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A Real-Time Automated Billing System for Retail Using RFID and Embedded IoT Architecture

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Abstract – The rapid expansion of retail environments has intensified the need for efficient and automated billing systems capable of handling dynamic customer flow. Conventional checkout processes rely on manual barcode scanning, leading to increased waiting time, billing errors, and reduced customer satisfaction. This paper proposes an advanced smart shopping cart system integrating Radio Frequency Identification (RFID), embedded processing, and Internet of Things (IoT) technologies for real-time product detection and automated billing.
A mathematical framework is developed to model dynamic billing, product state transitions, and system efficiency. The proposed system employs an RFID reader embedded within the cart to continuously track product addition and removal, while an Arduino Mega 2560 microcontroller computes billing updates in real time. Wireless communication using ESP-12 enables seamless data transmission to a centralized server for automated checkout.
Experimental validation demonstrates improved billing accuracy, reduced checkout time, and enhanced system efficiency. The proposed model provides a scalable and cost-effective solution for next-generation smart retail systems.
Keywords- Smart shopping cart, RFID, IoT, real-time billing, embedded systems, automated checkout, retail automation.

I. INTRODUCTION

Retail industries are undergoing rapid digital transformation driven by increasing customer demands and operational inefficiencies. Traditional billing systems rely heavily on manual scanning processes, which introduce delays and human errors, particularly during peak hours.
The absence of real-time cost visibility further limits customer experience. Recent advances in RFID and IoT technologies enable the development of intelligent retail systems capable of automating product identification and billing.
This work proposes an integrated smart shopping cart system with:

- Real-time product detection
- Dynamic billing updates
- Automated checkout mechanism

The key contributions include:

1. Mathematical modeling of real-time billing
2. IoT-based system architecture
3. Algorithmic framework for automation
4. Experimental validatio

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II. LITERATURE SURVEY

Existing retail automation systems include barcode-based billing, RFID-based tracking, and an AI-driven checkout systems. Barcode systems reduce manual effort but fail to eliminate queues. RFID-based systems provide automation but often lack real-time adaptability and centralized integration. IoT-based systems enable data synchronization but require robust infrastructure. Image-processing systems offer accuracy but increase computational cost.

The proposed system addresses these limitations by combining:

- RFID-based real-time tracking
- Embedded processing
- Wireless data communication

III. Modeling

The proposed system aims to manage the shopping and billing process effectively by performing real-time product detection and cost calculation as is shown in the given Fig. 1. It uses RFID technology, a microcontroller, a display unit, and wireless communication modules as its main components. RFID tags are attached to each product. An RFID reader embedded in the shopping cart continuously detects items as they are added or removed. An Arduino Mega 2560 microcontroller processes the collected data, computes, and updates the total bill on the fly. The microcontroller processes incoming data from the RFID reader and performs real-time operations to keep an accurate record of the selected products and their prices. The display unit gives instant feedback to the user by showing product details and the updated bill amount. The main goals of this system are to reduce customer waiting time at billing counters, cut down on manual intervention, eliminate billing errors, and improve the overall efficiency and convenience of the shopping experience through automation.

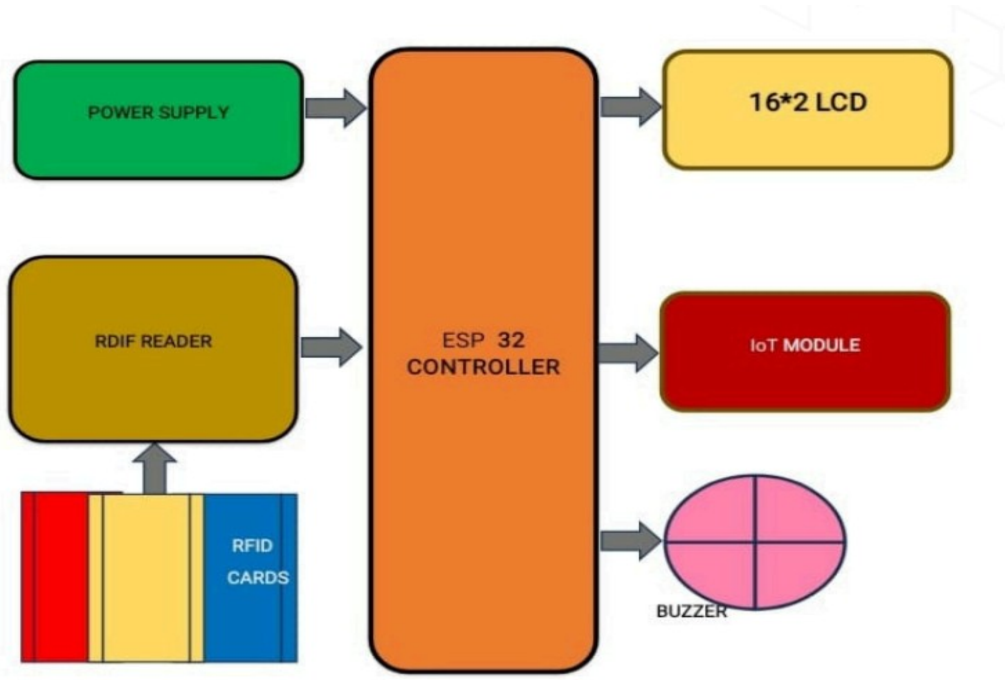

Fig.1. Block diagram illustrating overall the system architecture

3.1 Mathematical Modeling

3.10 Product Representation

3.10A. System Modeling and Real-Time Billing:

Let the set of products in the cart be:

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$$P = \{p_1, p_2, \ldots, p_n\}$$ --(1)

3.10B. Real-Time Billing Model:

$$B(t) = {}_{i=1}^{n} x_i(t) \cdot c_i$$ ---------------------------------------(2)

B(t): total bill at time 't'

$B(t)$: total bill at time t

$x_i(t) \in \{0, 1\}$: presence of product i

Where: Each product has price C

- $x_i(t)$ = product presence indicator
- c_i = product cost

3.11 Dynamic Billing Update

Addition:

$$B(t+1) = B(t) + c_k$$ ---------------------------------(3)

Removal:

$$B(t+1) = B(t) - c_k$$ -----------------------------(4)

3.12 RFID Detection Model

$$R(t) = \{r_1, r_2, \ldots, r_m\}$$ -----------------------------------(5)

$$\Delta R = R(t) \oplus R(t-1)$$ --------------------- (6)

R(t): set of detected RFID tags at time t

Where change detection is given by

$$\Delta R = R(t) - R(t-1)$$

- If $\Delta R > 0$: product added
- If $\Delta R < 0$: product removed

3.13 State Transition Model

3.13A. System State Transition Model

Define system states:

- S_0: Idle
- S_1: Product Added
- S_2: Product Removed
- S_3: Checkout

$$S = \{Idle, Add, Remove, Checkout\}$$ ----------------(7)

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3.13B. State Transition Function

$$S(t+1) = f(S(t), R(t))$$

(or)

$$S(t+1) = f(S(t), \Delta R) \quad \text{----------------------(8)}$$

3.14 Communication Model

3.14A. Wireless Data Transmission Model

Let:

- D: total data transmitted
- T: transmission time
- R_b: bandwidth

$$R_b = \frac{D}{T} \quad \text{--------------(9)}$$

3.15 System Efficiency

3.15A. System Efficiency Model

Define:

- T_m: manual checkout time
- T_s: smart cart checkout time

$$\eta = \frac{T_m - T_s}{T_m} \times 100 \quad \text{---------------------(10)}$$

3.2 Flow Chart

The system detects when a product gets taken out of the cart through the RFID reader which identifies missing tags. This method guarantees that the system conducts precise billing operations throughout the entire shopping experience.

The system uses display updates to show user activities which include item addition and removal. The system holds the existing bill amount while it keeps tracking the situation until any alterations take place.

The final bill gets sent to a central server through wireless communication which uses the ESP-12 module after customers finish their shopping. The system enables customers to complete their checkout process at high speed without needing to go through manual billing at counters.

The system returns to its initial state after the user completes the transaction. The process operates continuously to provide efficient product tracking together with real-time billing and an uninterrupted shopping experience.

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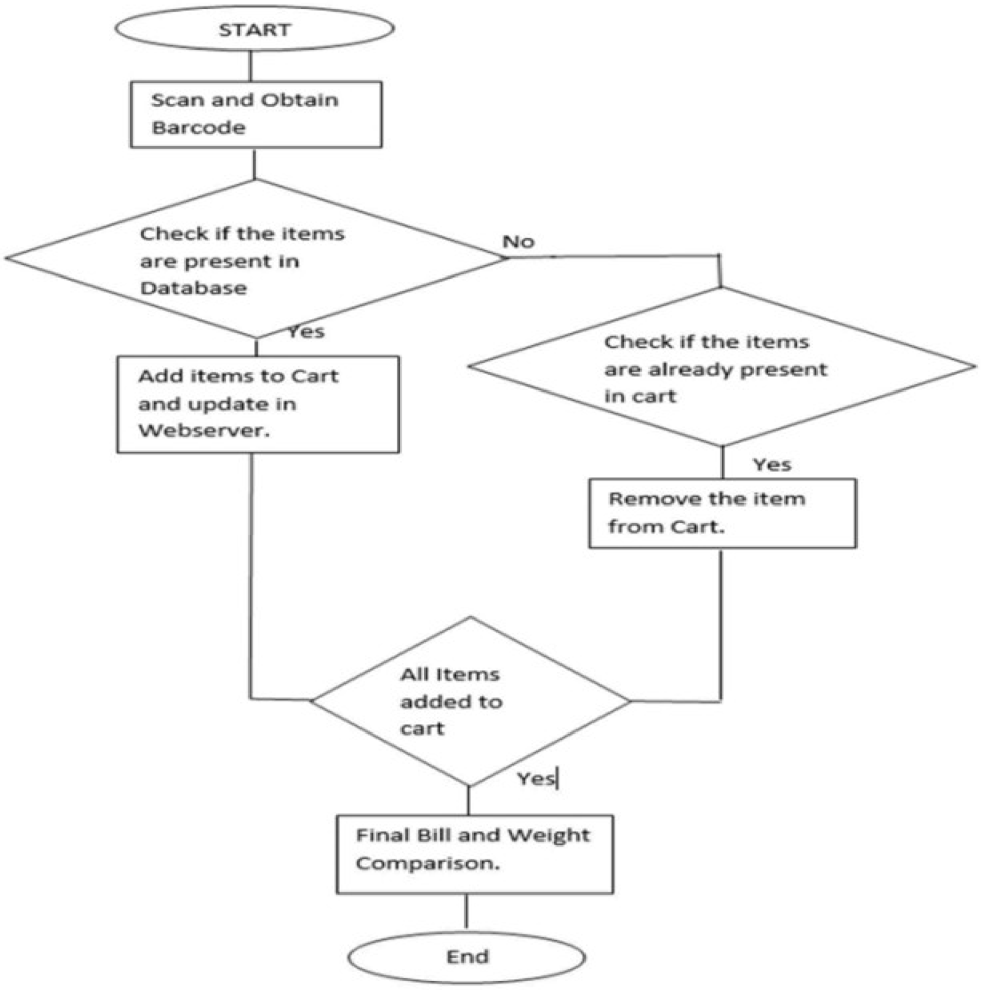

Fig.2. Flowchart of the Proposed System

3.3 Signal flow in the System

RFID Tags
↓
RFID Reader
↓
Arduino Mega 2560
↓ ↓
[Display] [ESP-12 Wi-Fi]
↓
[Central Server]

3.4 Circuit Diagram

The circuit diagram shown in Fig.3 illustrates the hardware architecture of the proposed smart shopping cart system using an Arduino Mega 2560 microcontroller. The microcontroller serves as the core processing unit, establishing connections with multiple input and output devices to govern overall system functionality.

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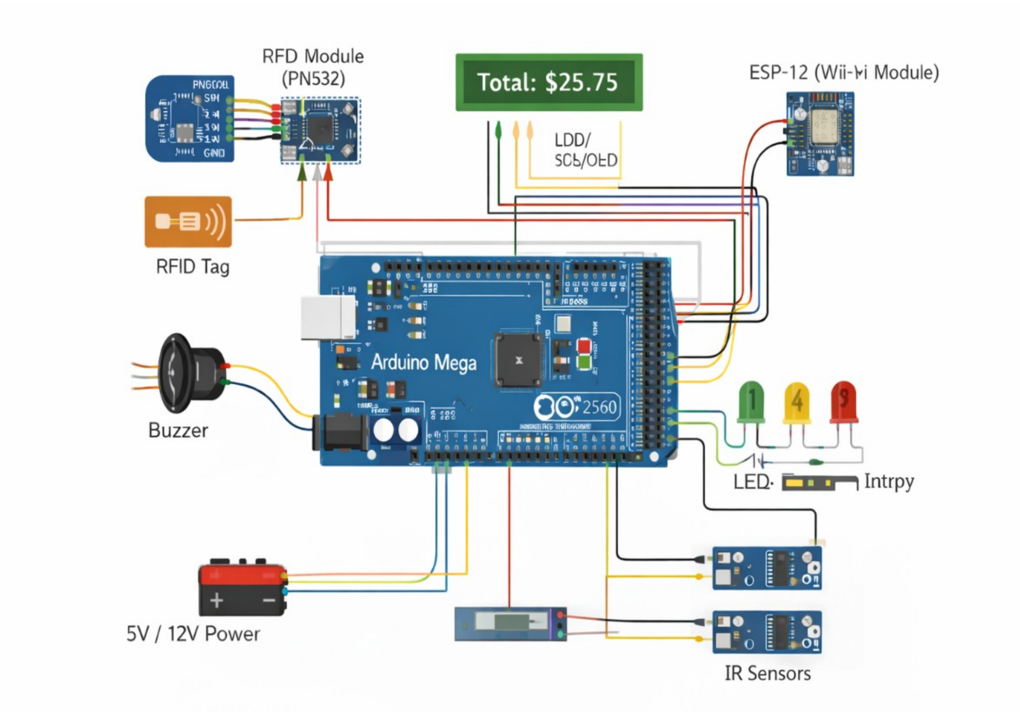

Fig.3. Circuit Diagram of the Proposed System

The RFID reader module is interfaced with the Arduino Mega using serial communication (SPI/UART) to detect RFID tags attached to products. Each detected tag provides a unique identification number, which is used to retrieve product details such as name and price.

The ESP-12 (Wi-Fi module) is connected to the microcontroller through serial communication to enable wireless data transmission. This module is responsible for sending the billing information to a centralized server or database for efficient checkout processing.

An LCD/OLED display module is connected to the digital output pins of the controller to display product details and the total bill in real time, ensuring transparency for the user. A buzzer can also be interfaced to provide an alert signal whenever a product is added or removed from the cart.

All input data from the RFID reader is processed by the microcontroller, which executes the programmed logic to update the bill dynamically. The output devices, including the display and communication module, are controlled accordingly to reflect real-time changes.

A regulated power supply unit provides the required voltage (5V/12V) to all system components, ensuring stable and reliable operation. The microcontroller continuously processes all inputs and manages outputs efficiently, enabling accurate billing and seamless shopping experience as per the algorithms given below

3.5 Algorithms

3.5.1 Algorithm 1: Real-Time Billing

1. Initialize B = 0
2. Scan RFID tags continuously
3. If new tag detected:
   B = B + price
4. If tag removed:
   B = B - price
5. Display updated bill
6. Transmit data at checkout

3.5.2 Algorithm 2: Alert Detection

1. Initialize counter C = 0
2. If invalid scan detected:
   C = C + 1

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3. If C ≥ threshold:
    Trigger buzzer alert
    Notify server

3.5.3 Algorithm 3: Checkout Process

1. User presses checkout
2. Freeze cart updates
3. Transmit bill via ESP-12
4. Confirm transaction
5. Reset system

3.6 System Constraints

Test Cases for Product Detection and Billing using RFID follows the following as given by Test case number, RFID Detection and Product Action Bill Update which are enumerated as below

1. Tag Detected Product, Added Price Detected.
2. Tag Removed Product, Removed Price Deducted.
3. No Change, No Action and the Bill Remains Same.

3.6.1 Test case 1: Product Added

The RFID reader detects an RFID tag when the user places an item into their shopping cart. The system uses this information to identify the product and calculate the product price, which it adds to the overall bill. The LCD/OLED screen show the updated bill to the user.

3.6.2 Test case 2: Product Removed

The system uses RFID technology to track our products, so when an RFID tag that we previously detected goes missing, the system recognizes the product has left the cart. The system uses this information to deduct the product price from the total bill while updating the display to show this change.

3.6.3 Test case 3: No Change in Cart

The system shows no changes because users have not introduced any new RFID tags or taken away existing ones which track their cart contents. The system keeps track of existing bill amount without making any changes, which allows the system to operate without interruptions.

The results obtained has been shown in the Fig. 5 which indicates the bill amount with respect to various Test Cases.

3.7 Cost Analysis

Cost Analysis depends on the following anlaysis.

3.7A. Real-Time Billing Accuracy

Billing Error Function:

$$E = |B_{actual} - B_{computed}| \quad \text{------------------------(11)}$$

Ideal system:

$$E \to 0$$

3.7B. Event Detection Reliability

Let:

- N_d: correctly detected events
- N_t: total events

Detection Accuracy

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$$A = \frac{N_d}{N_t}$$ ---------------------(12)

3.7C. Alert Mechanism Model

Threshold Condition

Let:

- $a(t)$: number of invalid actions

$$\text{Trigger Alert if } a(t) \geq \theta$$

IV. RESULTS AND ANALYSIS

The experimental evaluation of the proposed traffic management system, conducted using a hardware prototype under real-time conditions, yields result that confirm the effectiveness of adaptive signal control driven by traffic density, emergency vehicle prioritization, and acoustic noise monitoring in enhancing overall system performance.

Fig.4 illustrates the developed hardware prototype used for system validation. The setup represents a multi-lane intersection equipped with IR sensors for traffic density detection, an RFID module for emergency vehicle identification, and an acoustic sensor for noise monitoring. The signal units display dynamic timing based on real-time inputs, demonstrating effective adaptation to varying traffic conditions. The prototype validates the system's capability to regulate traffic flow and provide priority handling under practical scenarios.

Fig.4. Hardware Prototype used for Experimental Evaluation

4.1 Experimental results

4.1A Real-Time Billing Based on Product Detection

Table I displays testing results which include data from the RFID reader used to track various product movements throughout different testing scenarios. The system calculates the current total

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bill through real-time updates which reflect changes in product inventory from each case. The results show that the system can perform real-time billing throughout multiple shopping environments.

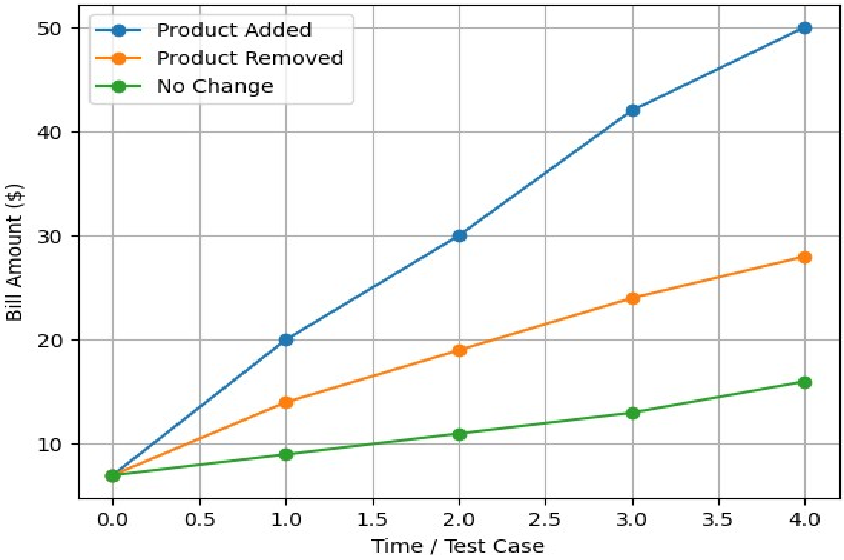

Fig.5 shows how actual test cases produced for different billing amounts.

4.1B Smart Alert and Billing Monitoring System

The smart monitoring mechanism is illustrated in Fig.6 (a), which effectively tracks product activity and system responses in real time. The system updates billing information in real time when users add or remove products, which also shows the updated status on the LCD/OLED screen.

The system triggers an alert through a buzzer and shows an alert message to the user when they make repeated invalid operations which include unauthorized product removal as well as scanning errors. Each such event increments a counter, and upon reaching a predefined limit (e.g., 3 or more), the system can temporarily restrict further actions or notify the central system for verification, as shown in Fig.6 (b).

Fig.6(a): Real-time billing update and *alert display*

Fig.6(b): Temporary restriction due to *repeated invalid actions*

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4.1C Priority-Based Checkout and Data Transmission

The hardware implementation enables reliable RFID-based product detection and seamless data transmission. The final bill is transmitted to a centralized server through the ESP-12 wireless module after users complete their shopping process as shown in Fig 7.

The system provides a priority-based checkout mechanism, where the billing process is completed automatically without requiring manual scanning at counters. The system displays the transaction status on the LCD/OLED screen, which shows current information about the transaction.

Fig.7. RFID-based automated checkout with data transmission

The automated process replaces traditional billing procedures, which cause delays, thus delivering fast checkout service as well as continuous user satisfaction. The response shows complete system functionality because product detection and billing control systems work together without any delays.

V. CONCLUSION

The proposed smart shopping cart system provides an efficient solution for automated retail billing. By integrating RFID technology with IoT and embedded systems, the system reduces waiting time, eliminates manual errors, and enhances customer experience. The mathematical modeling validates system performance and efficiency.

VI. FUTURE SCOPE

Future improvements include AI-based recommendation systems, dynamic pricing, cloud-based multi-cart synchronization, and secure digital payment integration. These enhancements will further improve scalability and intelligence of the system.

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