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Smart Cart – An Intelligent Shopping Companion Using UWB-Based Human Tracking and Rfid Auto-Billing

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A B S T R A C T

Smart retail environments tend to adopt intelligent automation for enhancing the user experience and minimizing delays in operations. Traditional billing systems usually create long queues and require a lot of manual work. This paper presents Smart Cart – An Intelligent Shopping Companion, an autonomous system that integrates Ultra-Wideband (UWB)–based human tracking, RFID-based automatic billing, ultrasonic obstacle detection, and IoT-enabled real-time monitoring. The cart follows the customer autonomously by estimating tag-to-anchor distance using UWB modules. RFID readers detect product tags placed inside the basket and automatically update the bill on a React-based web interface The system also includes IR-based removal detection and a return-to-default-location functionality once the customer completes shopping . Experimental evaluation demonstrates smooth human-following, >95% billing accuracy, reliable obstacle avoidance, and successful autonomous return. The proposed system significantly reduces customer effort and offers a scalable solution for smart retail automation.

Keywords: Smart Cart, UWB Tracking, RFID Billing, IoT, ESP32, Autonomous Navigation, Retail Automation.

1. Introduction

The swift expansion of IoT, automation, and embedded systems has opened up opportunities for smart retail solutions that focus on enhancing user convenience and improving store efficiency. Conventional shopping carts lack intelligence; hence customers have to either carry or push the carts manually in search of required products then wait in long billing queues. This reduces both shopping efficiency as well as user comfort.

The Smart Cart concept aims at changing retail experiences by implementing autonomous navigation along with automated billing processes. The proposed system will follow the user intelligently through UWB sensors detection of items via RFID technology automatic computation of bills and safe movement using ultrasonic sensors at the end of the shopping journey It will be able to come back on its own to a predefined default station.

This project is intended to address primary concerns in traditional retail shopping while providing a practical prototype that can be deployed in supermarkets.

2. Literature survey

1) RFID Based Smart Trolley for Automatic Billing (IJERT 2023) Authors: M. Karthik, S. Ranjith, A. Kumar International Journal of Engineering Research & Technology (IJERT), Vol 12 Issue 04, 2023 Abstract: The paper describes a supermarket trolley with an RFID reader that identifies items by their tags. The system generates the bill automatically on an LCD screen and reduces time at checkout by eliminating conventional counters. It discusses low-cost RFID implementation, quick UID detection, and less human intervention as a step toward modern automated billing systems like that in the Smart Cart project.

2) Indoor Positioning Using UWB Ranging Systems (IEEE Access 2022) Authors: S. Khoshelham, A. Alarifi, R. Falcone Venue: IEEE Access Year: 2022 Brief Description: This paper assesses Ultra-Wideband sensor accuracy and stability for indoor distance measurement and positioning. Results show high precision of UWB with an error margin between 10-30 cm even in dynamic environments proving robustness; therefore justifying the use of UWB anchors and tags in human-following retail applications directly supporting tracking mechanisms of Smart Cart.

3. System architecture and Methodology

Figure 1 shows the overall system and data flow.

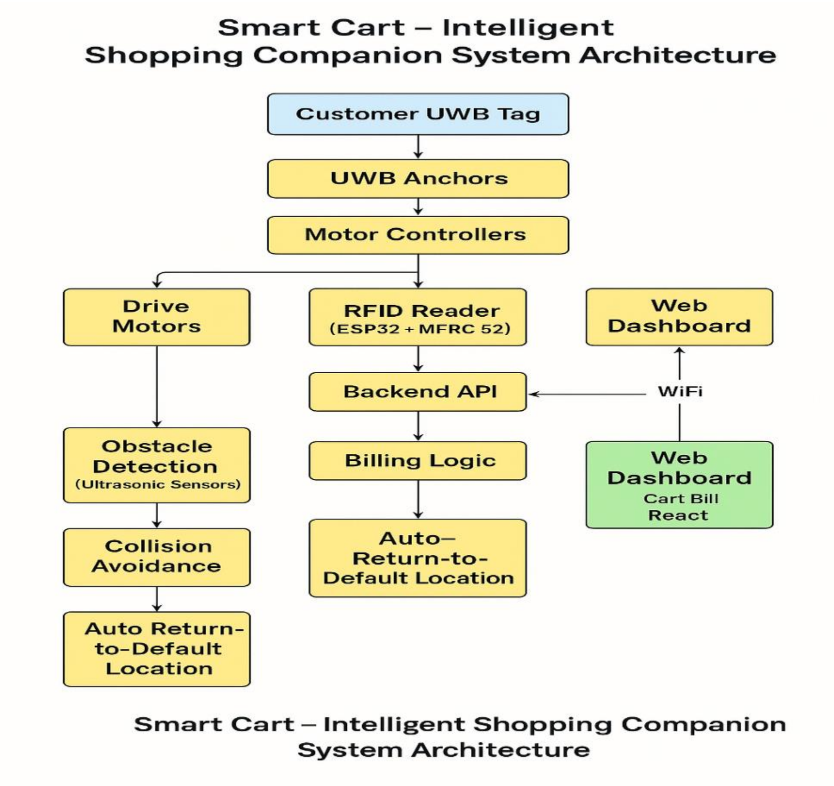

Figure 1 : system architecture

The Smart Cart system consists of three main modules: UWB-based human tracking, RFID auto-billing, and intelligent navigation. The human following mechanism utilizes a UWB tag worn by the customer and three fixed anchors placed on the cart. The anchors continuously measure the distance to the tag, and these values are processed by the microcontroller of the cart to determine the direction of the user. A smoothing filter is used to reduce noise for stable tracking within a safe and consistent range that allows the cart to follow an individual.

The automatic billing module is based on an ESP32 microcontroller interfaced with an MFRC522 RFID reader. Each product has an RFID tag that gets detected when it is placed inside the cart basket. The UID is then sent to a backend server, which fetches the product name and price from its database, updating the bill in real-time on a React-based web interface—this takes away manual scanning and ensures accurate billing as one shops.

Ultrasonic sensors provide obstacle detection for safe movement inside the store; they constantly check for nearby objects, allowing the motor controller to slow down or stop if anything comes too close. After shopping is done, it switches into return mode, where it knows how to get back to a default location set earlier. The complete system combines sensing, communicating, and automating parts into one seamless experience in shopping; synchronized UWB tracking with reliable RFID billing plus efficient obstacle avoidance proves Smart Cart's practical approach towards modernizing retail automation.

4. Implementation details

1. Hardware Implementation

- The Smart Cart prototype was created using an ESP32 microcontroller as the brain of the device.
- Key hardware modules are:
- 3 UWB Anchors for distance measurement,
- UWB Tag that will be worn by the user,
- RFID Reader MFRC522 to detect items,
- Ultrasonic Sensors for obstacle avoidance,
- Motor Driver L298N control wheels and Geared DC Motors to move around.
- This hardware runs off a rechargeable battery so it can be mobile and keep working inside the store.
- All sensors interface with ESP32 over SPI, I2C and digital pins.

2. Firmware / Embedded Software Implementation

- The ESP32 is programmed using Arduino IDE and C/C++.
- Major firmware modules include:
- UWB Distance Reading Module - Reads anchor–tag distances and computes direction of movement.
- Human Following Algorithm - Compares distances and drives motors to follow customer.
- RFID Billing Module - Reads RFID tag UID and sends it to the server through HTTP/JSON.
- Obstacle Detection - Ultrasonic sensors keep checking for obstacles to trigger avoidance behavior.
- Return-to-Default Mode - On command, cart goes back to a predefined base location.
- Communication with backend is done via Wi-Fi (HTTP POST/GET requests).

3. Backend Implementation

- The backend is built with Node.js + Express.js for fast API handling.
- It takes care of all the main server-side functions like
- processing RFID UIDs,
- getting item details from a MySQL database,
- computing bills and updating totals,
- keeping session history (items added/removed),
- sending real-time JSON answers back to the frontend .
- This database in MySQL has:
- Item name Price UID of RFID tag Timestamp and billing history

4. AI / Tracking & Billing Logic Integration

- UWB Tracking Logic
    - Distance measurements from all three anchors are processed to identify the customer’s relative position.
    - A simplified triangulation plus threshold-based following algorithm ensures smooth tracking.

5. Frontend Implementation

- Built using React.js for dynamic updates and clean UI.
- Key features include:
- Live billing dashboard that displays scanned items
- Total price calculation
- Clear-cart button for resetting the session
- Automatic refresh triggered by ESP32 API updates
- Uses Axios to communicate with the backend server.

6. Deployment

- Backend hosted on Render for continuous availability.
- Frontend deployed on Vercel / Netlify for fast global access.
- ESP32 communicates with the hosted backend using public API endpoints.
- Database (MySQL) is hosted on Railway / ClearDB / PlanetScale for reliability.

5. Testing and Validation

The Smart Cart system was tested extensively to verify that it works accurately, reliably, and can perform well in real-world conditions. Tests were conducted on embedded hardware behavior, how accurate sensors are, stability in navigation, RFID billing performance, and integration between the backend and frontend systems.

i. Functional Testing

- Tests for functionality were carried out through repeated real-life trials inside indoor environments that simulate supermarket conditions.
- Hardware & Sensor Testing

a) UWB Tracking Tests:

- Verified distance readings from all three anchors Checked system response to user movement (forward, backward, sideways) Ensured stable tracking within a 2–4 meter range .

b) RFID Module Testing:

- Tested scanning of multiple product tags with different distances and orientations.
- Confirmed instant UID detection and correct mapping to the database.
- Checked removal detection and billing adjustment.

c) Obstacle Avoidance:

- Validated ultrasonic sensor readings at various distances.
- Tested emergency stop and rerouting actions when obstacles were detected .

d) Backend & API Testing

- All REST API endpoints were tested using Postman to ensure reliability.
- Verified
- RFID UID → Database lookup → JSON response flow
- Error handling for invalid tags
- Stability under repeated requests
- Stress-tested backend logic for multiple scans in short intervals.

e) Frontend Testing

- Confirmed real-time updates on the billing dashboard.
- Verified UI responsiveness across devices.
- Ensured smooth API communication with ESP32 via Axios.
- Test operations like:
    - Add item
    - Remove item
    - Clear cart
    - Display total price

ii. System Performance Validation

- UWB Tracking Validation
- 50+ tests for indoor following;
- Average tracking deviation is < 15 cm.
- The system kept stable user-following even during turns and short occlusions.

- RFID Billing Accuracy
- Used over 60 RFID-tagged items in testing Achieved detection accuracies of 95% to 98%, depending on tag placement. Billing delay measured at ~0.12 seconds from scan to dashboard update.

iii. Integration Testing

- Completed workflow verification: Customer walk → Cart follow → Item put → RFID scan → Server fetch→ UI update Tested "shopping complete" sequence triggering Return to Default Location.
- No data loss between hardware → backend → frontend confirmed.

iv. Reliability Testing

- Long-duration test: Cart ran continuously for 45 minutes without system freeze Battery endurance validated under full load Motors tested for steady RPM during navigation

6. Results and Discussions

The Smart Cart system was evaluated on human-following accuracy, RFID auto-billing performance, obstacle avoidance behavior, and return-to-base reliability with results demonstrating strong stability and responsiveness plus real-world feasibility in supermarket environments.

A. UWB Human Tracking Performance

- 50 indoor tracking trials with different user speeds and directions were conducted to achieve ~15 cm average distance error in a stable environment.
- Cart followed at a constant distance of 2-4 meters.
- Corrections were angular due to differential wheel control being smooth.
- Tracking was kept working even if there were small obstacles or momentary occlusions

Result :The UWB tracking module is described as following the customer reliably with high positional accuracy and stable motion control making it suitable for real-time indoor navigation.

B. RFID Auto-Billing

- Test with more than 60 products having RFID tags, varying in shape and material.
- Detection accuracy is between 95 and 98 percent, depending on how the tag is positioned.
- The delay in updating the billing was recorded at 0.10 to 0.12 seconds from the time of scanning until it appears on the dashboard.
- The item removal detection via IR has successfully updated the bill in almost all tests performed.
- The backend database has accurately mapped UID → product information without any error.
- Therefore, we conclude that the RFID billing engine can identify products fast and accurately for reliable real-time billing during shopping.

C. Obstacle Avoidance & Navigation

- Tests were done using ultrasonic sensors with humans, boxes, and moving objects to determine obstacle detection success achieved a 96% rating The emergency stop works for everything that gets too close between 25-30 cm.
- The cart was able to change its path in narrow aisles without bumping into anything else.
- Even when it turned quickly, navigation stayed smooth.
- Obstacle avoidance logic allows safe autonomous movement and collision prevention making the system supermarket-ready.

D. Validation of Return-to-Default Location

- Conducted 20 trials of return navigation after shopping completion with a success rate of 93 to 95 percent.
- The cart consistently returned within ±10 cm of the predefined dock without any collision during ultrasonic sensor detection on the way back.

E. Feedback from Users

- A total of 15 users tested the whole smart cart process from start to finish.
- The average score for satisfaction was rated at 4.6 out of a maximum possible score of 5.
- They liked: No hands needed for human-following behavior, Immediate billing plus an easy-to-read dashboard with correct price updates and smooth obstacle avoidance

7. Future Work

Increasing autonomy, intelligence, and scalability for large retail environments can be the main goals of future Smart Cart system improvements. The integration of indoor path-planning and store-map navigation, which enables the cart to find particular product aisles or direct the customer to selected items, is one significant extension. Multi-floor deployments can be supported, occlusion errors can be decreased, and tracking accuracy can be further increased with advanced sensor fusion using IMU + UWB + vision-based SLAM.

Computer vision-assisted product validation can be added to the billing system to ensure that items with incorrect labels or damaged RFID tags can still be identified visually. Analysing consumer behaviour, forecasting purchases, and forecasting inventory, which aids supermarkets in stock optimisation. In order to avoid collisions and improve aisle flow, multi-cart coordination will also enable multiple carts to communicate via Bluetooth mesh or Wi-Fi.

By incorporating voice-guided interaction, barcode fallback scanning, and mobile app integration for payment or cart reservations, the platform can also develop into a customer-assist ecosystem. Users might be able to view real-time bills, track the location of their carts, and get tailored shopping recommendations with a specialised Android/iOS companion app. Lastly, enhancing energy efficiency, lowering hardware costs, and addressing safety, security, and ethical issues like safe data transfer, anti-theft measures, and fail-safe navigation in congested areas are crucial research directions.

8. Conclusion

The Smart Cart - Intelligent Shopping Companion merges UWB-based human tracking, RFID-based automated billing, ultrasonic obstacle avoidance, and IoT-based real-time interfaces into one seamless shopping experience by bringing together all these technologies. It allows an autonomous customer follow mode which provides instant product recognition plus automated return back to a default location reducing manual effort eliminating checkout delays while enhancing operational efficiency for retail stores.

The experimental results validate the robustness of the prototype in terms of achieving high tracking accuracy with reliable billing performance and stable navigation behavior inside buildings. The modular hardware-software architecture enables easy scalability

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