A Comprehensive Approach to Design and Implement an IoT-Enabled Intelligent Shopping Cart System with Obstacle-Aware Navigation and Enhanced Customer Engagement for Elevated Consumer Experiences

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Abstract

Supermarket shopping is an experience that everyone has in life. This project aims to design an intelligent and user-friendly shopping cart and interactive web page, to elevate the overall customer shopping experience. The shopping cart designed in this project integrates multiple functionalities that allow users to access information about the items within the cart via the interactive web page and exert control over the movement of the cart. While moving, the shopping cart can autonomously detect obstacles in its path and navigate around them. Simultaneously, users can check the total cost of their selected items by reviewing the cart's contents, enabling them to decide whether the cart should continue following them. The project primarily utilizes an ultrasonic module to determine the cart's location and trail a specific customer. The shopping cart employs automatic barcode scanning to identify various products, and the WiFi module facilitates communication with the server via the MQTT protocol, enabling seamless interaction. The fruition of this project serves as a tangible representation of the Internet of Things application, demonstrating how connectivity through the internet enhances people's lives with greater convenience.

Keywords: Internet of Things, ultrasonic ranging, STM32singlechip, smart shopping cart

1. Introduction

The widespread of information, and communication technology, coupled with the advancements in Internet of Things technology, has brought our life into the stage of a smart city. The increase in electronic devices and applications has significantly improved convenience in our daily lives. With the increasing prevalence of mobile devices, the development of smart cities naturally falls toward this technological landscape. Therefore, it is necessary to develop intelligent equipment [1].

In the shopping scene, an intelligent shopping cart can greatly enhance the shopping experience. Essential and fundamental functions of an intelligent shopping cart include automatic following the user as well as automatic obstacle identification and avoidance. Another convenient feature is the automated calculation of the total price of items in the shopping basket. This enables customers to view the items and their respective prices on the web page from their mobile phones, eliminating the need for manual price calculations.

2. Literature Review

In the past, numerous researchers have conducted diverse studies on smart shopping carts. Supermarket owners benefit from these innovations in terms of time savings, reduced manpower, and space efficiency, leading to decreased investments. The smart shopping trolley can be used in all retail shopping malls, supermarkets, hypermarkets, and clothing showrooms [2].

Several innovative concepts have emerged to revolutionize shopping cart design, aiming to enhance the overall shopping experience and reduce human efforts. Sadia *et al.* [3] proposed the integration of RFID technology to bolster the durability of product identification tags. They suggest the implementation of RFID in shopping carts, creating an intelligent shopping system where all supermarket carts are equipped with RFID tags to reduce wait times during the checkout process and improve the customer purchasing experience.

Gunawan et al. [4] installed an IOIO microcontroller and an Android smartphone together with sensors and a controller in a shopping cart. The basket is configured in the shape of a two-wheeled mobile robot.

Tai *et al.* [5] also utilized the ultrasonic sensor because of the advantages include a wide detection area, reduced sensitivity to light, the ability to detect glass and shiny surfaces, compact size, lightweight construction, minimal memory usage, cost-effectiveness compared to Laser Range Finder (LRF) or cameras, and lower power.

These investigations into shopping cart functionality and application technology have significantly expanded the research landscape of intelligent shopping carts. As a result, tasks have become more focused and precise, yielding results that align smart shopping carts more closely with people's evolving needs.

3. Methodology

Figure 1Figure 1 shows a flow chart for the smart shopping cart system from the user side whereas Figure 2 illustrates a flow chart for the operation of the shopping cart.

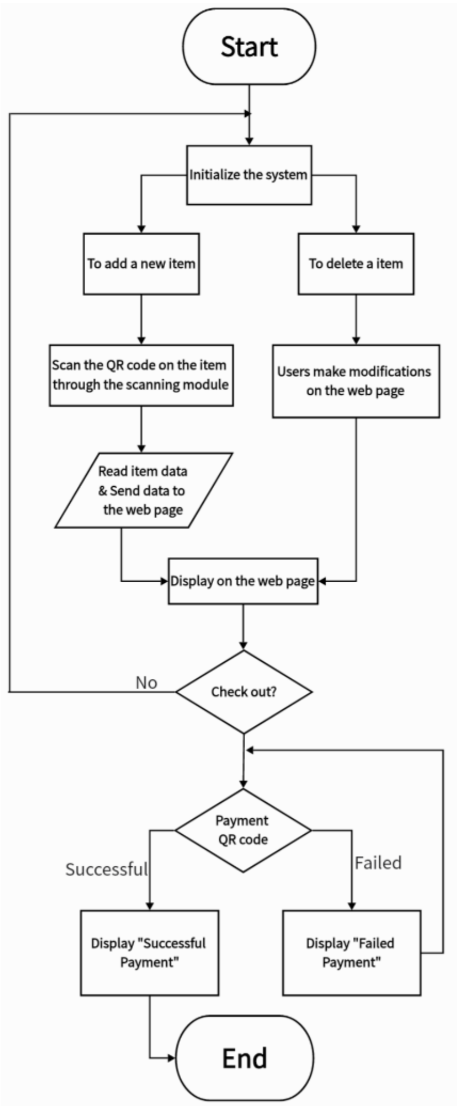

Figure 1 Flow chart for the smart shopping cart system from the user side

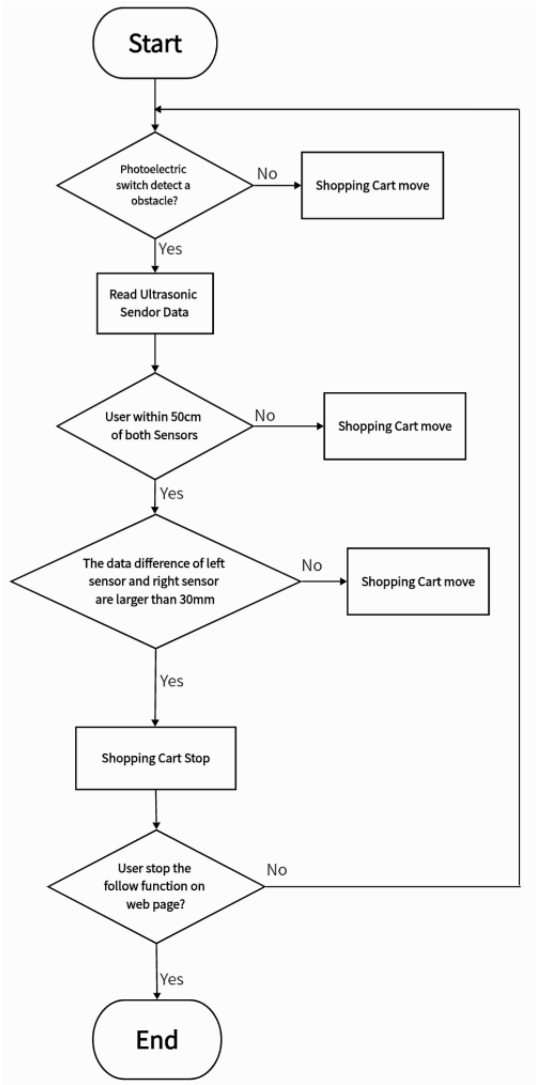

Figure 2 Flow chart for the operation of the shopping cart

When the shopping cart is started, it will detect obstacles by photoelectric switches and avoid them. The ultrasonic sensor will provide real-time feedback on the distance between the user and the shopping cart. If the distance between the shopping cart and the user, as well as the orientation of the shopping cart, exceeds the set range, the shopping cart will move and adjust the distance and direction. The mobile function of the shopping cart will continue until the user stops the function on the webpage. In addition, users can use the QR code scanning module on the shopping cart to scan the QR code of the product and add it to the shopping list on the webpage, to manage the list and settle the payment on the webpage.

3.1. Microcontroller

STM32 F407 ZET6 is used as the main controller of the shopping cart. By handling the information obtained from sensors and servers, the controller is able to control the movement of the shopping cart and communicate with the user.

3.2. PCB Module

The PCB circuit board consists of STM32 F407ZET6 main control board, DC-DC buck module, A4950 dual motor drive module, ultrasonic sensor, photoelectric switch sensor, two-dimensional code module and motor encoder as shown in Figure 3 and Figure 4. The circuit board is highly integrated and the modular design makes it easy to update and repair.

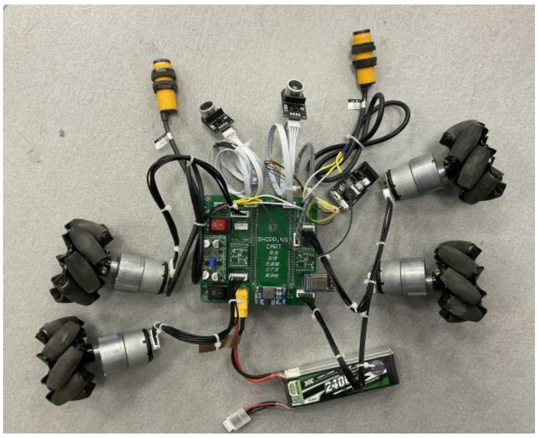

Figure 3 Connection between the main board, sensors, and wheels

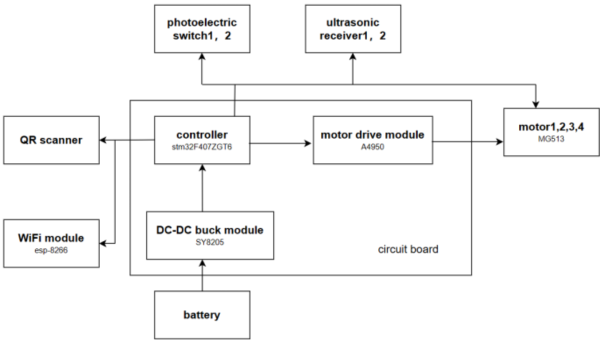

Figure 4 Block diagram for the circuit connection

3.3. DC-DC Antihypertensive Module

The DC-DC antihypertensive module employs the SY8205 chip, a high-efficiency synchronous stepdown DC-DC converter capable of delivering a 5 A output current. The SY8205 operates over a wide input voltage range from 4.5 V to 30V and integrates the main switch and synchronous switch with very low RDS(ON) to minimize the conduction loss. The module consists of two voltage outputs, one 5V voltage and another output to meet the diverse voltage requirements of various modules.

The chassis for the shopping cart is crafted from a 6 mm thick POM plate through laser cutting as shown in Figure 5(a). The chassis is used to hold the shopping cart bracket, circuit board and various sensors. Furthermore, 3D printing technology is used to print the clamp to hold the ultrasonic sensors as shown in Figure 5(b).

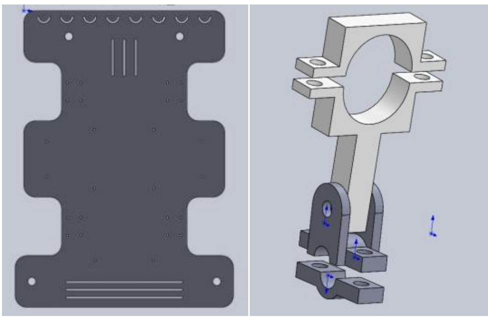

Figure 5 (a) The chassis and (b) the ultrasonic clamp

3.4. Mecanum Wheel

The outer ring of the Mecanum wheel as shown in Figure 6 is equipped with rollers arranged a 45° to the axle and contact with the ground. During rotation, the friction generates a 45° reverse thrust force along the axle. This oblique thrust force can be divided into two vectors which are longitudinal and transverse. The entire vehicle is propelled by two pairs of Mecanum wheels, each featuring a mirrored arrangement of rollers. Each wheel generates its own vector, and the combined force of these vectors determines the final motion of the car [6].

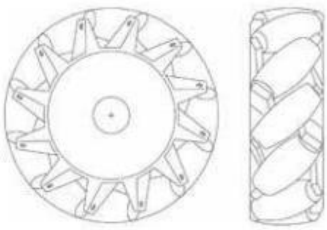

Figure 6 Mecanum wheel

Omnidirectional motion is achieved by installing four Mecanum wheels at the corners of the chassis. The overall velocity, V, can be obtained through Eq (1), where V_x, and V_y indicate velocity in the x-direction and y-direction respectively and ω is the angular velocity, as shown in Figure 7.

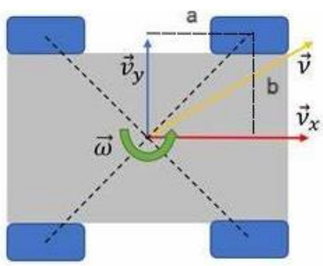

Figure 7: The direction of velocity.

$$\rightarrow \quad \rightarrow \quad \rightarrow \quad \rightarrow \tag{1}$$

$$\vec{V_1} = \left|\vec{V_X}\right| - \left|\vec{V_Y}\right| - \left|\vec{\omega} \times (a+b)\right|$$
$$\vec{V_2} = \left|\vec{V_X}\right| + \left|\vec{V_Y}\right| - \left|\vec{\omega} \times (a+b)\right|$$
$$\vec{V_3} = \left|\vec{V_X}\right| + \left|\vec{V_Y}\right| + \left|\vec{\omega} \times (a+b)\right|$$
$$\vec{V_4} = \left|\vec{V_X}\right| - \left|\vec{V_Y}\right| + \left|\vec{\omega} \times (a+b)\right|$$

3.5. Ultrasonic Ranging

To measure the distance between the user and the shopping cart, two ultrasonic sensors were positioned at the front end of the shopping cart as illustrated in Figure 8. These sensors were positioned roughly parallel to the user's waist.

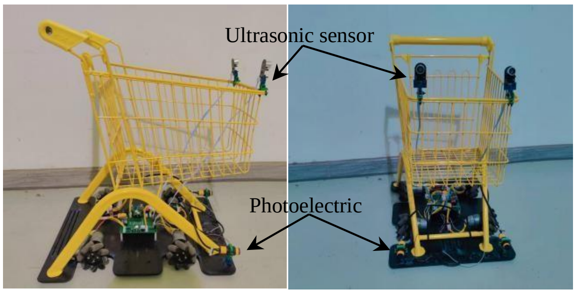

Figure 8: Overall view of the shopping cart.

By taking an ultrasonic transmitter in users' hands, the receivers can receive the ultrasonic waves and calculate the distance between the transmitters and receivers. These distances are denoted as X_1 and X_2 respectively [7]. The concept of the transmitters and the receivers is illustrated in Figure 9.

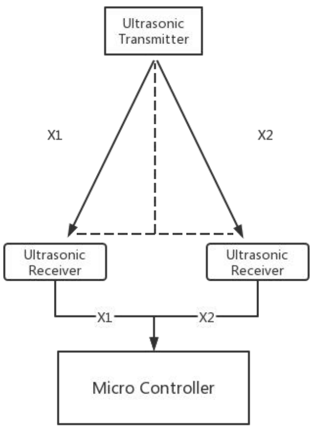

Figure 9: The concept of the transmitters and the receivers

3.6. Cascade PID

Cascade control is one of the most successful methods for enhancing single-loop control performance, particularly when the disturbances are associated with the manipulated variable and the final control element exhibits nonlinear behavior [5].

In the controlling of the Mecanum wheelbase, two desired distances between the ultrasonic transmitter and receivers are denoted as X_3 and X_4 serve as the input of the cascade PID. To control the distance between the user and the shopping cart, the distance $(X_1 + X_2)/2$ is considered as the feedback and 0.5 m is set as the desired input for the Position PD control. To ensure the front of the cart always faces the user, $(X_1 - X_2)$ is considered as the feedback and zero difference as the desired input of the Angle Loop PD control. With position control and angle control, V_x, V_y and ω can be calculated. By utilizing the calculated V_x, V_y and ω as the input for the Velocity Loop PID, the final PWM signal is conveyed to the motor as shown in Figure 10.

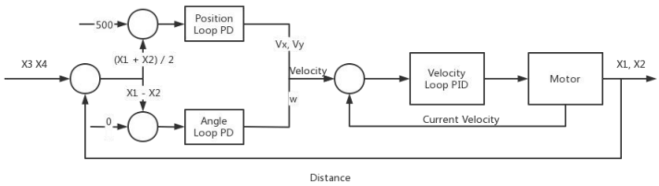

Figure 10: Block diagram of PID control.

3.7. Obstacle Avoidance

Two E18-D80NK photoelectric switches are placed on the front of the cart as illustrated in Figure 8. Upon any obstacle is detected, the cart will stop following the user and overtake the obstacle. As soon as the cart overtakes the obstacle and no other obstacles exist, the cart will continue the job.

3.8. Server Communication

Advancements in the Internet of Things (IoT) have enabled innovations in smart home and industrial automation, offering possibilities for remote monitoring and controlling devices. These solutions contribute to energy efficiency and cost saving, as appliances are monitored and controlled by small, resource-constrained embedded devices [8].

To establish communication with the server, an esp-8266 WiFi module is connected to the microcontroller board. By using the Message Queuing Telemetry Transport (MQTT) protocol, the controller is able to publish topics containing commodity information to the server and subscribe to topics conveying user input from the server.

In this system, the server initiates requests to the front-end controller through HTTP and utilizes the MQTT protocol for communication with the embedded device. The back-end is developed in Java, leveraging the SpringBoot framework to simplify the complexity of the development, and incorporates MySQL for database connectivity and data persistence. In practical scenarios, the server needs to establish a long connection with a large number of embedded devices. The traditional blocking I/O involves threading, and the frequent switching between threads can lead to significant overhead. Therefore, domestic smart sockets are employed as the underlying I/O container to address these challenges.

A prototype incorporating these features has been successfully implemented and tested within a simple home automation network to validate its functionalities. The results demonstrate that the system responds rapidly, preventing overconsumption and electrocution hazards. This capability positions the technology to contribute to creating safer and smarter homes in the next generation [9].

The multiplexing of threads is achieved using thread pool and asynchronous callback technologies. This approach effectively reduces the overhead associated with thread creation and destruction, resulting in a substantial improvement in the system's load capacity.

3.9. QR Code Scanner

QR codes are a cost-effective technique because they are easily created and printed on a surface for distribution, often being incorporated into existing print materials. This is why the QR code was selected as a fundamental component in the design of this shopping cart [10]. The packaging of the goods is equipped with a corresponding QR code. To identify commodity information, a QR code scanner is employed, and the gathered data is transmitted to the microcontroller. The QR scanner is attached to the back of the shopping basket as shown in Figure 11.

Figure 11: QR code scanner

3.10. Interactive Webpage

Users can communicate with the shopping cart and decide whether to enable the shopping cart to follow. Alternatively, even when the shopping cart is not set to follow during the shopping process, it can still be utilized for remote communication, allowing the shopping cart to resume following the user as needed, achieving the effect of remote communication.

There is also a shopping cart commodity settlement interface where users can view the product information in the shopping cart through the web page. Additionally, each time a product is added, users can monitor the total cost and the quantity of items in the shopping cart through the settlement function. This process allows users to easily track if they exceed their estimated budget, minimizing the need for users to independently calculate commodity prices. Users can also modify the quantity of goods on the webpage or remove items from the shopping cart, contributing to a smoother shopping experience as illustrated in Figure 12. In short, this system enhances the user's shopping experience by streamlining the checkout process and providing greater control over the shopping cart contents.

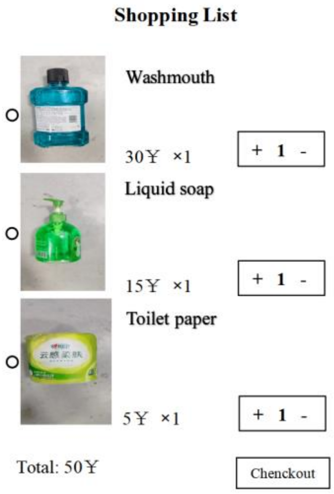

Figure 12: Example of web interface.

4. Results and Discussions

To assess the stability and accuracy of the shopping cart in actual operation, conducting relevant tests becomes imperative.

4.1. Maximum Start Distance

To evaluate the maximum distance capability of the shopping cart's following function, a test involves initiating the following function in front of the shopping cart while it is in a static state. This method allows the observation of the shopping cart's following stability under varying distances between individuals and the cart.

Under unchanged conditions, the start distance between the user and the shopping cart was set to 10 cm, 50 cm, 100 cm, and 200 cm with the desired follow distance maintained at 40 cm. Figure 13, Figure 14, Figure 15 and Figure 16 show the results of the distance between the cart and the user against time. In the legend, 'Left' represents the data from the left ultrasonic receiver, and 'Right' indicates the data from the right ultrasonic receiver.

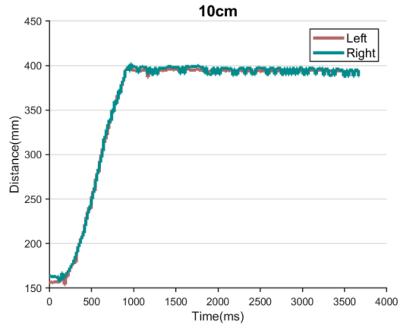

Figure 13: 10 cm starting distance between the user and the shopping cart against time.

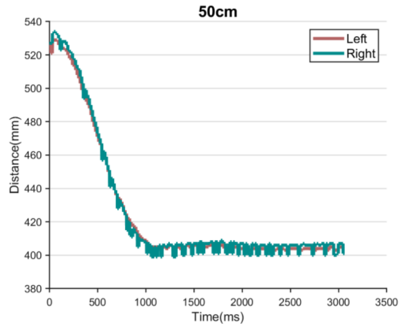

Figure 14: 50 cm starting distance between the user and the shopping cart against time.

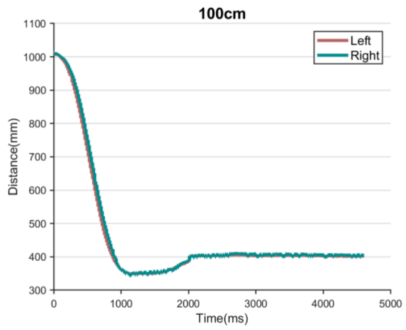

Figure 15: 100 cm starting distance between the user and the shopping cart against time.

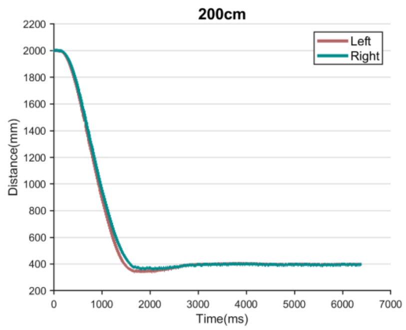

Figure 16: 200 cm starting distance between the user and the shopping cart against time.

From the test results, when the distance between the user and the shopping cart is between 10 cm to 200 cm, the shopping cart can quickly adjust the distance to the user after the start of the follow function. When the distance between the user and the shopping cart exceeds 200 cm, the ultrasonic module experiences unstable data reception. This instability prevents the shopping cart from promptly adjusting itself after activating the follow function, resulting in a failure to follow accurately. Therefore, the effective start distance for the shopping cart is set between 20 cm and 200 cm.

4.2. Turning Test

To test the follow function of the shopping cart during the user's turning process, two circular experiments were conducted. The tester walked along circles with radii of 1m and 2m at normal speeds, while the shopping cart followed. Figure 17 and Figure 18 show the turning test results.

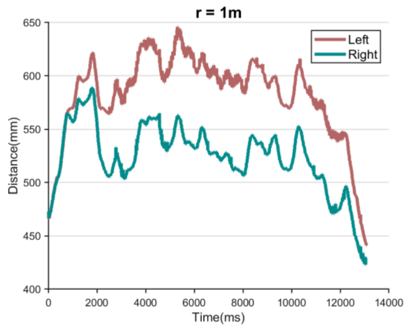

Figure 17: Distance between the user and the shopping cart against time for the tester walking along a circle with a radius of 1 m.

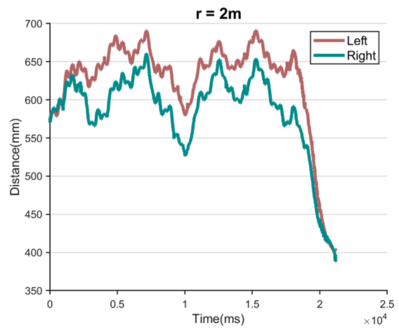

Figure 18: Distance between the user and the shopping cart against time for the tester walking along a circle with a radius of 2 m.

According to the test results, it is observed that when the turning radius is greater than 1 m, the shopping cart promptly adjusts its distance to the user.

4.3. Walking Test

To evaluate the follow function in a shopping scenario, two circular experiments were conducted. The tester walked at speeds of 1.5 m/s and 3 m/s, representing normal walking and jogging speeds, while the shopping cart followed. The test results are illustrated in Figure 19 and Figure 20.

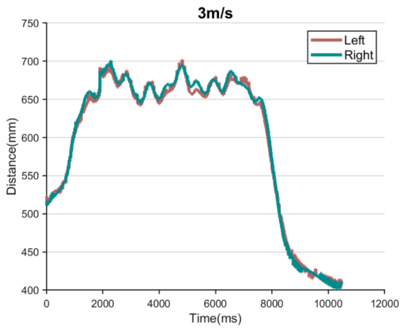

Figure 19: Distance between the user and the shopping cart against time with 3 m/s walking speed.

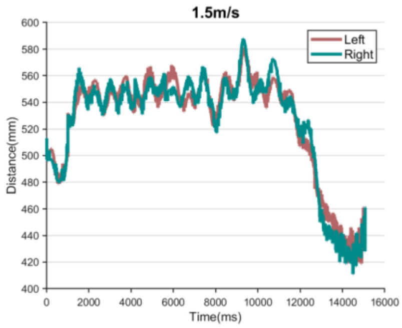

Figure 20: Distance between the user and the shopping cart against time with 1.5 m/s walking speed.

Based on the test results, when walking at a normal speed and activating the follow function, the shopping cart can successfully follow the user throughout the shopping process.

5. Conclusion

This paper highlights the accomplishments in developing a smart shopping cart system with automatic following, obstacle avoidance, and web interface-generated shopping lists. The acknowledgement of potential improvements, such as performance optimization and enhanced user interfaces, adds a realistic and forward-looking perspective. The mention of future research directions, including adaptability to different shopping scenarios, demonstrates an awareness of potential advancements.

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