews, I first asked participants about their demographic background(e.g., age, gender, and descriptions of mobility impairments).

Current experience on the sidewalk

I then asked our participants about their current navigation experience. Sample questions included, how was the sidewalk quality in your neighborhood? How was your daily navigation experience? Extended questions were asked for them to explain and zoom in on their daily experiences.

Introducing sidewalk robots

Afterward, I asked them whether they had heard of or encountered any kind of sidewalk robot. If they had experience, I inquired about their experience. Otherwise, I showed multiple resources to introduce sidewalk robots. The materials included a video delivery robot operating and images of different types of PDD (Fig 6).

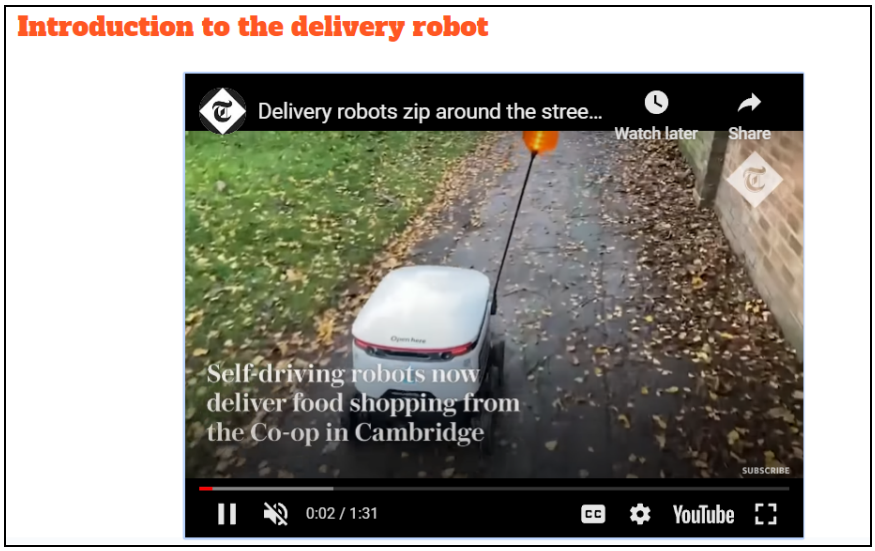


Fig 6: Videos that introduce the robot operation on the sidewalks.

Examining Design and environmental factors

Afterward, I introduced participants to design factors used in HRI from the literature (See section). I chose eight design factors and four environmental factors in total (See Fig 7). Participants were introduced to the meaning of those variables. To ensure participants understood the various design factors and their levels, I created introduction slides for each design factor by including figures from the online annotated analysis diagram. For factors that are hard to fully illustrate through images alone (e.g., the speed of the robot on the sidewalk), I created simulation videos using the virtual simulation tool (as described in Section 2.3). Then participants discussed how those factors would impact their perceptions and brainstormed new factors. I wrapped up the discussion of the relevant factors in this by showing all the design and environmental factors and asked the participants to identify combinations of environmental and design factors that were not yet discussed and to allow participants to explore and describe the possible relationships between factors.



Fig 7: Design factors and environmental factors that were discussed during the interview.

Interactions preference and scenarios

Following the introduction and the discussion of factors, I inquired about participants' interaction preferences and scenarios of interaction with the delivery robots. To facilitate the discussion, I presented them with prompts such as text and images of scenarios. I asked about three main themes relating to interactions:

- ***Necessary functionalities:*** I probed the functionalities they expected the robot to be equipped with, and that might lead to direct interactions with the robot (i.e. more than simply passing by the robot.) To encourage open-ended discussion, I emphasized possible functionalities such as dealing with emergencies and seeking beneficial information from the robots.
- ***Interaction modalities:*** I listed six interaction modalities (e.g., sounds, facial expressions, icons, and texts) from previous literature and asked how the interaction methods varied in different social contexts (e.g., alone or with others; alone with the robot or with other co-presenters).

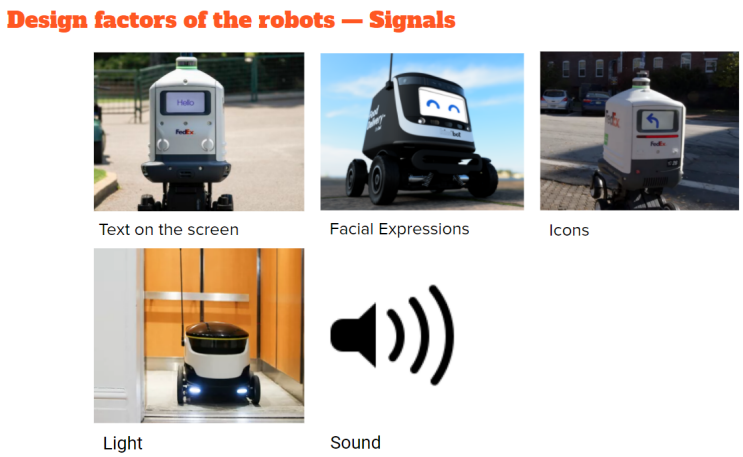


Fig 8: Different interaction modalities that we discussed

- ***Interaction scenarios:*** I presented three robot-initiated interactions (e.g., the robot wanted to bypass PWMD from behind) and three human-initiated interactions (e.g., the PWMD wanted the robot to move way for them) and asked them to consider how the interaction unfolded.

Safe Deployment

At the conclusion of the study, I sought participants' perspectives on the prerequisites for the safe deployment of delivery robots in public spaces. Specifically, I asked what information they needed to be aware of and what conditions or requirements they believed were necessary from both governments and robot companies to ensure the safe and equitable use of delivery robots. Additionally, I asked participants to provide a negative and positive scenario to better understand their hopes and concerns for the future of robot deployment in public spaces.

4.2.2 Data Analysis

The semi-structured interviews were conducted through Zoom, and all interviews were audio-recorded and transcribed. After the interviews, I cross-coded with another Ph.D. student in HCI to build up the code book. We use bottom-up coding strategies. Then, I met with advisors to discuss their codes and resolve any conflicts (e.g., missing code, disagreement on codes). After the five researchers reached a consensus and consolidated the list of codes, they performed affinity diagramming.

4.3 Findings

Based on the coding of the ten transcripts, I identified three primary groups of findings: 1) **How mobile robot design factors affect PWMD's navigation**, which encompasses potential conflicts and the specificity of PWMD, 2) **Interaction choices and preferences between sidewalk robots and PWMD**, focusing on the discussion of interaction modalities and scenarios, and 3) **Future deployments of sidewalk robots**, which delves into the needs and expectations of future functionalities and deployment.

4.3.1 How do mobile robot design factors affect PWMD's navigation on sidewalks

4.3.1.1 Potential Conflicts on the Sidewalk and PWMD's Responses

All the participants shared different levels of concern about the sidewalk robots, including failing to communicate with the robots when needed, robots taking essential sidewalk resources with or without purpose, and mental fear of certain behaviors like robots running really fast. In the following sections, I will illustrate them in detail.

4.3.1.2 Conflicts when robots take essential sidewalk resources

A common concern expressed by 80% of the participants was the limited sidewalk space available, especially on narrow sidewalks. This issue has significant implications for PWMD, as it poses challenges in maneuvering around the robots and may force them to make dangerous or inconvenient adjustments to their paths. P1 imagined a scenario where they went to a narrow sidewalk and saw that a delivery robot was running in the opposite direction expressing concern that they would get stuck on the sidewalk:

> *…especially if there are also trees, and bricks that might obstruct me. Do I have any space to move around? Most likely, I would have to go down the sidewalk! But after I get down, can I come up again, or is there any way to make [the robot] move away?…*

Similarly, there are six other participants who voiced the same concerns, especially when the sidewalk condition is really narrow (P4, P3, P8). In response to these challenges, participants proposed various coping strategies: avoiding the robots, backing up, giving way to the robots by going off the sidewalk onto the road (P9), moving onto grass or uneven or other potentially hazardous surfaces (P4, P9), or changing the original route (P10). P8, responding to the scenario where a big-size delivery robot is running on a narrow sidewalk, said that their first instinct would be to "*back up and look backward to see if [they] could possibly pull into the front of a residence or a store*." However, some actions might be hard to achieve because of motor impairments. For example, they might fail to go back to the sidewalk once going down (P1, P4). P9, a power chair user, said the wheelchair can "*sink into the grass easily, especially if it's raining*."

Moreover, if the robots compete for road resources, 70% of participants believed that there will be cases they need to make ways for the robots. The inevitable yields can also arise negative emotions like frustration, fear, and even anger. P6 shared their irritation when faced with a potentially immovable robot:

> "*If there wasn't anybody else around to move the robot for me, I would be stuck. You know, I'd have to go back home or something. So that can be really, really irritating*."

P3 claimed that they would even "*knock it over…if that thing was in the way.*"

Another critical resource for people with motor disabilities is curb cuts. All participants expressed the indispensability of curb cuts and how their absence could increase insecurity when navigating sidewalks. P4 explicitly shared their worry that "*...the curb cuts could be a point of contention when I need the curb cut and the robot also needs the curb cut when we're trying to get on through a crosswalk.*" Over half of the participants mentioned that their access to curb cuts is often jeopardized by other pedestrians (P3, P4), insufficient numbers (P8), or poorly designed infrastructure (P9).



Fig 9: The scenario of multiple robots running on the road

Concerns intensified when considering multiple robots operating simultaneously on sidewalks. When shown an image of several robots on the sidewalk (Fig 9), nine out of ten participants reacted negatively to the idea of a robot fleet. P2 commented that:

> "... *If I encounter such a series of small robots in the street, they are in the process of transporting goods, then I may choose to stop first, even if I have more urgent things, I will stop a little first so that they all finish first*."

Participants P1 and P9 shared similar concerns about feeling overwhelmed by a robotic fleet. Even with space between the robots, they expressed that they would hesitate to pass them due to difficulty assessing whether the space was sufficient and due to uncertainty about robot movement patterns. P9 noted, "If I happen to meet (the robots) at the same time going 2 different directions. I can't move." P7, a cane user, expressed concern about their limited ability to stand for long periods: "I cannot stand for a long time, for like 2 minutes." Thus, if the robot groups blocked the way for an extended period, it could cause both emotional and physical distress.

Participants also raised concerns about how different environments could compound the issue of robots occupying essential road resources. For example, P3 worried that a robot's algorithm might prioritize better road conditions, forcing them to navigate poorly maintained areas. P2 and P8 mentioned concerns about hardware reliability in adverse weather conditions. The combination of poor sidewalk conditions and inclement weather could lead to unexpected conflicts. P2 pointed out potential issues with potholes

causing splashes on rainy days and reduced visibility of black and white robots in winter conditions. P6 shared their perspective on encountering robots during snowy weather:

> ”*It's funny that you picked a snowy day because that's definitely one that I would worry about. These things are wheeled vehicles, they're gonna get stuck in the snow just like I have experienced. Unless they put treads on them or something… then I could see it can be very concerning (If I meet the robot on the snowy road). But I don't really leave the house when it starts snowing because I've gotten stuck on a sidewalk before. It's super embarrassing and a big pain in the butt. So now if it snows or it's going to snow, I don't leave the house.*”

The assertion that PWMD may go out less often when sidewalk conditions are bad, for example, due to poor weather, is something that was supported by four other participants and by previous literature \cite[]. While this potentially reduces the number of encounters with a sidewalk robot during adverse conditions, the consequences might be graver should a conflict occurs.

4.3.1.3 Concerns Regarding Timely and Safe Responses

Adding to negative feelings when robots take the essential road, some robots' behavior may also bring obstacles for PWMD to maneuver timely and safely. One prominent issue arises when the robot is traveling at high speeds (faster than 10 mph). P3 likened these speeds to those of bicyclists and felt that robots were less trustworthy than human bicyclists because of their ability to dodge and communicate. There are also comparisons between high-speed robots with rushing pedestrians. The primary source of apprehension is the limited time available for participants to respond, especially when turning. Three power chair users (P4, P5, and P9) expressed concerns about their ability to turn at high speeds, with P5 stating, "*That might be harder to turn quickly if I need to maneuver around the robot quickly. That could pose another issue like I might get stuck on other places...*". There are also worries raised by P9 about their wheels cracking together which might lead to damage to both robots and them.

As sidewalk robots are relatively new to most participants and the public, sudden changes in their operation may make it difficult for PWMD to respond appropriately and timely. For example, P8 mentioned that when the robot stops, they might be curious about "*If something is going wrong and if [the robots] have issues*". And they probably would also slow down because they worried that *"the robot stops for a particular reason".* P2 shared similar sentiments, stating, "*I would probably choose to stop and let them pass first because I am a little afraid.*" These uncertainties, coupled with an unwillingness to be near the robots and the fear of causing damage, may result in difficulties for PWMD when navigating around these machines.

The same confusion happens when the robot changes its speed or gets closer to them. Previous literature already indicated that PWMD needs to process more information and thus tends to be more nervous about the sidewalk, the compounding effects of unorganized pedestrians and mysterious robots change can easily let them feel overwhelmed. Over half of the participants indicated that they might get frozen or take a gamble trying to alter the ongoing trajectory.

4.3.1.4 Sense-Making and Communication with Sidewalk Robots

As previously mentioned, PWMD may choose to stop when they are unclear about a robot's actions to avoid potential conflicts. This could occur even when a robot is operating normally and stopping intentionally, such as giving way or slowing down to ensure that PWMD has priority to pass firstly. A lack of clear communication between robots and PWMD can reduce navigation efficiency for both parties because they will be in a confrontation with each other for a period of time.

With all the participants recognizing the importance of communications, robots announcing their presence were called by 60% of participants (P1,P2,P3,P4,P5,P7) in cases of turning, speed change, trajectory change, and getting closer. I presented five communication modalities with accompanying explanations during the interviews. Voice announcements were considered effective and intuitive for conveying a robot's presence and intentions on public sidewalks. P4 suggested that a soft, polite beep

could indicate that "*the robot recognized [them].*" P5 also considered a beep to be a helpful hint if the robot wants to change directions. P9 emphasized the need for detailed verbal communication from robots to avoid confusion and misinterpretation:

> "*I'm assuming that when you turn a corner, you don't typically shout 'turning right'. That's an inhuman action that immediately alerts me that there's a different situation happening. If someone says 'turning right', I'm probably going to instinctively move away from that corner… The problem with the robot is that even if it stops for 5 seconds and then turns, it's still going to bump into someone turning around the corner. If it doesn't stop, it should let people on the other side know that it's turning and how long it will wait*."

P1 expressed the same thoughts and believed that sometimes the robot even needs to give out instructions for them to take the next move, especially when there are potential conflicts.

> "*...I hope the robot can convey information and more importantly, guide me on how to avoid it. It can say something like I will stop, you can go this way. Let's not bump into each other. Let's not touch each other.*"

In addition to auditory cues, visual cues such as text and icons were considered lightweight yet effective channels for communication, particularly when sidewalks are crowded, and sounds may not be easily discernible. Texts on screens were regarded as a clear method for conveying information and instructions by P3, P4, P5, P7, and P9. P4 appreciated the unambiguous nature of using text::

> "*...because the text is very unambiguous and very discreet. I think that having a screen with a multi-functional display like that also is useful. Because then where they are showing an icon in places to kind of show what it's going to be navigating…*"

P2 mentioned that robots' low height might hinder the interpretation of the text in front of them. Also, considering the cognitive load of comprehending text, P5 suggested that icons could be combined with text to display turning behaviors and speed changes. Another important visual cue is lighting. P4 drew an analogy between the lighting system of cars and robots to show signals such as turning and stopping. And analogous to communicative signals of cars, they also called that all sidewalk robots should share the same visual systems. Otherwise, it will lead to confusion and accidents because of misinterpretation. Another visual aspect is the color of the robots themselves. All participants expressed a preference for higher contrast colors, as they are more distinguishable. Based on their perception of the visual cues, the clarity and accessibility of visual cues are crucial in addition to the design of the visual cues themselves.

One potential pitfall of using signals for communication is oversimplification. For instance, P9 expressed confusion upon seeing an icon indicating a left turn on an external screen, stating, "*I don't know whether that sign means I need to turn or it is the robot that wants to turn over.*" To make the situation clearer, P9 suggested incorporating text to explain the situation explicitly, ensuring that the robot's intention to turn is understood. This also applies to auditory cues; some participants (P9 and P5) expressed concern that if they heard bumping sounds on a crowded sidewalk or if a robot appeared suddenly around a corner, they might struggle to identify the source of the sounds, potentially leading to conflicts.

4.3.1.5 Dealing with mobility aids

Distinct from people walking on foot, PWMD often relies on mobility aids like manual wheelchairs, power wheelchairs, canes, and walkers. I have participants using all except walkers. Previous literature has suggested that PWMD exhibits different movement patterns in terms of turning angles, speeds, and stop times, which our participants also confirmed. As they believe the navigation algorithm is developed based on ambulatory pedestrians' data, whether the robots can smoothly navigate around PWMD is under concern. For example, when shown videos of robots stopping

to yield, P1 and P3 pointed out that the robots' stopping points would require them to adjust their wheelchairs' trajectories, which could be time-consuming.

PWMD's social distance is also extended by mobility aids in comparison to people walking on foot. There is sparse research about how people with motor impairments approach and keep their distance from a mobile robot in public spaces. However, the previous paper has implied that they need a larger distance compared to walking people. P1, P4, P8, and P9 all noted that their social circle is extended by their wheelchair, with bags or other attachments, and when extending their arms to manipulate the wheels. P9 stated that "*some power chairs with a large radius can take up the whole single-person sidewalk*" The way mobility aids function in behavioral transitions can also enlarge PWMD's social circles. P7, a cane user, mentioned that they would spread her cane out when navigating stairs. Similarly, P5, a power chair user, claimed that they always needed to make a wide turnaround. They all expressed concerns about whether the robot can maintain enough distance or respond to trajectory changes.

PWMD's specificities in terms of navigation modes prompt them to seek recognition from robots. P8 shared the thoughts that It will be more reassuring if the robot could display some indication that it has noticed they are wheelchair users. P4 referred to the user interface of autonomous driving, where the movements of pedestrians and their relative positions to the car can be shown. They hoped that the robot could: 1) recognize them, 2) recognize their mobility devices, and 3) communicate its intentions.

However, concerns also arose about the robot's ability to precisely recognize various mobility aids and respond to their differences, as sometimes it is even challenging for users to describe their navigation patterns. P9 stated that "*people use different wheelchairs in such drastically different ways…*". Furthermore, more precise recognition and intelligence could raise privacy issues. P7 expressed that they "*found it reassuring to see that the robot knows they use canes*" but also wanted to "*make sure that the data will be deleted.*"

4.3.1.5 Tensions in Design Factors

During the interviews on design factors, tensions emerged between different choices. On the one hand, tensions were built on participants' diverging opinions. On the other hand, they revealed the intricacies of designing robots for public scenarios. In terms of the form of robots, big-size robots were more likely to obstruct sidewalks and invoke fear. P2, responding to the image of FedEx robots, expressed concern:

"*...Compared to my height, it seems to be very large, and visually prominent. Especially for females, encountering something much larger than oneself can cause psychological fear… I also worried it might flip and hurt me…*"

Small-sized robots tended to generate less fear and take up fewer resources on the sidewalk. However, they also posed the problem of easily trapping people. P8 said that "*(Wheelchair users) will just not see the smaller robot if you don't see it from up ahead.*" Thus, P8 considered a flag to be a clever design element because it ensures the robot's visibility even if the main body is low to the ground. However, they also worried that it might get caught on wheelchair attachments like bags.

The form of robots was also related to the problem of signal visibility and interaction reachability. 3 participants shared worries that some information on the robots, such as a screen displaying text and images, might be difficult to see. P1 expressed concerns about interacting with lower robots:

> "*I feel that the (small robot) is actually less friendly to me because I can at least touch the top of the taller one. In my imagination, the taller one might have some operational or interactive functions on top, so I can clearly convey to it or create a way to let it know that it has affected me…I can only touch the smaller ones on the left and right sides, so I think I have to turn sideways. Like this, my kidneys start to ache, so I can't accept it. And I feel that when there is a significant height difference, its camera recognition range is limited.* "

Dynamic behaviors can also easily invoke tensions because of the different technical acceptance. For instance, while high speeds could lead to negative responses from PWMD, if the robot is too slow, it might fail to adjust when needed (e.g., on a narrow sidewalk where a wheelchair user wants the robot to back off). 90% of participants found walking speed more acceptable, but P5 raised the question, but P5 also raised the question: "*If the robot is just a walking speed, why I don't hire one more bicyclist to deliver that could be more efficient?*"

The tensions behind speed examples are the tradeoff between efficiency and safety. The same tension also applies to when a robot wants to approach. I showed participants two videos as prompts: one where the robot turned around early and another where it turned later. 60% of participants preferred the robot turning early, as it allowed more time and space for them to prepare for potential adjustments. However, P1 believed that turning late was more realistic:

> "*From the perspective of what it does now, it seems very close, but the second option is actually more realistic. It should turn when it is at a safe minimum distance from me as if it anticipates my behavior and there is a long delay between our actions, it may need to make a second turn. For example, in this situation, it is facing to its right and moving towards me from its left. I may misjudge it and think it is moving in the opposite direction*."

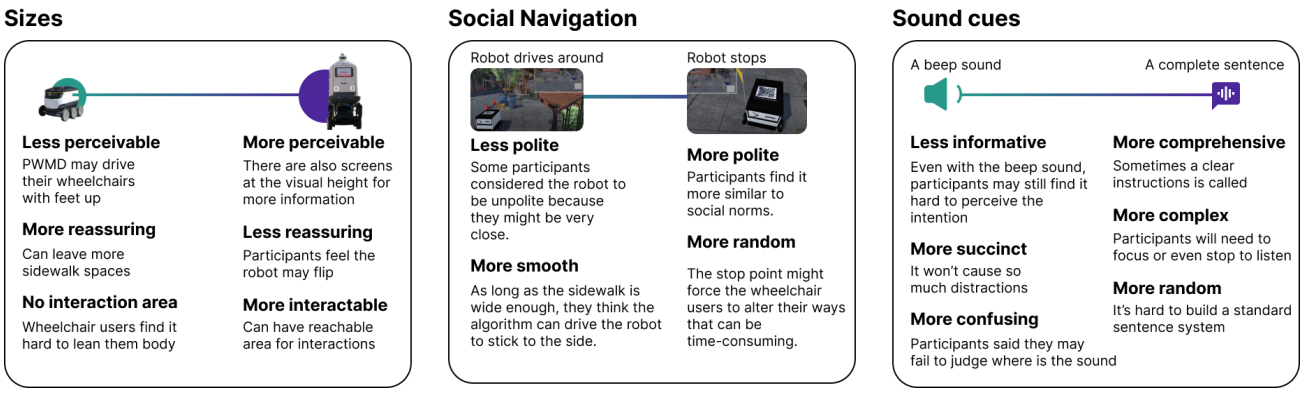


Fig 10: Design tensions in sizes, social navigation, and sound cues.

Another design tension is the level of explicit communication and the potential for robots to distract PWMD. P3 shared that they already experience significant stress navigating sidewalks, and constant sounds from the robot "*only add to the stress*" because that

“*will never be enjoyable because they have to mean something, perhaps alerting*”. While most participants acknowledged the importance of communication, their preferences for how it should be conveyed varied. For example, regarding auditory cues, some participants preferred simple mechanical sounds, while others favored more comprehensive communication based on natural language.

4.2 Interaction choices and preferences between sidewalk robots and PWMD

4.2.1 Usability of different interaction modalities

During the interview, I proposed 6 possible interaction modalities (see Table 3) that are possible to interact with the delivery robots. I also asked participants to come up with ways to interact with the robots.

Modalities	Opinions	Use case examples
Voice interaction between users and robots	Effective, intuitive, want it to have the parse functionalities.	Human -> Robots: when the robot blocks ways, ask them to remove it. Robots -> Human: When they are having behavior changes
The controller on the power wheelchair	Might be a good way. But I don't know how to connect.	When the robot blocks the way, use the joystick to move the robot.
Touchpad on the robots	Afraid of direct touching due to sanitary reasons. And it should be touchable, meaning that the robot will be taller	Can be useful to control the robots because it is very concise. Compared to voice interaction, and there will be

		no ambiguities.
Buttons on the robots	Afraid of direct touching. The buttons should be very straightforward. Feel like it should be necessary when others fail. It can be very quick.	When other modalities fail, the button can be used to call the people behind.
Robots recognize user's gestures	Worrying about remembering and recognition.	Could be useful for simple interactions like letting the robot turn directions.
Phone interaction	Will be hard for people using canes, Afraid of using another app.	Remote controlling the robots when needed

Table 3: Different interaction modalities and users' feedback

Commonly chosen modalities included voice interaction and touchpads. P5, P6, and P9 believed that voice interaction was the most feasible and lightweight way as it didn't require them to stop moving. However, P4, expressed distrust of the voice interaction because they "*found that to be very inaccurate in recognizing the accent.*" They also considered that casual conversation might be hard to reach because "*there will always be cases that I need to talk again and again*". Thus, they would prefer the interface-based interaction because "*the UX design can give clear instruction and meaning without ambiguity.*"

P1 and P3 shared the same thoughts that compared to voice interaction, physical interactions prevented vague meanings and potential miscommunications. There are essential functionalities that are required when it comes to touch interaction. For example, P9 emphasized the need to instruct the robot to go down the sidewalk. Contacting the operators behind the scene is another function of strong needs. When the operator fails to respond or the situation requires timely intervention, P1 believed that some level of robot control is required so that they can manipulate the robot or ask

others to help. P1 recalled a scenario in which she was blocked by a delivery robot in a hospital:

> "*...It was a hospital robot, quite tall, like a large floor-cleaning machine. It recognized me, and it moved to its right, I moved to my left. I met in a narrow passage, and then it immediately recognized me. I were both trying to navigate through this narrow passage but kept colliding with each other. It moved to its right, I moved to my right, and I collided again. It was like a game of chicken, with both of us twisting and turning at high speed.*"

Referring back to the constrained interaction capacities, participants also shared concerns about whether they can access the robots, especially given the complexity of the sidewalk. The need to remotely interact with the robot is expressed by P3, 6 because of the fear or sanity concern when touching the robot directly. Using an App on the phone is the naturalist way based on that. Gestures, a comparatively novel interaction way, showed advantages in interaction naturality, but also suffer from learning curves and accuracy. Another possible way is to utilize the controller or the interface on the power chair. Despite the technical feasibility, P8,9 were worried about whether the connection is stable, and whether switching from the modes of controlling the wheelchair to the robots might bring unexpected problems.

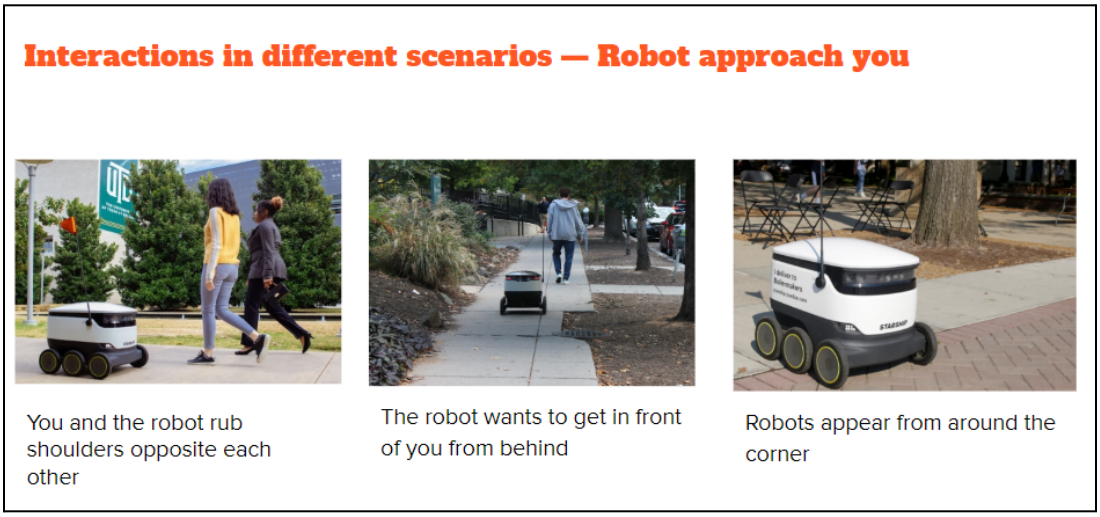
Another notable tendency was participants considered physically pushing the robots using their wheelchairs if they were unable to interact with the robots in other ways. For example, P3 and P9 expressed a similar intention:

> "*If the robot blocks the way. I'd probably use my chair to push it off to the side, so it's not anybody else's way, and I just kind of help somebody outside… but in that case considering the size and width of my chair, my wheels are going to bang into the robot's wheels.* "

Arguably, interaction modalities should be as versatile as possible. Three participants

argued that there should be at least one physical interaction and voice interaction option available. If certain modalities fail, the robot should instruct participants to use an alternative method.

4.2.2 Interactions in Adversarial Scenarios



The contexts in which PWMD have to interact with robots always contain potential conflicts. This might include competing for access to the ramp or avoiding strolling in a dangerous area like grasses or poor sidewalks. Participants considered voice interactions to be the most usable way to interact in that case. P6 believed that they would shout aloud to the robots to move from the robots. P8 said that if needed, they would also be comfortable sharing her feelings:

> "*I don't mind communicating what I need. I won't mind telling the robot my feelings. If the robot makes some movement that could lead me to a problem. I will say that can you choose another way? Or is there another option…Because I'm not comfortable*"

Considering the importance of the curb cut for PWMD especially when they want to go on the sidewalk, four participants share their needs in the case that they want to instruct the robot to go down the sidewalk by pushing a button or voice command. P9 provided an example:

> "*The biggest thing for any sidewalk robot, regardless of its job, regardless of its size, is, there is just no way around that it has to be able to get off the sidewalk… I should have ways to know, whether by public announcement or the robot telling me that there's some way to verbally instruct it to get off the sidewalk... It can be a sentence or can be a number, but that should work*"

The same needs can also be achieved by a touchpad or the buttons with explicit instructions of letting the robot get off the sidewalk or leave the curb cut. P1 and P3 also considered hand gestures could be useful in this case, because they can "*wave hands to let the robot retreat*". The interactions prompting robots to go off the sidewalk also applied to scenarios like wanting the robot to surface on the grass to make ways or instruct the robot to be further.

4.2.3 Interactions in Scenarios Where there is no conflict

Participants generally find it less motivated to interact with the robots in non-conflict scenarios, because firstly, they already have trouble when navigating the sidewalk, and also they find it less reasonable to interrupt the robots' job. However, they acknowledged that the capability to communicate and interact with robots could effectively alleviate their anxiety and improve their trust in the robot.

Previous literature has implied how can a robot become polite and socially acceptable. Four participants mentioned that they would expect the robot to say hi to them. P4 said when the robot passes close by, they would expect the robot to say "excuse me," similar to what other pedestrians do. P6 and P7 also expressed the desire for the robot dialogue system to mimic human responses on the road. P1, based on the human-human conversation, said that robots' dialogue should have a clear end: "*The conversation should have a clear beginning and end, so I can determine if it's the interaction has come to an end instead of waiting.*"

Besides auditory cues, participants suggested that robots should display behaviors that

adhere to social norms to be more socially acceptable. P6 appreciated the idea of the robot having a smiling face when encountering them, which could potentially "*make their day.*" P4 stated that the robot should always stay to the right and wait for other pedestrians when needed, like waiting for traffic lights.

Although the need for interaction with robots in non-conflict scenarios is low, the acceptance could be high. P1 and 6 all shared the thoughts that they are more comfortable talking with robots than humans. P6 explained:

> "*It's a tool. It's a machine. You never feel bad about expecting something from your hammer, you know, or like a screwdriver.I think it would be easier. I mean, you can tell a robot anything you can Google search anything. You can't talk to a person about anything.*"

P1 compared seeking help from a sidewalk robot to asking assistance from other pedestrians and found the former more appealing:

> "*As a physically disabled person, I mind when others mention this. I am very afraid that others will be kind person and says, "Oh, let me push you." I hate that… I feel that it is a machine, and it has no preferences or dislikes towards me. Moreover, its intelligence can be much higher than that of ordinary people in some situations.* "

This willingness to interact with robots in a socially acceptable manner could lead to potential interactions when PWMD requires assistance, which will be discussed later.

4.2.4 Interactions in different social contexts

All of the participants believed that having companions can relieve their concerns about robots and dealing with robot failures. That leads to a complex perception of the scenario involving other pedestrians. On the one hand, they felt more reassured, but on

the other hand, the complex navigation agents may lead them to worry about potential conflicts. Additionally, some participants expressed concerns about other pedestrians interfering with the robots, making it harder for them to navigate smoothly. Based on this, P9 specifically suggested the implementation of authorization features to ensure that "*not anyone can stop and control the robots and mess up the sidewalk.*"

In addition to the crowd group, crow robots are also mentioned in a different social context. P8, responding to the idea of multiple robots on the road, expressed concerns about the possibility of different norms and interaction settings for each robot:

> "*When there are multiple robots. I would be curious if that is one robot in charge of the whole fleet or do they have different patterns… If they are from different companies, will they navigate and interact with me in different ways?* "

They also wondered how different robots would interact with each other, especially if they were from different companies. P4 similarly mentioned that the interaction patterns of different robots should be unified.

Another social context involved malfunctioning robots. There have been emerging discussions about robot failures in public\cite, and people's willingness to help the robots. However, considering the vulnerability of PWMD, their capacity to help to fail robots is more limited. Instead, they might need to help themselves if a malfunctioning robot blocks their path. P3,10,9 mentioned they would try to contact the robot operators. P9 said that if the operator failed to respond, he might ask surrounding people for help. In that case, the robot should provide instructions, like a QR code for people to scan, so that people can know how to help them. There were also calls for reimbursement later to incentivize people to help.

PWMD as users of robots were considered in another social context. For example, P6 compared his experience communicating with human delivery personnel and believed there were ways the robot could be better:

> "*So I think it would be really neat if you could tell the robot which door of your house to go to. I mean. There's a huge difference between a package being dropped off at my door or the back… I always try to notify the deliveries that I want to receive my packages at the back door and they seldom listen… I even put a stick on the front door but that's also in vain.*"

4.3 Future Deployments of Sidewalk Robots

4.3.1 The Expectations and Criteria of Safe Sidewalk robot deployments

All the participants valued the importance of handling technical failures for safety reasons. P3 argued that technical failures are just inevitable to happen, "*but there should be ways to mitigate*". As mentioned in the interaction section, participants suggested alternative modalities when one fails to function. This is also one of the failure-handling functions called for by P3, P1, and P6, ensuring that robots remain communicative. P1 suggested emergency buttons so the robot can move itself to a corner when stuck on the road. Alternatively, when the robot cannot move, it should be designed to be touchable and stop generating alert sounds when people attempt to grab and move it.

When the robot operates normally, participants expect the interaction to be stable and accountable, regardless of environmental effects. If certain interaction modalities fail, the robot should communicate this explicitly. For example, P4 expressed the need when the voice system has low accuracy in recognizing their sounds, it should be transparent and provide instructions on how they should use other interactive methods, like a touchpad, to achieve their goals. P1, P4, P10, and P7 mentioned that they would like to know how to interact with the robots as well as their performance parameters in different conditions.

Another critical piece of information that participants often mentioned is the frequency of encountering the robots. P3, drawing a parallel to Amazon trucks, speculated that "*the robots would go all over the places*". Privacy concerns related to robots equipped with cameras and sensors also emerged. Considering the need for robots to adapt to PWMD,

the recorded data would contain more identifiable information. "*If the robots were everywhere, I would worry about the device being hacked*" worried P3. P4 also shared the thoughts that if the robot doesn't show up many times a day, he wouldn't find privacy to be a problem.

In addition to data, criteria, and functionalities that contribute to the sense of safety around sidewalk robots, 70% of participants called for more comprehensive public announcements containing parameters, operation instructions, and interaction setups for the robots before they are deployed. "*I think the technology is beneficial, if the governments introduce them in the right way.*", said P10.

4.3.2 Future Functionalities that Can Benefit Disabled Communities

4.3.2.1 Road Sensing and Road Data Sharing

During the interviews, I asked participants what data would be beneficial if robots could help detect road conditions. The feedback on robots sharing road information is generally very positive. P4 mentioned that they had already installed a local app reporting roadblocks and believed the robot "*can definitely help more because they are patrolling all the time and the data will be more up-to-date*." Pothole detection was suggested by P1, P3, P6, P7, and P8. P8 added that the depth of potholes is another crucial parameter for PWMD since they often lack vision until "*they actually stuck by the potholes*". Information on roadblocks and obstacles like sticks and pipes was also recognized as contributing to the navigation experience of PWMD.

Participants from northern areas mentioned that icy roads during winter prevented them from going out. P1 expressed that "*If the robot can notify me which roads to avoid, I might be braver to get out during winter*." As sidewalk robots typically include lights, another scenario where the robot could help is in detecting and alerting on road conditions at night. Participants also mentioned the way they want the robot to communicate this information, for example, through crowdsourcing platforms, prompt messages when the robot appears, or being available when people ask about it.

4.3.2.2 Altruistic Functionalities Called for by PWMD

More than half of the participants expressed hope in sidewalk robots but felt that the delivery functionality alone was insufficient for serving and benefiting the disabled community. I mentioned in the interviews that there are emerging snow-sweeping and safeguarding robots, which received positive feedback from participants. P3, who strongly opposes delivery robots, still thinks the snow robots are "*an exciting idea*". P8, a female cane user, recalled an advertisement she saw about personal following robots that carry cargo and considered that as a beneficial functionality for most motor-impaired people. P1, who had heart disease, believed that if the robot can carry first-aid drugs and provide first-aid instructions when needed, she would "*feel very reassuring if she knows that there is a sidewalk robot nearby.*" P6 suggested a multi-functional robot that could deliver food most of the time but also spread salt when needed and assist with first aid.

Apart from the main roles, there are also general functions that could make the robot more altruistic. P3 mentioned that it could provide information to disabled people when they are using them to order things:

> "*You know, there are a lot of disabled people who can't get out of their homes, so this is just another resource for them to be able to connect more with the outside world. They can get their video games delivered or whatever they need, and they can be brought straight to their door. As far as cons go, I mean all technology fails, so I could see it being annoying if it delivers to the wrong house.*"

5. Discussion

The findings from the interview revealed how PWMD potentially perceives and interacts with the future sidewalk robots as well as their expectations. Reflecting on these findings, I will discuss future research opportunities and retrospect previous research that ties to the accessible design of sidewalk robots.

5.1 HRI Design Factors and Interactions Regarding Sidewalk Robots

Referring back to previous literature on accessible robot design factors, I find that they are often too broad to apply to public robot designs. Crucial functionalities, interaction principles, and communication norms are often missing from the literature. Additionally, when robots operate on public sidewalks, previously established benchmarks such as social distancing, speed, and sizes must be adapted. Our work serves as a starting point for studying interactions between PWMD and sidewalk robots. However, some of our findings are also applicable to other public sidewalks. For example, conflicts may also arise in indoor scenarios, and the social norms, interaction preferences, and challenges are relevant to other social contexts.

Recent progress in HRI has shown the possibility of implementing some of the functionalities I mentioned earlier. For example, road sensing has been extensively studied by previous work, but from the angle of technical feasibility. Furthermore, a Wizard-of-Oz study showed public attitudes toward garbage-seizing robots in the real world, people feel pressure to generate garbage for the robots, and people's interactions assume the robots' awareness of each other[17].

5.2 A socially-acceptable Sidewalk Robot, where are the Missing Pieces

Our work presented ways of making sidewalk robots more acceptable and accountable from obeying social norms to adding more altruistic functionalities. However, considering the benefit-cost analysis, some functionalities might be less feasible. One future direction could be to figure out where are the low-hanging fruits that make small efforts but receive more benefits. Another direction could be useful in expanding the positive social effects is that to consider what other needs PWMD might have. For example, during the interview about their navigation experience, participants shared that

they had trouble interacting with other pedestrians and vehicles about the importance of curb cuts for them. P3 mentioned that:

"*People will often sit and wait for the light to turn green right where the curb cut is, and I'll be like," Hello! It's my turn, and they'll be like. What do you want? And then it's very difficult for me to communicate with 'Hey? You're in the way.*'"

So, if the robots are equipped with voice interactions, they can probably talk with other road users which could make PWMD's life much easier.

5.3 Deploy and test future sidewalk robots

All the findings in our work will benefit from more testing both in the real world and in lab environments. When discussing the data they need to know about the robots. P3 specifically mentioned that "*I don't trust data. I don't need to be intelligent to know that you can play with data. I trust what I see. I need experiment results from independent researchers like you*". The physical tests are also called by P8 because she thought that the acceptable distance regarding the robot should also be tested physically because it is hard to decide based purely on the images. Other opinions, preferences, and interactions all need more tests and data to validate. Also, another discussible topic is how can different stakeholders to gather together to facilitate the tests and then share with the public in ways that they can also understand. Especially considering the complexity of sidewalk environments, the tests as well as the report can be endless,

6. Conclusion

With the two studies shown below, I explored tool buildings as well as interviewing methods to study emerging sidewalk robots in public spaces. By showing two design activities, the virtual simulation tool offers an early exploration of using virtual simulation tools to support the future study of HRI in public spaces. I also generated and showcased various scenarios of HRI and demonstrated the potential for users to engage in immersive experiences and critical reflections. And the tool is also used to

support the interview by providing the design discussions. The interview study with 10 PWMD deepened my understanding of their perceptions, preferences, and attitudes toward sidewalk robots. It unearthed key themes that elucidate potential impacts, interaction scenarios, and future design opportunities. Together, these studies underscore the need for a multi-faceted approach in the design and deployment of sidewalk robots, considering both the technical and social aspects of HRI. They demonstrate the importance of inclusive design that respects and accommodates the needs of all sidewalk users, especially PWMD.

7. Limitations

Our study also revealed room for improvement in the WoZ process used in our prototype. For example, recording a scene sometimes took 3–5 times when the scenario road was narrow, obstacles were present, or robot operators lacked experience in manipulating the joystick. To address this, future virtual simulation tools could incorporate ways for manipulators to preset trajectories and adjust joystick settings. For instance, the speed could be set slower than the initial setting when the operator used the joystick, and the trajectory could be adjustable to avoid the need for re-recording every time. Additionally, integrating navigation algorithms into the platform could supplement the creation of robot trajectories, leading to more variances and improved flexibility.

Admittedly, the findings are only built on 10 participants that are mostly based in the United States and all have access to online meeting platforms. Although I claimed that I was not the designer of the robots, there might still also be potential demand characteristics that people tend not to be critical of the new technology. Only one participant strongly opposed the sidewalk robot, with others generally still believing the technology could at least be useful in some ways. Considering the already strong opposition and protests from the disabled community of the use of delivery robots, I admit that the small sample bias might fail to incorporate a broader scope of

participants' opinions. In the future, I will also try to connect with local disabled organizations to recruit more diverse groups.

8. Future work

In the future, I plan to conduct more usability tests and user studies to unpack our tool's potential fully. An improved world-building feature could also be beneficial. For example, road widths, volumes, and weather conditions could be adjustable to examine how they affect participants' navigation experiences. Leveraging the capacity of virtual simulation in combination with more world-building functionality would enrich scenarios and help shed more light on real-world deployments. Additionally, crowdsourcing edge cases and problematic scenarios could help bridge gaps between real-world and virtual scenario-making. While there is a need for more development and knowledge in this topic, I hope our work can serve as an exemplar for building virtual simulation tools to test public robots.

Involving more stakeholders is another future direction. Another ongoing work is interviewing robot practitioners about the feasibility, attitude, and knowledge of designing accessible robots.

9. Acknowledgements

I completed the HRI experiments with Alana Levene and Aparna Warrior during Henny Admoni’s Human-robot interaction class. Garrett Duarte engaged in the development of the virtual simulation tool during his summer internship

I would like to extend my heartfelt appreciation to my exceptional advising team, Daragh Byrne, Sarah Fox, and Nikolas Martelaro, for their unwavering support throughout the past year and for the future. They not only teach me to do this research but teach me research and how to be a better researcher.

In addition, I am deeply indebted to Henny Admoni and Laura Dabbish for sharing their expertise, knowledge, and invaluable guidance, which enabled me to successfully complete this work.

My sincere thanks also go to Franklin Li and Wesley Deng for their insightful discussions and counsel. Furthermore, I am grateful to my previous teammates Alana Levene, Aparna Warrior, Garrett Duarte, CODE lab friends, and the Beeler group for their constant encouragement and backing. Lastly, I would like to acknowledge all the participants whose contributions were essential in making this work possible.

10. Citation

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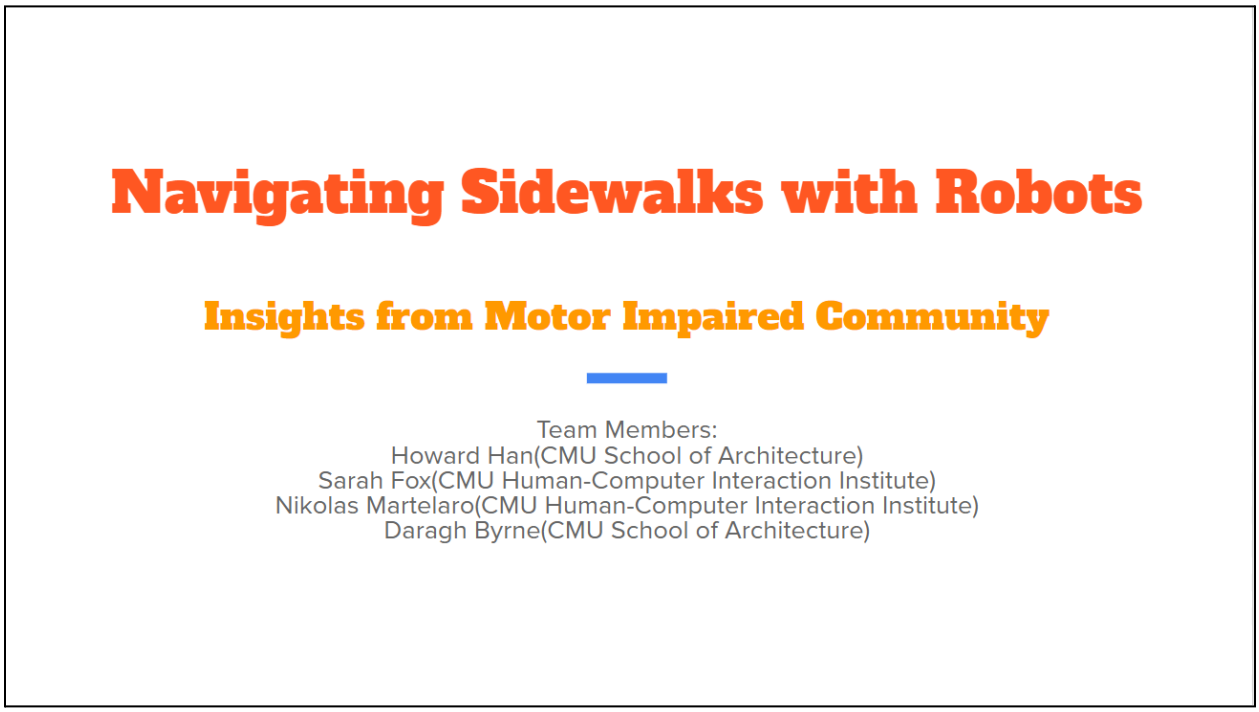
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11. Appendix

Hello, and welcome to our interview on navigating the sidewalk with robots! Thank you for taking the time to share your thoughts with us today.



Agendas

- Your daily experience on the sidewalk (5 minutes)
- Introduction to the sidewalk robot (5 minutes)
- Environmental & design factors (25 minutes)
- Future relationship with the robots (20 minutes)
- Conclusion (5 minutes)

Introduction to the delivery robot



Personal delivery devices (PDDS) are **small delivery vehicles** that operate on public sidewalks and perform tasks such as delivering packages and food.

Image Source: https://news.asu.edu/20200904-asu-news-starship-aramark-launch-contactless-robot-food-delivery

Introduction to the delivery robot



Have you ever heard of them?

Have you ever encountered one?

Image Source:
https://www.forbes.com/sites/greggardner/2022/02/16/starship-technologies-expands-robot-grocery-delivery-to-second-northern-california-store/?sh=56217c1a31ae

Introduction to the delivery robot



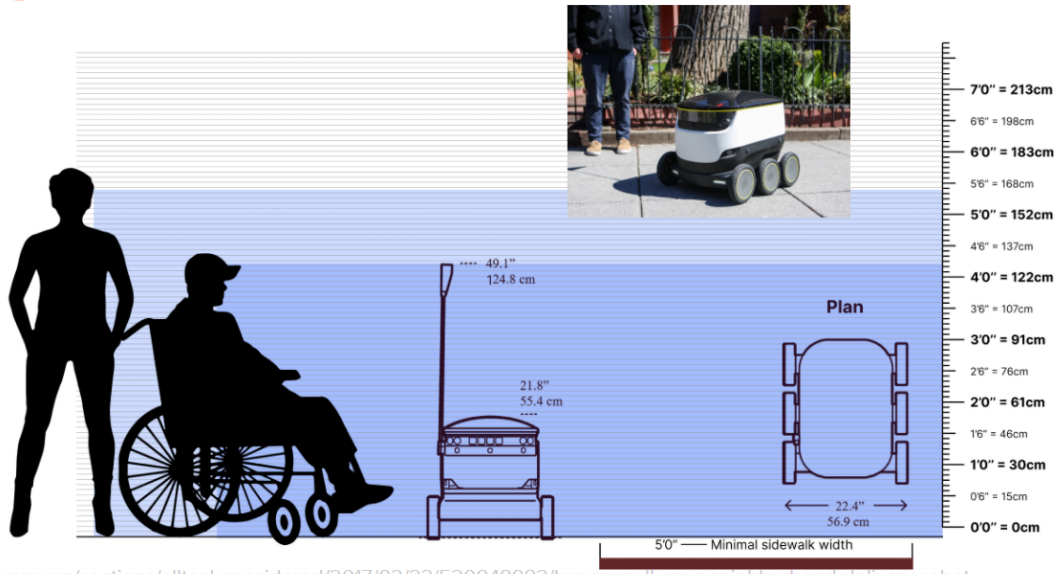
Your first impression of the delivery robot



What's your first impression of the delivery robot?

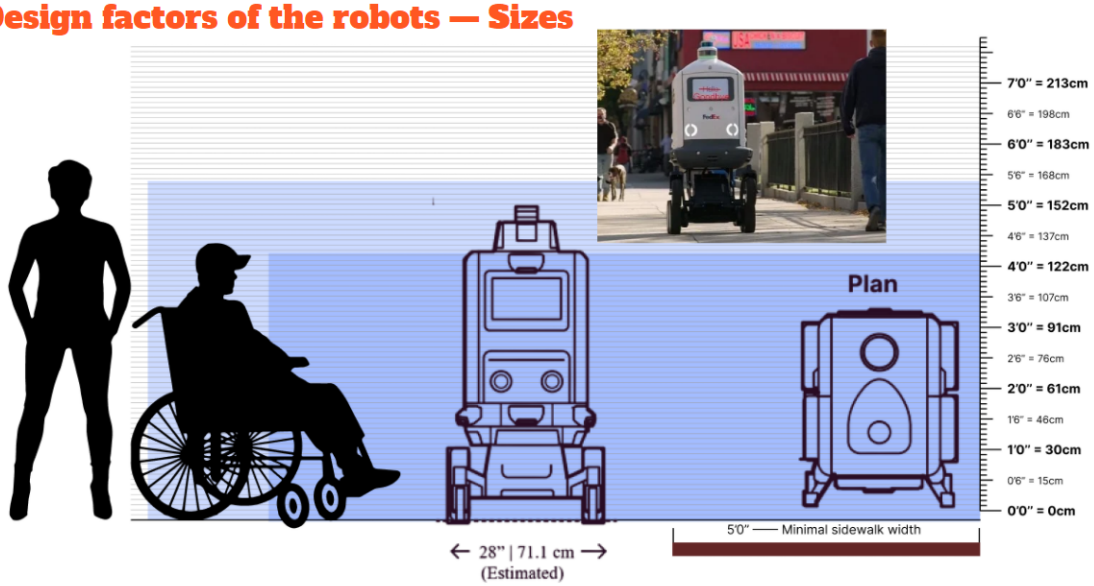
Image Source: https://wheelchairtravel.org/pittsburgh/sidewalks/

Design factors of the robots — Sizes



https://www.npr.org/sections/alltechconsidered/2017/03/23/520848983/hungry-call-your-neighborhood-delivery-robot

Design factors of the robots — Sizes



https://www.npr.org/sections/alltechconsidered/2017/03/23/520848983/hungry-call-your-neighborhood-delivery-robot

Design factors of the robots — Number on the road





Design factors of the robots — Color contrast





Image Source: https://wheelchairtravel.org/pittsburgh/sidewalks/

Design factors of the robots — Signals



Text on the screen



Facial Expressions



Icons



Light



Sound

Design factors of the robots — Speed



Design factors of the robots — Approach Strategy





Design factors of the robots — Social Navigation



Design factors about the delivery robot

Turning Signals	None Sound cues Visual cues	Approaching Strategy	Implicit Explicit
Numbers On the road	Single Double	Social Navigation	Slow down/stop Normal Speed
Sizes	Big Middle Small	Proxemics	Close Normal Far away
Color Contrast	High Low	Speed	Normal High

What are other design factors that you think would be worthy paying attention?

Environmental factors of the robots — Weather



Sunny days



Snowy days



Rainy days

Environmental factors of the robots — Road Conditions



Smooth



Fair



Poor

Environmental factors of the robots — Road Sections



On the road



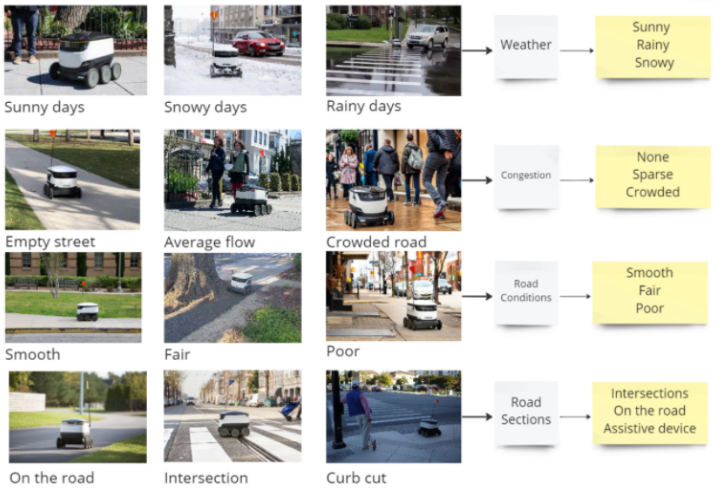
Intersection



Curb cut

Environmental factors about the delivery robot

What are other environmental factors that you think would be worthy paying attention?



All together



Are there any associations you would like to point out?

Functionality



What are the functionalities you think the delivery robot should equip?
What information would you like to get from the robot?

Interactions



Voice input



Touch pad



Controller on the wheelchair



Buttons



Gestures



Phone

Do you want to interact with the robots?

What methods you would prefer to use if you interact with the robots?

Interactions in different scenarios — Passive



You and the robot rub shoulders opposite each other



The robot wants to get in front of you from behind



Robots appear from around the corner

What are the preferred communicative ways in different conditions?

Interactions in different scenarios — Active



You want to across the road, but the robot stopped on the curb cut.



It's a narrow street.
You and the robot are confronting each other. You want it to get out of the way for.



It is snowing outside, you want to ask the robot whether the road in the neighborhood has snow all over it

How you want to interact with it?

Interactions in different scenarios — Conditions

Are there any differences between the following scenarios when you interact with the robots



You are the only person with it on the road

Versus



There are lots of other co-presenters



You meet the robots individually

Versus



You meet the robot with companions

Scenarios

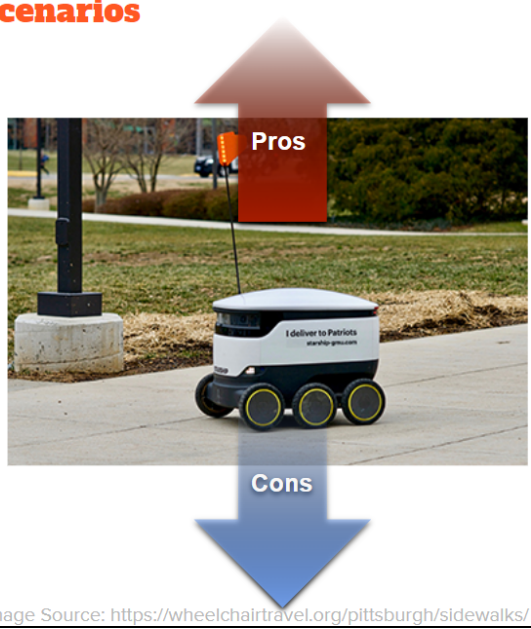


Image Source: https://wheelchairtravel.org/pittsburgh/sidewalks/

We talked about your experience on the sidewalk. Let's say when delivery robots are common, can you imagine a positive scenario and a negative scenario?

Safe Deployment



What are the things you would like to see happen in your mind before deployment and coexistence?

What are the information you would like to know for future sidewalk robot deployment?

Thank you for your participation !



Do you have other questions for me?