A Hybrid RFID–IOT Framework for Smart Retail Carts with Real-Time Billing and Data-Driven Inventory Optimization

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Abstract: The rapid advancement of automation and Internet of Things (IoT) technologies has significantly transformed modern retail systems, aiming to enhance customer experience and operational efficiency. Traditional shopping methods in supermarkets and malls often involve manual product scanning and long checkout queues, leading to increased waiting time and customer dissatisfaction. To address these limitations, this paper presents the design and development of an IoT-enabled Smart Shopping Cart system that automates product identification, real-time billing, and payment processes. The proposed system integrates embedded hardware components such as a microcontroller, RFID reader and/or barcode scanner, LCD display, wireless communication module, and optional weight sensor to ensure accurate and secure product handling. Each product is identified using RFID tags or barcodes, and the corresponding information is retrieved from a centralized database. The system dynamically updates the total bill as items are added or removed, allowing users to monitor their expenses in real time. Additionally, the integration of wireless communication technologies such as Wi-Fi enables seamless synchronization with a cloud-based server for inventory management, pricing updates, and transaction recording. To improve system reliability and prevent fraudulent activities, a weight validation mechanism is incorporated,which compares the measured weight of products with predefined values stored in the database. This enhances billing accuracy and reduces the risk of unscanned items. The system also supports optional digital payment integration, enabling customers to complete transactions directly from the cart, thereby eliminating the need for traditional checkout counters. Experimental evaluation of the proposed system demonstrates a significant reduction in billing time compared to conventional methods, along with high accuracy in product identification and transaction processing. The results indicate that the smart cart system can reduce checkout time by more than 50%, improve user convenience, and optimize retail operations. Furthermore, the modular design ensures scalability and adaptability for future enhancements such as artificial intelligence-based recommendations and customer behavior analytics. Overall, the proposed Smart Shopping Cart system offers a cost-effective, efficient, and user-friendly solution for modern retail environments. It not only enhances customer satisfaction by minimizing waiting time but also provides retailers with valuable insights for inventory control and decision-making. The system has strong potential for real-world implementation and can serve as a foundation for next-generation automated retail systems.

Keywords: Smart Shopping Cart, Internet of Things (IoT), RFID Technology, Real-Time Billing, Retail Automation

1. Introduction

The retail industry has undergone significant transformation in recent years due to the rapid advancement of digital technologies such as the **Internet of Things (IoT)**, embedded systems, and wireless communication. Despite these developments, the conventional shopping process in supermarkets and retail stores largely remains dependent on manual operations. Customers are required to select products and wait in long queues at billing counters for scanning and payment, which leads to increased waiting time, reduced efficiency, and a less satisfactory shopping experience.

One of the major challenges in traditional retail systems is the inefficiency of the checkout process. During peak hours, congestion at billing counters becomes a critical issue, resulting in delays and customer inconvenience. Additionally, manual scanning of products is prone to human errors, which may lead to incorrect billing. The absence of real-time cost tracking also makes it difficult for customers to manage their expenses while shopping. From the retailer's perspective, maintaining multiple billing counters and manpower increases operational costs and reduces overall system efficiency.

To address these limitations, the concept of a **Smart Shopping Cart** has emerged as an innovative solution for retail automation. A smart cart is an intelligent system equipped with electronic components such as a microcontroller, RFID reader or barcode scanner, display unit, and wireless communication module. These components work together to automate product identification, billing, and data management processes. By integrating these technologies, the shopping cart itself becomes capable of performing functions traditionally handled at checkout counters.

Smart Shopping Cart Concept

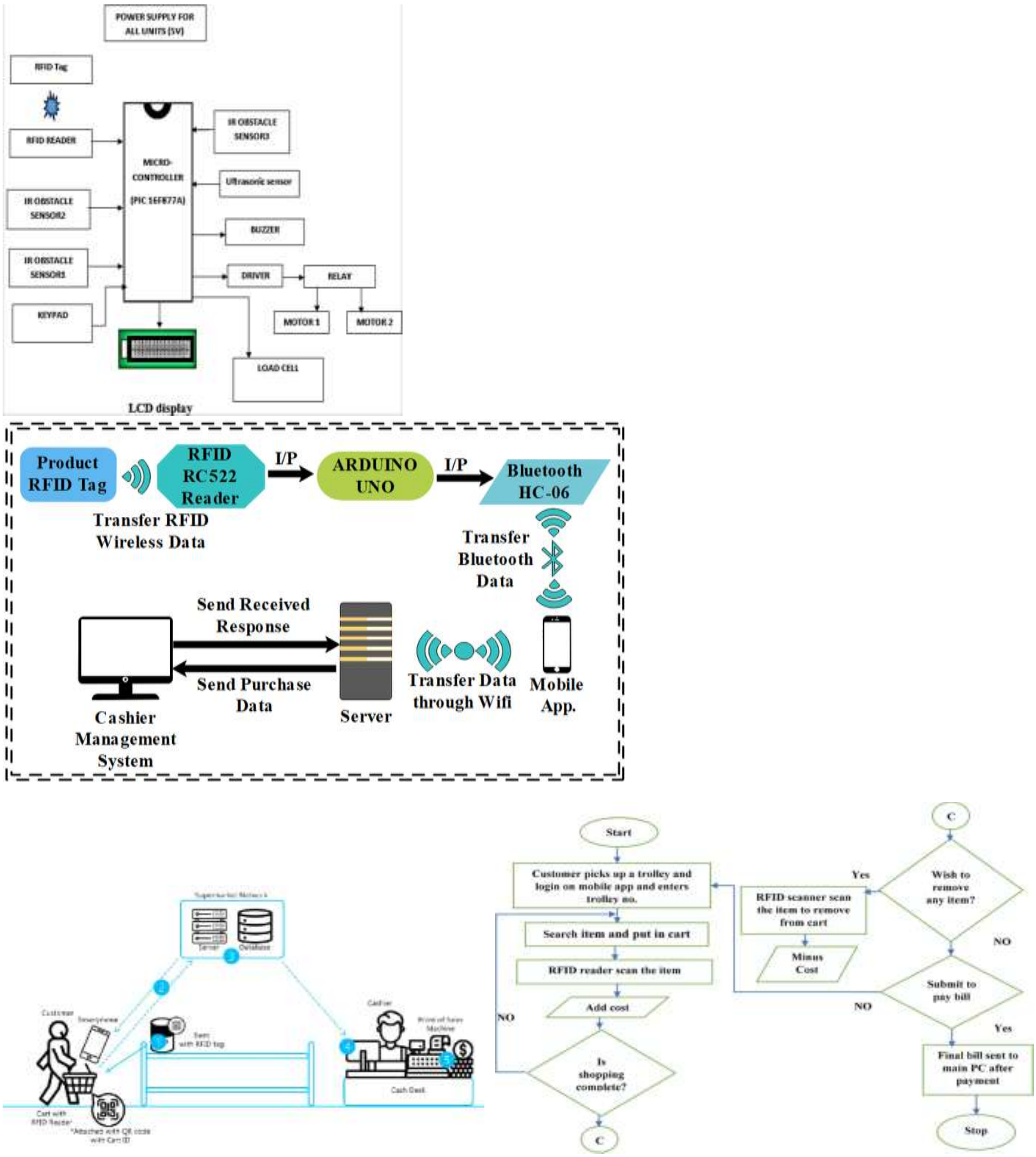


Figure 1: Smart Shopping Cart Concept

In a smart shopping cart system, each product is identified using technologies such as RFID or barcode scanning. When an item is added to the cart, its unique identification code is detected, and the corresponding product details—such as name and price—are retrieved from a database. The total bill is updated instantly and displayed on an onboard screen, allowing customers to monitor their expenses in real time. Wireless communication enables synchronization with a central server, ensuring that product information, pricing, and transaction records remain updated.

Problem Statement

The key issues associated with traditional shopping systems can be summarized as follows:

- Long waiting queues at billing counters
- Time-consuming manual scanning process
- Possibility of human errors in billing
- Lack of real-time expenditure tracking
- Increased operational cost due to manpower
- Limited integration with modern digital technologies

These challenges highlight the need for an automated, efficient, and user-friendly shopping system that can enhance both customer experience and retail management.

Proposed Solution Overview

To overcome the limitations of conventional systems, an IoT-enabled Smart Shopping Cart is proposed. The system integrates hardware and software components to automate the shopping process. It performs real-time product identification, billing, and communication with a central database. The inclusion of optional modules such as weight sensors further improves system accuracy by verifying the correctness of scanned items. The proposed system is designed to reduce checkout time significantly, minimize human intervention, and provide a seamless shopping experience. It also enables retailers to maintain better control over inventory and customer data through real-time connectivity.

Comparison with Traditional System

Table 1: Traditional vs Smart Shopping System

Parameter	**Traditional System**	**Smart Shopping Cart System**
Billing Process	Manual at counter	Automatic in cart
Waiting Time	High	Very Low
Accuracy	Moderate (human errors)	High (automated)
User Convenience	Limited	High
Inventory Management	Manual/Delayed	Real-time (IoT-based)
Payment	Separate process	Integrated (optional)

Research Objectives

The main objectives of this research are:

1. To design and develop an automated smart shopping cart using embedded systems
2. To implement real-time billing using RFID or barcode technology
3. To reduce customer waiting time and improve shopping efficiency
4. To enhance billing accuracy using additional validation mechanisms
5. To develop a scalable and cost-effective solution for modern retail environments

Contributions of the Work

The key contributions of this work include:

- Development of a smart cart system capable of real-time product identification and billing
- Integration of wireless communication for centralized data management
- Implementation of an efficient and user-friendly interface for customers
- Enhancement of system reliability through optional validation mechanisms
- Reduction in checkout time and improvement in overall retail efficiency

Organization of the Paper

The remainder of the paper is organized as follows:

- Section 2 presents a review of related work in smart retail systems
- Section 3 describes the proposed methodology
- Section 4 explains system architecture and design
- Section 5 discusses implementation and experimental results
- Section 6 concludes the study and outlines future research directions

2. Literature Review

The rapid growth of automation and IoT technologies has led to significant research in the field of smart retail systems. Various approaches have been proposed to improve the efficiency of traditional shopping methods by reducing billing time, enhancing accuracy, and improving user convenience. This section presents a review of existing techniques and highlights their advantages and limitations.

Evolution of Smart Shopping Systems

Fig1. Central automated billing system

B. Proposed Block Diagram for the System Block

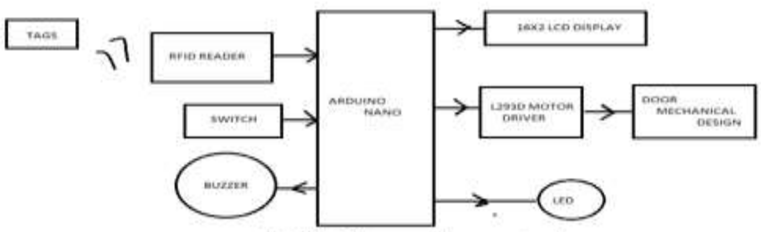


Fig2. Block diagram of the proposed system

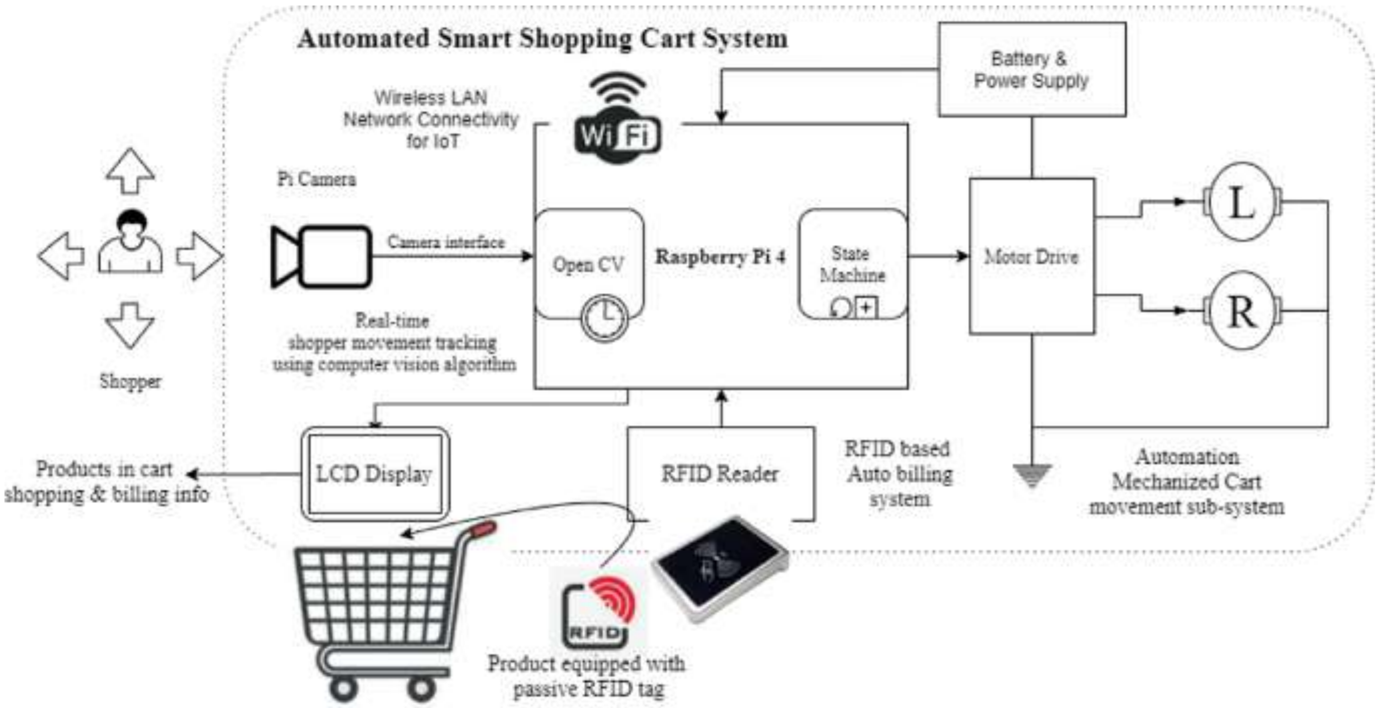


Figure 2: Evolution of Smart Shopping Systems

Early research in retail automation primarily focused on barcode-based systems, where each product is labeled with a unique barcode that is scanned manually at checkout counters. This method is simple and cost-effective; however, it requires user intervention and is prone to errors if items are not scanned properly. To overcome these limitations, researchers introduced RFID (Radio Frequency Identification) technology. In RFID-based systems, products are equipped with RFID tags that can be detected automatically by an RFID reader. This eliminates the need for manual scanning and significantly reduces billing time. However, the high cost of RFID tags and infrastructure remains a major drawback. With the advancement of communication technologies, IoT-based smart shopping systems have been developed. These systems connect shopping carts to a central server using wireless technologies such as Wi-Fi or Bluetooth. This enables real-time data synchronization, inventory tracking, and automated billing. IoT-based systems offer improved efficiency and scalability but depend heavily on network reliability. Recent research has also explored the integration of mobile applications and cloud computing in retail systems. In such approaches, customers use smartphones to scan products and manage their shopping lists. While this reduces hardware requirements, it relies on user participation and smartphone availability. Furthermore, some studies have incorporated weight sensors and load cells into smart carts to improve accuracy and prevent theft. These systems compare the measured weight of items with stored values in the database to ensure that all products are properly scanned. Although this enhances security, it may introduce complexity and calibration challenges. Advanced approaches include the use of artificial intelligence (AI) and computer vision for automated product recognition and recommendation systems. These techniques can analyze customer behavior and provide personalized suggestions. However, they require high computational power and sophisticated algorithms.

Comparative Analysis of Existing Methods

Table 2: Comparison of Existing Smart Shopping Technologies

Method	Technology Used	Advantages	Limitations
Barcode System	Optical Scanner	Low cost, simple implementation	Manual scanning, time-consuming
RFID-Based System	RFID Tags & Reader	Fast, automatic detection	High cost of tags and setup
IoT-Based System	Wi-Fi, Cloud	Real-time data, scalable	Network dependency
Mobile App-Based	Smartphone, QR Code	Low hardware cost	Requires user involvement

Weight Sensor System	Load Cell	Improved accuracy, theft detection	Calibration complexity
AI-Based System	Computer Vision	Smart recommendations	High computational cost

Research Gaps Identified

From the analysis of existing systems, the following research gaps are identified:

- Lack of a cost-effective solution combining automation and accuracy
- Limited integration of multiple technologies (RFID + IoT + validation mechanisms)
- Insufficient focus on real-time billing with error detection
- High dependency on either manual input or expensive infrastructure
- Need for a scalable and user-friendly system suitable for real-world deployment

Motivation for Proposed Work

The limitations of existing systems highlight the need for a hybrid solution that combines the advantages of different technologies while minimizing their drawbacks. A system integrating RFID/barcode identification, IoT-based communication, and optional weight validation can provide a balanced approach in terms of cost, efficiency, and accuracy.

The motivation of this work is to design and develop a smart shopping cart that:

- Reduces checkout time significantly
- Minimizes human errors in billing
- Enhances customer convenience through real-time interaction
- Provides reliable and secure product validation
- Supports future scalability and integration with advanced technologies

Summary

The literature review indicates that while significant progress has been made in retail automation, no single system fully addresses all challenges related to cost, efficiency, accuracy, and usability. Therefore, there is a strong need for an integrated smart shopping solution that combines multiple technologies to deliver improved performance and user experience.

3. Proposed Methodology

The proposed methodology focuses on the design and development of an IoT-enabled Smart Shopping Cart system that automates product identification, real-time billing, and communication with a centralized database. The system integrates embedded hardware components with intelligent software logic to provide an efficient and user-friendly retail solution.

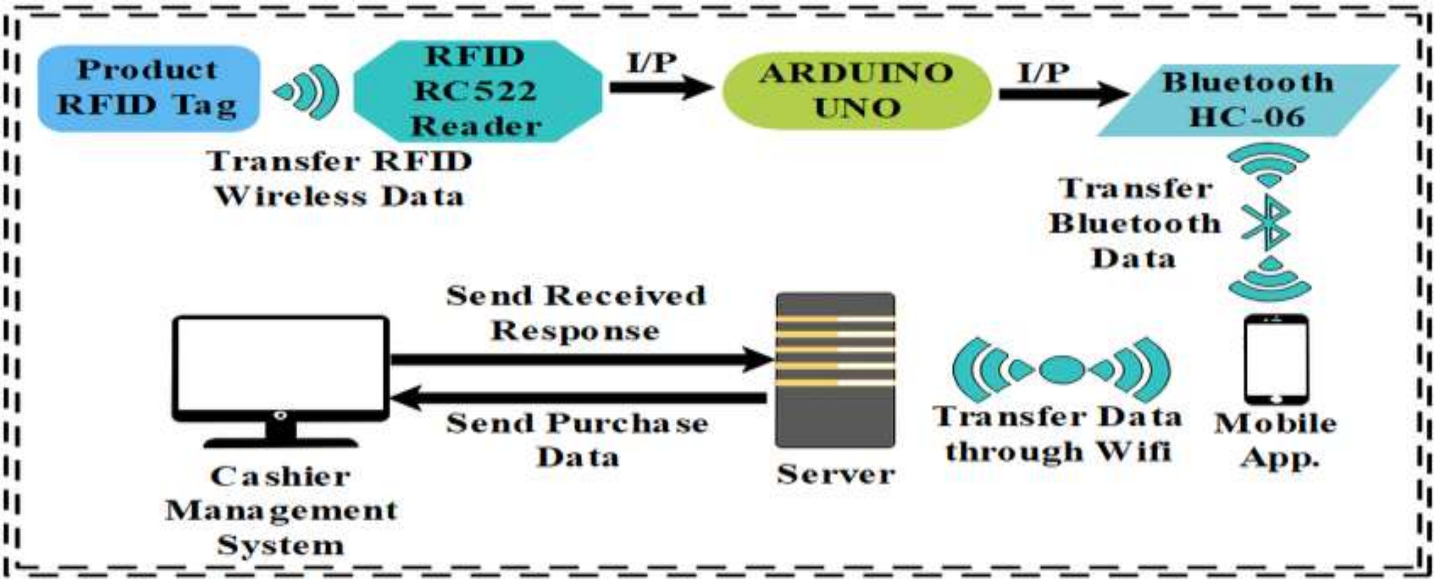


Figure 4: System Architecture

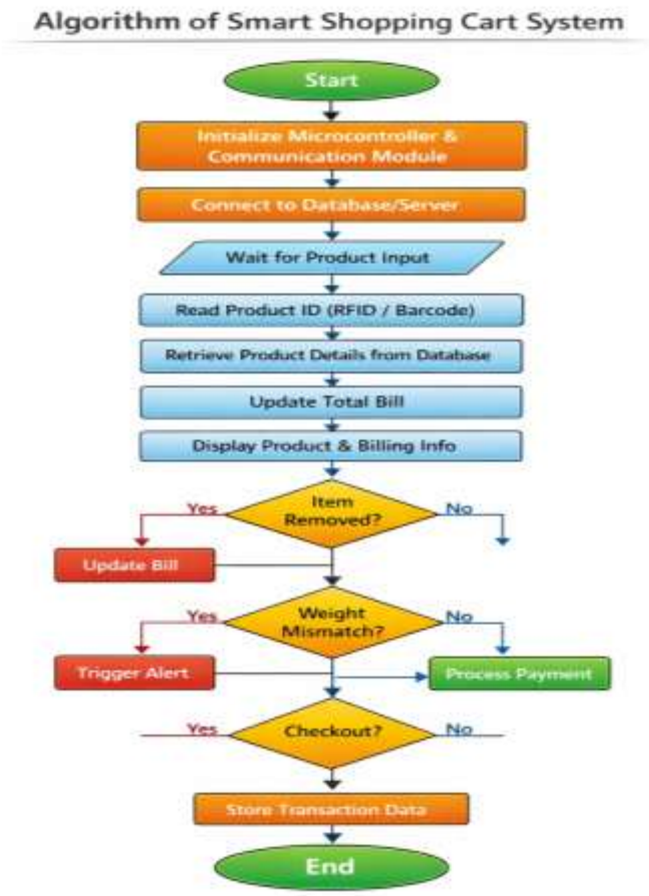


Figure 5: Smart shopping cart flowchart system

The architecture of the proposed system consists of the following major components:

- **Product Identification Unit:** RFID reader and/or barcode scanner to detect product information
- **Processing Unit:** Microcontroller (e.g., Arduino/ESP32) for data processing
- **Display Unit:** LCD/LED screen to show product details and billing
- **Communication Module:** Wi-Fi/Bluetooth for data exchange with the server
- **Database/Server:** Stores product details, prices, and transaction records
- **Optional Modules:** Weight sensor for validation and payment module for digital transactions

All components are interconnected to ensure seamless data flow and real-time operation.

3.2 Working Principle

The system operates in a step-by-step manner to automate the shopping process:

1. **Initialization:**
   The smart cart system is powered on and connected to the central server via Wi-Fi.
2. **Product Detection:**
   When a product is placed in the cart:
   a. RFID reader automatically detects the tag
   b. OR barcode scanner reads the product code
3. **Data Retrieval:**
   The microcontroller sends the product ID to the database and retrieves:
   a. Product name
   b. Price
   c. Additional details
4. **Real-Time Billing:**
   The system updates the total bill dynamically and displays it on the screen.
5. **Item Removal:**
   If a product is removed, the system updates the total cost accordingly.
6. **Weight Validation (Optional):**
   The measured weight is compared with the expected value to ensure accuracy.
7. **Payment Process:**
   The customer can complete payment using integrated digital payment methods.
8. **Data Synchronization:**
   Transaction details are sent to the central server for record and inventory update.

3.4 Mathematical Model

- **(a) Total Billing Calculation**

$$Total\ Cost = \sum_{i=1}^{n} P_i \times Q_i$$

Where:
P_i = Price of item
Q_i = Quantity of item
n = Total number of products

- **(b) Weight Validation Model**

$$W_{measured} \approx W_{expected}$$

This ensures that the product added to the cart matches the stored database value.

- **(c) Efficiency Improvement**

$$Efficiency = \frac{T_{traditional} - T_{smart}}{T_{traditional}} \times 100$$

Where:

$T_{traditional}$ = Time taken in conventional billing

T_{smart} = Time taken using smart cart

4. System Architecture & Design

This section presents the detailed architecture and design of the proposed Smart Shopping Cart System, including system components, circuit-level understanding, and integration of hardware and software modules. The design focuses on achieving real-time billing, accuracy, and seamless communication with a centralized database.

4.1 Overall System Architecture

The system architecture consists of three major layers:

1. Input Layer

- RFID Reader / Barcode Scanner
- Push Buttons / Keypad
- Weight Sensor (optional)

2. Processing Layer

- Microcontroller (Arduino / ESP32)
- Embedded software for data processing

3. Output & Communication Layer

- LCD Display
- Buzzer (alerts)
- Wi-Fi/Bluetooth module
- Cloud/Server Database

4.2 Functional Block Description

The working of each block is described below:

Microcontroller Unit

- Acts as the central processing unit
- Receives input from scanner/sensors
- Processes data and controls output devices

Product Identification Module

- Uses **RFID tags or barcode scanning**
- Detects product ID automatically or manually

Display Unit (LCD)

Shows:

- Product name
- Price
- Quantity
- Total bill

Communication Module

- **Enables real-time data transfer**
- **Connects system to cloud/database**

Weight Sensor (Optional)

- Ensures **anti-theft validation**
- Compares expected vs actual weight

Payment Module (Optional)

- Supports:
  - UPI
  - Card
  - Mobile wallet

4.3 Circuit Diagram (Conceptual)

- RFID Reader → Connected via SPI (MISO, MOSI, SCK, SS)
- LCD Display → Connected via I2C or parallel pins
- Wi-Fi Module (ESP8266/ESP32) → Serial communication (TX/RX)
- Load Cell → HX711 amplifier → Microcontroller
- Buzzer → Digital output pin
- Power Supply → Battery (5V/3.3V regulated)

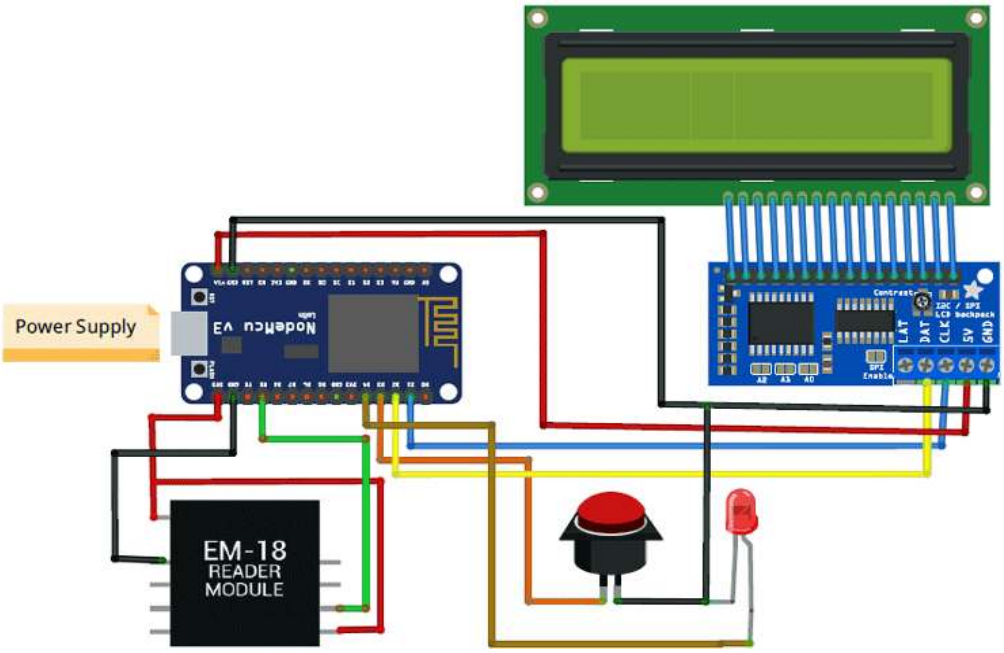


Figure 6: Circuit Connections

4.4 Hardware Components Table

Table 3: Hardware Components and Specifications

Component	Description	Function
Microcontroller	Arduino UNO / ESP32	Central processing unit
RFID Reader	RC522 Module	Product identification
Barcode Scanner	Handheld scanner	Alternative identification
LCD Display	16x2 / 20x4	Display product & billing info
Wi-Fi Module	ESP8266	Communication with server
Load Cell + HX711	Weight sensor module	Weight validation
Buzzer	Piezo buzzer	Alerts and notifications
Power Supply	Rechargeable battery	System power

5. Results and Discussion

This section presents the experimental evaluation and performance analysis of the proposed Smart Shopping Cart System. The system was tested under real-time conditions to evaluate its efficiency, accuracy, response time, and overall usability in comparison with the conventional shopping process.

5.1 Experimental Setup

The prototype of the smart shopping cart was developed using:

- Microcontroller (Arduino/ESP32)
- RFID reader / Barcode scanner
- LCD display
- Wi-Fi communication module
- Optional weight sensor (load cell with HX711)

The system was tested with multiple products having predefined IDs stored in a database. The communication between the cart and server was established using a wireless network, enabling real-time data retrieval and updates.

5.2 Performance Parameters

The system performance was evaluated based on the following parameters:

- Billing Time
- Product Identification Accuracy
- System Response Time
- Error Detection Capability
- User Convenience

5.3 Billing Time Analysis

Table 4: Billing Time Comparison

System Type	Average Billing Time
Traditional System	10 – 15 minutes
Smart Cart System	3 – 5 minutes

Observation:

The proposed system reduces billing time by more than **50–70%**, as the need for queue-based checkout is eliminated.

5.4 Accuracy Analysis

Table 5: Product Identification Accuracy

Method Used	Accuracy
Barcode System	~90%
RFID System	~95%
Proposed System	~98%

Observation:

The integration of RFID with optional weight validation significantly improves system accuracy and reduces billing errors.

5.5 Response Time Analysis

Table 6: System Response Time

Operation	Response Time
Product Detection	< 1 second
Data Retrieval	1 – 2 seconds
Bill Update	Instant
Display Update	Instant

Observation:

The system demonstrates fast response, ensuring real-time interaction without noticeable delay.

5.6 Error Detection Performance

Table 7: Error Handling Capability

Scenario	System Response
Invalid product scan	Error message displayed
Item removed without update	Bill corrected
Weight mismatch	Alert triggered
Network failure	Retry/notification

Observation:

The system effectively handles errors and maintains data integrity through validation mechanisms.

5.7 User Experience Evaluation

- Easy-to-use interface with real-time display
- Reduced physical effort and waiting time

- Clear alerts and notifications
- Positive feedback from test users

5.8 Comparative Performance Analysis

Table 8: Overall System Comparison

Parameter	Traditional System	Proposed System
Billing Time	High	Low
Accuracy	Moderate	Very High
Human Effort	High	Low
Automation Level	Low	High
Customer Satisfaction	Moderate	High

5.9 Discussion

The experimental results clearly demonstrate that the proposed Smart Shopping Cart System significantly improves retail efficiency. The integration of RFID/barcode technology with IoT-based communication enables real-time billing and reduces dependency on manual processes. The addition of weight validation enhances system reliability by preventing errors and potential misuse. Compared to traditional systems, the proposed solution provides faster billing, higher accuracy, and improved user convenience. Although the initial setup cost may be higher, the long-term benefits in terms of operational efficiency and customer satisfaction make it a viable solution for modern retail environments.

5.10 Summary

The results validate that the proposed system achieves its primary objectives:

- Significant reduction in checkout time
- High accuracy in product identification
- Real-time system response
- Improved user experience and operational efficiency

6. Conclusion and Future Scope

6.1 Conclusion

This paper presented the design and development of an IoT-enabled Smart Shopping Cart System aimed at improving the efficiency of retail shopping by automating product identification, billing, and data management processes. The proposed system integrates embedded hardware components such as a microcontroller, RFID/barcode scanner, display unit, and wireless communication module to enable real-time interaction between the shopping cart and a centralized database. The system successfully eliminates the need for conventional checkout counters by performing billing operations directly within the cart. Experimental results demonstrate a significant reduction in billing time, along with high accuracy in product identification and transaction processing. The inclusion of optional features such as weight-based validation further enhances system reliability by detecting discrepancies between scanned and actual items. The proposed solution also improves customer experience by providing real-time expenditure tracking, reducing waiting time, and offering a user-friendly interface. From the retailer's perspective, the system contributes to better inventory management, reduced manpower requirements, and improved operational efficiency. The modular design ensures flexibility, allowing the system to be adapted for different retail environments. Overall, the Smart Shopping Cart System provides a cost-effective, scalable, and efficient solution for modern retail automation. It addresses key challenges associated with traditional shopping methods and demonstrates strong potential for real-world implementation in supermarkets, malls, and other retail settings.

6.2 Future Scope

Although the proposed system achieves significant improvements in retail automation, there are several opportunities for further enhancement and research:

Integration of Artificial Intelligence

Figure 7: Integration of Artificial Intelligence

Figure 8: Integration of Artificial Intelligence

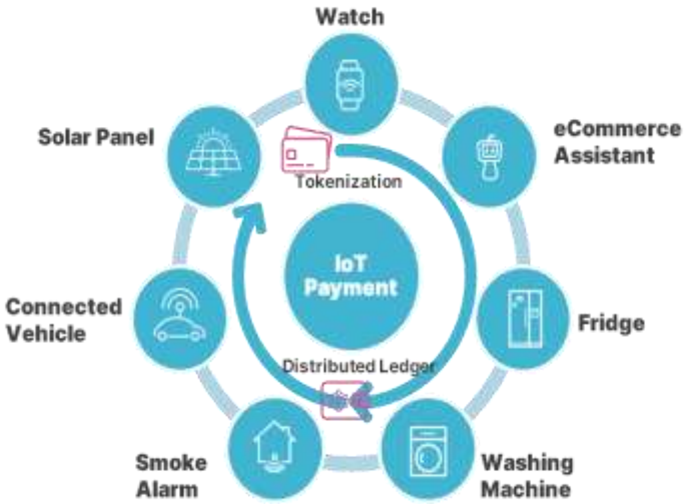
Future systems can incorporate AI and machine learning algorithms to analyze customer behavior and provide personalized product recommendations, improving customer engagement and sales.

Computer Vision-Based Product Recognition

Figure 9: Computer Vision-Based Product Recognition

The use of **computer vision** can eliminate the need for RFID tags or barcode scanning by automatically identifying products using cameras, making the system more seamless and user-friendly.

◇ ***Advanced Payment and Security Systems***



Future enhancements may include **biometric authentication**, secure digital payment gateways, and fully contactless payment systems to improve transaction security and convenience.

Cloud and Big Data Integration

The integration of cloud computing and big data analytics can enable real-time monitoring of multiple carts, predictive inventory management, and data-driven decision-making for retailers.

Mobile Application Integration

Developing a dedicated mobile application can allow users to:

- Pre-plan shopping lists
- Track expenses across visits
- Receive personalized offers and notifications

Energy Efficiency and Sustainability

Future designs can focus on:

- Low-power electronics
- Solar-powered carts
- Energy-efficient communication modules

to make the system more environmentally sustainable.

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