2024 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)
July 15-19, 2024. Boston, MA, USA

Robotic Shopping Guidance System for the Visually Impaired Users Using Servo Brakes*

Zhan SHI, Yusuke TAMURA, Zhenyu LIAO, Weizan HE and Yasuhisa HIRATA

***Abstract*— People with visual impairment often face great challenges when shopping in supermarkets because they cannot accurately determine the location of the products they need and hard to understand their own location in the unknown area. To assist visually impaired people achieve daily shopping tasks, in this paper, we proposed a novel shopping cart-type robot system. This robotics system could achieve targeted and accessible navigation using a camera with ArUco markers embedded in the environment. Also, this system uses a passive control policy to guide users safely. Besides, this system provides verbal and haptic feedback to users to make them aware of where they will go. Using the proposed system, we completed 12 times validation experiments. The results show in all trials, the blindfolded users could find the desired spot guided by the system.**

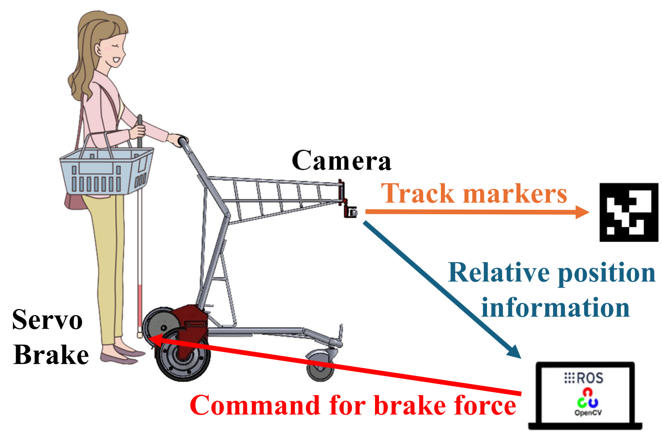


Fig. 1: Concept: using ArUco markers and servo brakes to guide visually impaired people.

I. INTRODUCTION

As society becomes increasingly focused on inclusivity and accessible environments, the daily needs of specific groups, particularly the shopping experience of people with visual impairment, have become a focus of our research. Recently, supermarket shopping is one of the most common daily activities. However, for people with visual impairment, completing shopping tasks independently becomes a significant challenge due to their inability to recognize product labels and navigation signs [1]. Besides, the location of products may frequently change and supermarkets often lack navigation aids designed specifically for the visually impaired. These facts not only limit their possibility to shop independently but also negatively impact their shopping experience and overall quality of life [2]. Therefore, developing a system that can assist visually impaired individuals in daily shopping tasks is a necessary topic.

There are several researches to assist the visually impaired persons to move around space using robotics technologies. Ye et al. [3] has developed a cane-shaped navigation aid that effectively helps people with visual impairments to understand objects around them. Asakawa [4] has developed an AI Suitcase that allows robots to navigate seamlessly and naturally in urban environments to assist people with visual impairments. While these studies demonstrate the ability to guide users in public spaces, but in certain scenarios these systems require additional functionality to perform specific tasks, such as guiding users to a specific shopping location. In addition, there are some studies focus on guiding healthy persons in the supermarket. MetraLabs GmbH Ilmenau developed a robot called TOOMAS [5] to help customers in home improvement stores find the products they want to buy. Jayananda et al. [6] developed an application that integrates augmented reality and remote shopping technologies to guide shoppers to the products they need and to make healthier and more beneficial choices when shopping. However, these technologies have been developed primarily for able-bodied individuals and lack interaction methods for visually impaired people, which limits their applicability in certain situations.

To help the visually impaired persons, we presents an innovative system for guiding visually impaired users in shopping, based on servo brakes, as depicted in Fig. 1. This system is expected to be suitable for supermarket environments and can provide a safer and more reliable shopping experience for people with visual impairment through passive human-robot interaction. The passive human-robot interaction here means the robot system only moves when users give some input like using their hands to push the robot. This kind of interaction can reduce the risk of accidental collisions because the robot does not move autonomously without users' motion. In addition, the passive system gives the user a sense of self-efficacy, by allowing the robot to assist as much as possible in the way the user wants. We use two servo brakes one of each wheel to achieve the passive interaction.

*This work was partially supported by JST [COI-NEXT][Grant Number JPMJPF2201]

The authors Zhan SHI, Yusuke TAMURA, Zhenyu LIAO, Weizan HE and Yasuhisa Hirata are with the Department of Robotics, Graduate School of Engineering, Tohoku University, Sendai 980-8579, Japan (email: z.shi@srd.mech.tohoku.ac.jp; ytamura@tohoku.ac.jp; z.liao@srd.mech.tohoku.ac.jp; w.he@srd.mech.tohoku.ac.jp; hirata@srd.mech.tohoku.ac.jp).

When users are moving toward the desired direction, the brakes give no torque to the robot. When users deviate from the desired route, the brakes provide resistance torques to the wheels. The difference in the two wheels' torque contributes to the intuitive turn for users when they push the robot. Besides, compared to the servo motors, the servo brakes have relatively lower energy consumption. Many types of markers are being used in real-world supermarkets to help people navigate [7]. The markers could include the item and directional information, and in this paper, we integrate the marker named ArUco into the system. This efficient visual positioning method helps the shopping cart to accurately identify its location and direction within the supermarket. We envisage a simplified supermarket environment where ArUco markers are strategically placed, allowing the cart to recognize these markers through its visual sensors and navigate precisely to specific product areas. This method is more suitable for indoor environments and offers greater accuracy than traditional positioning technologies such as GPS or Wi-Fi [8]. Additionally, our system integrates several feedback modalities, including verbal feedback and haptic feedback, to enhance the users' shopping experience. Verbal feedback tells clear directional guidance for users. Haptic feedback corrects users' moving directions via resistance feelings generated by the servo motors and conveyed directly by physical contactions.

The arrangement of this paper is as follows: In Section II, we briefly describe the structure of the proposed system; in Section III, how the passive robot move base worked is elaborated in detail, including the control policy of the servo brakes; in Section IV, we introduce how to guide users to walk along with desired path; in Section V, we verify the the practical effectiveness of our proposed approach through guidance experiments; in Section VI, we discuss the results derived from the experiments; and finally, in Section VII, we summarize the findings of this study and explore future works for this paper.

II. System Overview

In this study, we proposed an innovative solution aimed at assisting visually impaired individuals with indoor shopping tasks. The system consists of two functional parts, one is a robot move base and the other is a navigation module. The robot move base shown in Fig. 2 uses a passive servo brake system rather than traditional motor-driven active systems, to enhance safety. The navigation module is in charge of enabling real-time acquisition of position information of users in the environment. We use a camera mounted on our own robot move base to detect ArUco markers, which are embedded in the environment, to obtain a relative position between the markers and the robot move base. Then, by calculating the relative position with the markers' positions, the system knows where the user in the environment is.

III. Robot Move Base

The robot move base is modified based on a normal shopping cart. We added several parts to the shopping cart like a 24 V lithium battery, a system master controller (laptop), two embedded systems (Arduino), two brake controllers, and two servo brakes one of each wheel. Besides, we equipped a RGBD camera for detecting environmental information.

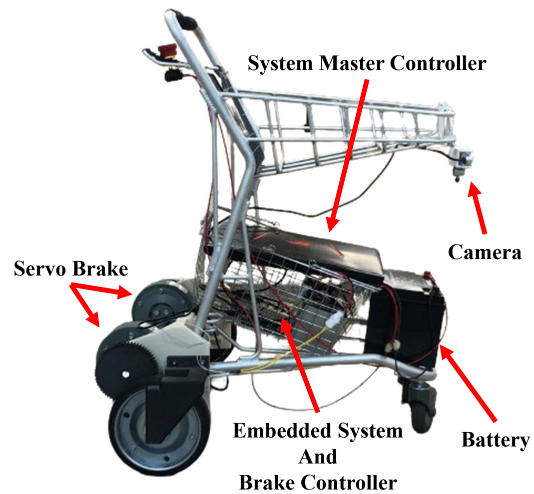


Fig. 2: Robot move base with camera.

A. Passive system

This system uses servo brakes to make a passive guidance to refine users' moving path. In robotics, passive systems are distinguished from active systems by their dependence on external forces or torques applied by the user [9]. The passive system features as their movement is entirely controlled by external power input, and they remain stationary in the absence of such external inputs. This feature makes this system guarantees users 'drive' the robot instead of the robot 'drives' the users. As a result, compared to active systems, passive systems significantly reduce the risk of accidental collisions as they do not move spontaneously without user input - a critical feature in applications with frequent human interaction. Besides, passive systems are more energy efficient, cause they only respond to motion when external forces are applied, significantly reducing energy cost. In addition, passive systems offer a more direct user control experience, where users can intuitively feel the system's response through the force they apply, increasing users' confidence, comfort in operating the system [10], and sense of self-efficacy. Considering these features of a passive control system, we decided to employ a passive system to guide the visually impaired persons going shopping.

B. Control policy

We controlled the servo brake's torque to finely adjust the steering behavior of the robot to guide the users. We established a linear relationship model between the left and right braking torques (τ_l and τ_r) based on the relative angle (θ), shown in Fig. 3. This policy enables the robot to detect subtle changes in direction caused by applying push force from the users, then provides a smooth and accurate

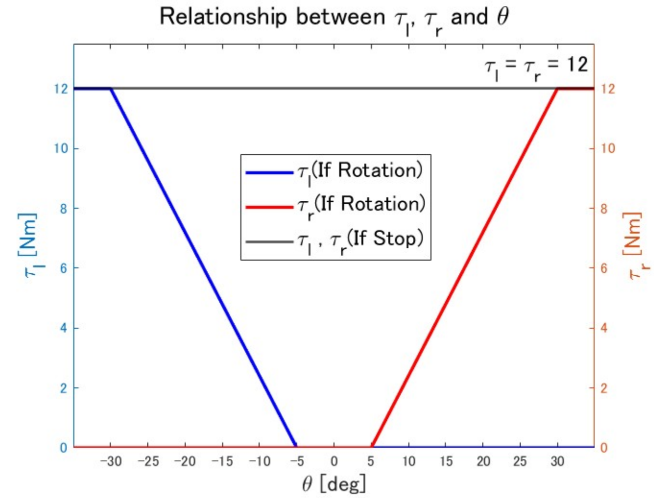


Fig. 3: The relationship between left brake torque τ_l, right brake torque τ_r, and the relative angle θ with markers and the robot.

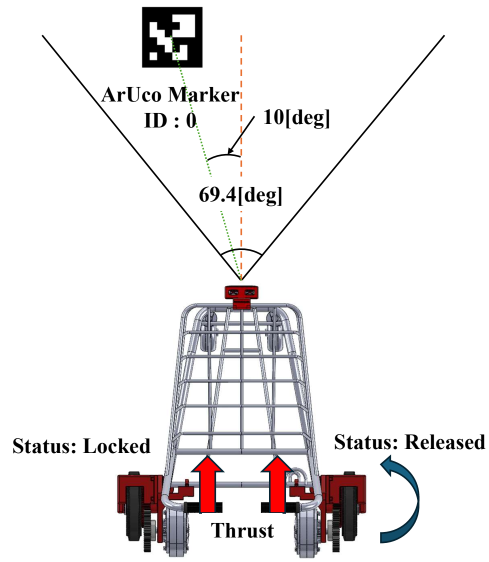


Fig. 4: Example of guidance policy using ArUco markers and servo brakes.

response. The quantitative relationships are defined below.

$$\begin{pmatrix}\tau_l\\ \tau_r\end{pmatrix} = \begin{cases} \begin{pmatrix}12\\0\end{pmatrix}, \theta < -30\,\text{(If Rotation)} \\ \begin{pmatrix}-\frac{12}{25}(\theta+5)\\0\end{pmatrix}, -30 \le \theta \le -5\,\text{(If Rotation)} \\ \begin{pmatrix}0\\0\end{pmatrix}, -5 < \theta < 5\,\text{(If Rotation)} \\ \begin{pmatrix}0\\ \frac{12}{25}(\theta-5)\end{pmatrix}, 5 \le \theta \le 30\,\text{(If Rotation)} \\ \begin{pmatrix}0\\12\end{pmatrix}, \theta > 30\,\text{(If Rotation)} \\ \begin{pmatrix}12\\12\end{pmatrix}, \text{(If Stop)} \end{cases} \tag{1}$$

Where τ_l and τ_r represents left and right wheel brake torques respectively; 12 is the max brake torques applied on wheels; 25 is the ration range of relative angle θ.

According to the defined (1), within the linear control range of the yaw angle θ from 5 to 30 degrees, the right braking torque (τ_r) increases linearly with the angle, while the left braking torque (τ_l) remains zero. In this case, users will tend to turn right. And when angle θ is from -5 to -30 degrees, robots will turn left intuitively. When the angle deviates to -30 degrees, the left braking torque (τ_l) is activated to its maximum of 12 Nm, and the right braking torque (τ_r) drops to zero, prompting the robot to rotate quickly to the left. On the contrary, when the angle deviates to +30 degrees, the right braking torque (τ_r) reaches its maximum, and the left braking torque (τ_l) is zero, enabling the robot to turn quickly to the right. When the relative angle is within the non-intervention zone of ±5 degrees, both the left and right braking torques (τ_l and τ_r) are zero, indicating that both wheels are free to roll, ensuring the user can push the robot smoothly. On the contrary, when the robot reaches the target, the left and right braking torques to their maximum to bring the robot to a stop.

IV. NAVIGATION MODULE

To navigate users, we have to ensure users' location in the supermarket. In this paper, we perform a route planning approach for the supermarket environment and make use of the ArUco marker-based method to locate users. The guidance policy is shown in Fig. 4. In this figure' case, the robot's camera reads an ArUco marker, and the system judges that the information from the marker that the user should walk left at 10 degrees. The system gives a command to the left servo brake to make it in a braking state with specific torque τ_l and gives a command to the right servo brake without any torque to make the right wheel a freewheel. As a result, the user can turn left intuitively by pushing the robot.

A. Positioning based on ArUco markers

Recently, several markers containing directional information have been used to guide people in public spaces such as markets. In this paper, we use one type of marker called ArUco to provide guidance information to people. ArUco markers [11][12][13], developed by Garrido-Jurado and others, are a specific type of reference marker consisting of black squares with embedded binary grids. These grids not only contain each marker with a unique identification

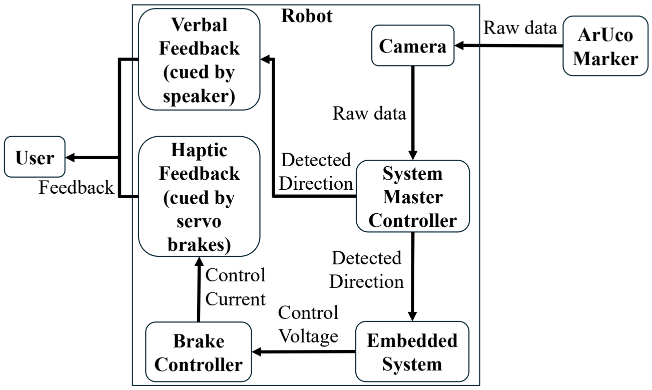


Fig. 5: System's control architecture.

code but also have orientation information. During image processing, all square-shaped objects are identified, and then binary grids are used to distinguish ArUco markers from other shapes. The pixel coordinates of the corners of the marker are extracted and refined to sub-pixel accuracy using the gradient information of the marker edges in the image. Subsequently, the position and orientation of the marker relative to the camera, including its translation and rotation vectors, can be precisely determined by solving the Perspective-n-Point (PnP) problem using the Perspective-Three-Point (P3P) algorithm. P3P is a typical algorithm used in the computer vision field for estimating the pose of a camera in a three-dimensional space based on the observations of specific known points. In addition, all scale measurements in the image are estimated based on the predefined size of the markers. As shown in Fig. 4, this paper uses the markers in a 6x6 format with a side length of 150 mm to ensure that there are enough unique graphics for use, in addition to experiments in indoor navigation where this form of marker is suitable for recognition [14].

Fig. 5 illustrates the detailed control architecture of the proposed navigation system, which is composed of several interconnected components designed to provide precisely navigational assistance. At the forefront of the system, a high-resolution camera, serving as the primary sensor, continuously captures real-time images of the surrounding environment and transmits them to the system master controller via a live video stream. Within the system master controller, a series of advanced image-processing algorithms are employed to identify and track ArUco markers—key reference points for environmental navigation—to extract relative positional information. Subsequently, the embedded systems analyze the extracted marker positions and calculate the necessary control voltages, a crucial step for generating accurate response signals for subsequent actions. At the end of the control chain, servo-brakes act as actuators, converting control signals into mechanical actions for physical braking. The servo brakes adjust their force in response to specific commands from the control unit, achieving precise control.

B. Route planning approach

Normally, the supermarkets are full of paths enclosed by goods shelves and the paths have right-angle turns. These features of the paths' layout require frequent straight and right-angle turns movements done by customers. Based on the aforementioned facts, we propose placing the ArUco markers in each right-angle turn and facing toward to paths. This arrangement could guarantee the robot can read a marker at any path. Then, the robot is located by recognizing the informative marker and the system plans the movements of the robot combining the location of the robot and the desired item that is inputed into the system by the staff of the supermarket. Once the planned path is determined by the system, by adjusting the braking force of the servo brakes users are guided to the desired item.

To improve the users' experience during guidance, we provide verbal feedback to the users using text-to-speech technology to convert the next desired motions from code to speech. Besides, we apply haptic feedback to help the users better understand the robot's maneuvers. The haptic here is generated by the resistance of servo-brakes and conveyed to the users through direct contact with the users' hands and the robot‘ handle.

V. EXPERIMENTS

In this section, we conducted a guidance experiment to validate the effectiveness of the proposed system. The experiment involved 6 healthy adult participants who had not received specific training for this guidance system beforehand. To ensure the participants had a basic understanding of the system feedback, we briefly introduced them to how to use this system. Specifically, to prevent the participants from reacting based on a known route rather than the system's feedback during turns, we had them wear blindfolds before entering the experimental area, and ensure they did not know the experimental environment.

A. Experimental Setup

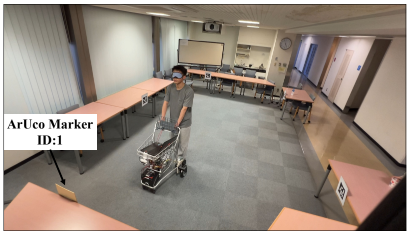
This experiment was conducted in an environment that mimics the markets in the real world. We arranged the designed different desired paths with similar widths to the paths in a real market and with right-angle turns for each path. As shown in Fig. 7, we designed two routes for this experiment to mimic a market scenario (right-angle turns and straight paths). At the end of each route, we positioned a food counter and a drink counter, respectively. In this experiment, each participant completed navigation tasks on two predetermined routes, a total of 12 trials were done. At the start of the experiment, we asked participants about the items they intended to purchase and manually entered the designated destination based on their responses. The navigation system then began guiding participants along the predetermined route.

The specific experimental process is as follows, as depicted in Fig. 6: The experiment begins with the robot moving forward to identify and position itself at marker 0 (see Fig. 6a). When the robot is about one meter away

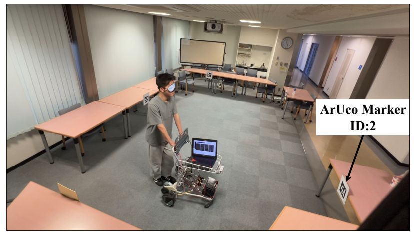
(a) The experiment begins, moving towards the identified marker 0.

(b) Begin to turn left when 1 meter away from marker 0.

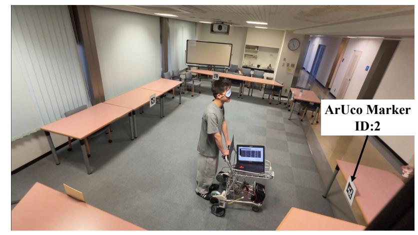
(c) Stop turning when marker 1 is detected, and advance towards it.



(d) Begin to turn left when 1 meter away from marker 1.



(e) Stop turning when marker 2 is detected, and advance towards it.



(f) Stop when 1 meter away from marker 2.

Fig. 6: Experimental scenarios

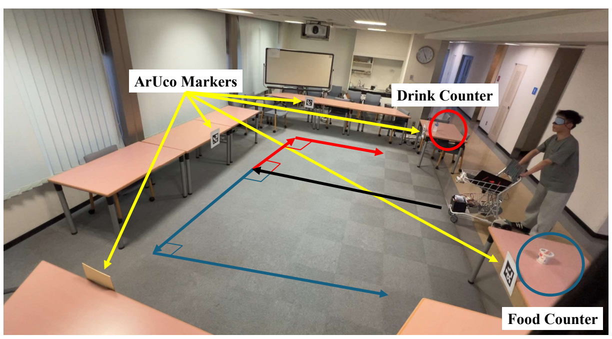


Fig. 7: Route planning. We decorate an open area as a "market" with two booths to sell food and drink respectively. Among the area, several AruCo markers are setted.

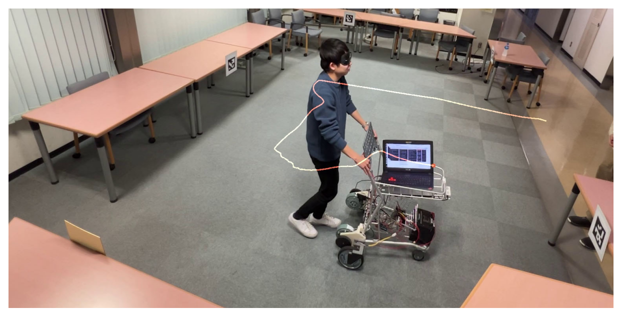


Fig. 8: Moving trajectory maps based on the optical flow method.

TABLE I: TASK COMPLETE TIME FOR EACH TRIAL

Participant	1	2	3	4	5	6	Average Time
1^{st} Trial[s]	46.0	14.0	39.0	36.0	29.0	17.0	30.2
2^{nd} Trial[s]	25.0	16.0	33.0	23.0	27.0	20.0	24.0

from marker 0, it begins to turn left (see Fig. 6b). Once turning is complete and marker 1 is detected, the robot stops turning and advances towards it (see Fig. 6c). Similarly when the robot is about one meter away from marker 1, it begins to turn left (see Fig. 6d), stops turning once marker 2 is detected, and advances towards it (see Fig. 6e), finally stopping when about one meter away from marker 2 (see Fig. 6f).

B. Experimental Result

Through the experiment, for all trials, the participants were successfully guided to their desired shopping counter. We recorded the completion times for each trial and the summary is shown in Table I. The results revealed that the average completion time for the 1^{st} trial was 30.2 seconds and for the 2^{nd} trial, it was slightly shorter, at 24.0 seconds. For both trials, this time is longer than the time that healthy people walk along the route, while it is reasonable for blindfolded persons who cannot use their eyes to watch out surroundings. To compare the completion time, we tested another three healthy participants in the same experimental space with blindfolds and we navigated the participants by referring to the methods of real-world caregivers. Each participant was tested twice, and the average completion time for all six trials was 32.2 seconds. We also collected the motion trajectory of participants based on the optical flow method [15] and we show an example in Fig. 8. From the trajectory, we notice the participants could walk along the desired route without much deviation.

Additionally, we conduct three surveys of participants. We ask them whether they feel scared during the test, how much the system could help them, and how strongly they feel they control the robot rather than the robot controlling them. All participants felt the system was safe enough to be used and they agreed that the system could help them to find desired goods. Most participants agree that they never felt they were controlled by robots.

VI. DISCUSSION

From the experiments, we observed that the proposed the system can help users effectively navigate to the desired item, and we also found that the average completion time with the proposed system in both 1^{st} trial (30.2s) and 2^{nd} trial (24.0s) are faster than the test which is a traditional navigation method by a caregiver (32.2s). However, through analysis of the data and experimental procedures, we also identified some potential issues. For instance, according to the data in Table 1, we noticed that when participants first time to use the system, participant 1 and 4 required more time to understand and adapt to the system, but their performance improved markedly during their second use. This finding suggests that in the practical application of the system, it is necessary to provide users with more comprehensive instructions and increase their practical experience with the system to help them better understand and adapt to it.

We also noted significant individual differences in the experimental results. As a passive system, the completion time of the experiment largely depends on the participants' walking speed and adaptability. In particular, we observed that Participant 2 completed the experiment at the fastest speed among all participants. However, due to the fast walking speed, compared to other participants, we noticed through the experimental video that there was a significant left-right swaying motion when approaching markers and turning corners. This may be because the system needs to apply strong braking to one side of the wheel to make large-angle corrections, and this correction leads to the exceeding steering angle if the user walks fast. In the future, we can modify control parameters like maximum torque for each user to make the system more suitable for them.

This experiment was not taken in the real market, while we have endeavored to replicate the characteristics of a real supermarket in the experimental environment like similar paths' design and turns' design. Therefore, we believe that the proposed system would also have similar performance in a real supermarket environment compared to the experimental results.

VII. CONCLUSIONS

In this paper, we introduced a novel shopping cart-type robot system to aid visually impaired individuals in their daily shopping endeavors. This robotic system employs a passive control policy to safely guide users to desired item spot. Besides, the system enables precise and accessible navigation by reading imformative markers integrated into the surroundings. Furthermore, the system offers verbal and haptic feedback to users, enhancing their awareness of their surroundings. Through 12 validation experiments, blindfolded participants successfully reached their intended destinations in all trials under the guidance of the system.

In the future, we would like to make this technology not only support accessible shopping but also provide valuable insights for developers and supermarket operators, promoting a more inclusive society. Specifically, we will improve marker recognisability by integrating the VisualTags system [16], which has proven effective in complex environments; we also plan to combine camera-based and odometry-based location detection systems [17] for more accurate user localization; and we will conduct extensive field testing to assess the system's robustness and the impact of verbal and tactile feedback on the spatial awareness of visually impaired people.

REFERENCES

[1] N. A. Giudice, "15. navigating without vision: Principles of blind spatial cognition," *Handbook of behavioral and cognitive geography*, p. 260, 2018.

[2] V. Kulyukin, "Robot-assisted shopping for the blind: Haptic and locomotor spaces in supermarket," in *Proceedings of the AAAI Spring Symposium on Multidisciplinary Collaboration for Socially Assistive Robotics Stanford University*, 2006, pp. 36–38.

[3] C. Ye, S. Hong, X. Qian, and W. Wu, "Co-robotic cane: A new robotic navigation aid for the visually impaired," *IEEE Systems, Man, and Cybernetics Magazine*, vol. 2, no. 2, pp. 33–42, 2016.

[4] C. Asakawa, "Interaction techniques with a navigation robot for the visually impaired," in *Proceedings of the 2023 ACM/IEEE International Conference on Human-Robot Interaction*, 2023, pp. 1–1.

[5] N. Doering, S. Poeschl, H.-M. Gross, A. Bley, C. Martin, and H.-J. Boehme, "User-centered design and evaluation of a mobile shopping robot," *International Journal of Social Robotics*, vol. 7, pp. 203–225, 2015.

[6] P. Jayananda, D. Seneviratne, P. Abeygunawardhana, L. Dodampege, and A. Lakshani, "Augmented reality based smart supermarket system with indoor navigation using beacon technology (easy shopping android mobile app)," in *2018 IEEE International Conference on Information and Automation for Sustainability (ICIAfS)*. IEEE, 2018, pp. 1–6.

[7] Y. Vijaya Kumar, "Blindshopping: Navigation system," 2014.

[8] M. Elgendy, M. Herperger, T. Guzsvinecz, and C. S. Lanyi, "Indoor navigation for people with visual impairment using augmented reality markers," in *2019 10th IEEE International Conference on Cognitive Infocommunications (CogInfoCom)*. IEEE, 2019, pp. 425–430.

[9] O. Y. Chuy, Y. Hirata, Z. Wang, and K. Kosuge, "A control approach based on passive behavior to enhance user interaction," *IEEE Transactions on Robotics*, vol. 23, no. 5, pp. 899–908, 2007.

[10] Y. Hirata, A. Hara, and K. Kosuge, "Motion control of passive intelligent walker using servo brakes," *IEEE transactions on robotics*, vol. 23, no. 5, pp. 981–990, 2007.

[11] G. Čepon, D. Ocepek, M. Kodrič, M. Demšar, T. Bregar, and M. Boltežar, "Impact-pose estimation using aruco markers in structural dynamics," *Experimental Techniques*, pp. 1–12, 2023.

[12] Z. Xu, M. Haroutunian, A. J. Murphy, J. Neasham, and R. Norman, "An underwater visual navigation method based on multiple aruco markers," *Journal of Marine Science and Engineering*, vol. 9, no. 12, p. 1432, 2021.

[13] M. F. Sani and G. Karimian, "Automatic navigation and landing of an indoor ar. drone quadrotor using aruco marker and inertial sensors," in *2017 international conference on computer and drone applications (IConDA)*. IEEE, 2017, pp. 102–107.

[14] Z. Siki and B. Takács, "Automatic recognition of aruco codes in land surveying tasks," *Baltic Journal of Modern Computing*, vol. 9, no. 1, pp. 115–125, 2021.

[15] A. Bruhn, J. Weickert, and C. Schnörr, "Lucas/kanade meets horn/schunck: Combining local and global optic flow methods," *International journal of computer vision*, vol. 61, pp. 211–231, 2005.

[16] J. M. Sáez, M. A. Lozano, F. Escolano, and J. Pita Lozano, "An efficient, dense and long-range marker system for the guidance of the visually impaired," *Machine Vision and Applications*, vol. 31, pp. 1–10, 2020.

[17] J. Engel, J. Sturm, and D. Cremers, "Camera-based navigation of a low-cost quadrocopter," in *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, 2012, pp. 2815–2821.