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Multi-Object Inventory System Using Ultra-High Frequency Radio Frequency Identification (UHF RFID) Based on Internet of Things

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ABSTRACT

This study develops an IoT-based inventory system that integrates UHF RFID technology with proximity sensors and an Android application to enable real-time multi-object tracking. The system automatically detects item movement direction (in/out) through sensor sequencing and provides cloud-based monitoring. Testing revealed exceptional single-object performance (100% accuracy at 1-5m distance; 1.53-1.62s avg. transmission time), but significant degradation with multiple objects, particularly beyond 3m (e.g., 5% accuracy for three objects at 5m). Although API integration enabled efficient data transmission, performance was constrained by ESP32 buffer limitations, RFID tag quality, and network stability. The solution demonstrates potential for low- to moderate-intensity inventory environments, providing a foundation for improving accuracy, although further comparative evaluation is required.

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1. Introduction

Inventory management constitutes a critical business function, with inventory assets representing approximately 50% of companies' capital investment [1]. Traditional inventory management often relies on manual methods, such as notebooks or software such as Microsoft Excel, Microsoft Word, and Google Spreadsheets. However, these approaches face several limitations, including lengthy data collection processes and potential data duplication [2], and risks of data loss or damage resulting in unrecorded items [3]. Inventory data inaccuracies can lead to financial losses and hinder effective decision-making [4]. Furthermore, manual systems make it difficult to achieve real-time tracking of inventory status and location, an increasingly important capability for modern supply chain operations [5].

Radio Frequency Identification (RFID) technology has been widely explored as a potential solution to improve automation and reduce manual errors in inventory management. By using radio waves to identify and track tagged items automatically [6], RFID systems can significantly reduce recording errors compared to manual approaches [7]. RFID tags, comprising microchips and antennas with unique identification codes, enable simultaneous multi-object reading [8], supporting near-real-time detection of multiple items. Advancements in tag design, such as PDMS/MWCNTs-based flexible tags with improved resonator arrays, have also extended read ranges and enhanced reflection characteristics [9], facilitating more reliable detection in various environments.

The integration of RFID with Internet of Things (IoT) architectures has further enhanced automation and monitoring capabilities, as demonstrated in several studies. For instance, previous research has shown that combining RFID with IoT systems can enhance stock visibility and reduce operational delays [10][11][12]. Tan and Sidhu [13] highlighted how IoT-enabled RFID systems can address interoperability and scalability challenges while supporting real-time data synchronization. However, despite these advancements, many implementations still face limitations such as the absence of mobile user interfaces or motion-direction sensing features.

Within the broader context of Industry 4.0, RFID has become a foundational component in digital supply chain transformation. Zhang et al. [14] reviewed seven enabling technologies for smart logistics, emphasizing the role of UHF RFID in enabling automated tracking and real-time visibility. The growing accessibility of mobile computing further supports the development of user-friendly inventory applications for example, as shown by Chen et al. [15], who demonstrated an IoT-based RFID system connected to a cloud database with an Android interface, which helped reduce human input errors and improved monitoring efficiency. Considering Indonesia’s large mobile user base (over 278 million people) and Android’s ≈ 88.7% market share [16], Android platforms are practical candidates for mobile inventory applications.

Therefore, this study focuses on developing a prototype IoT-based inventory monitoring system that combines UHF RFID, proximity sensors, and an Android-based application. The system aims to facilitate automatic item detection and movement-direction recognition while providing real-time access via a mobile interface. The findings from this work are expected to provide preliminary insights into the feasibility and performance of such integrated systems. However, further evaluation under varied environmental conditions and larger-scale deployments will be necessary to assess its efficiency, scalability, and long-term reliability comprehensively.

2. Literature Review and Comparison

The application of RFID technology in inventory management has been widely studied, with different implementations emphasizing trade-offs among functionality, performance, and system cost. Chen et al. [15] implemented a UHF RFID system capable of detecting tags within a 5-meter range. Despite demonstrating reliable single-tag detection, the absence of direction detection and mobile application integration limits its adaptability in dynamic inventory environments, and the overall hardware cost remains relatively high.

Motroni et al. [11] evaluated an autonomous robot scanning UHF RFID tags in a warehouse. An autonomous robotic system equipped with UHF RFID readers has been assessed for warehouse inventory management. By optimizing antenna placement, the system achieved 100% tag-counting accuracy under controlled indoor conditions. However, its dependence on a robotic platform and the absence of a user-interactive mobile interface make it less practical for small-scale or low-mobility applications.

Beauden [10] summarized several RFID–IoT case studies in the retail sector, such as Walmart’s large-scale deployment, which achieved a near 99% inventory accuracy and significant time reduction through IoT-integrated RFID readers. Nevertheless, these large-scale systems did not incorporate mobile applications or motion sensors, highlighting a gap in compact, user-oriented implementations.

This literature review identifies a gap in the development of RFID-based inventory systems that integrate direction detection, mobile access, and real-time monitoring at an affordable scale. The system proposed in this study addresses this gap by combining UHF RFID with proximity sensors and IoT connectivity. This design enables basic detection of movement direction and mobile monitoring while maintaining low hardware complexity. In controlled testing, the prototype demonstrated reliable single-tag detection at a range of 5 meters.

While these initial results indicate the system’s potential practicality in low- to medium-intensity environments, further evaluation is required to comprehensively validate its performance, cost-effectiveness, and scalability in real-world operational settings.

3. Materials and Methods

This section explains the research methods employed to develop a multi-object inventory system based on UHF RFID technology within the Internet of Things (IoT). The methodology includes prototype development, empirical testing, and quantitative analysis to evaluate system performance.

3.1. Research Design

This research employs a prototype-based system development approach, incorporating IoT, to develop a multi-object inventory system. The design includes three main components: 1) hardware development for RFID detection, 2) data communication system design, and 3) user application interface development.

3.2. Research Procedure

The research follows a structured five-stage methodology to ensure systematic development and evaluation. The planning stage begins with the identification of the project's hardware and software requirements. This preliminary assessment helps establish the technical foundation and resource needs for successful implementation.

During the design phase, detailed schematic circuits are developed along with the overall system architecture. This stage focuses on developing a practical framework that addresses the specific requirements identified in the planning phase while ensuring compatibility among system components.

The development stage involves implementing the designed circuits and programming the system functionality. Hardware components are assembled according to established schematics, while software modules are implemented and integrated to produce a functional prototype that meets the specified design criteria.

Testing procedures are then conducted to evaluate system performance against predetermined parameters. This phase includes functional testing, performance measurement, and validation of key system features to ensure the developed solution operates as intended under various conditions.

Finally, the analysis stage involves examining the test results to draw meaningful conclusions about system effectiveness. The data collected during testing is interpreted to assess whether the research objectives have been met and to identify any areas requiring further investigation or improvement.

3.3. Hardware Development

In developing this system, several functionalities must be addressed to enable RFID detection across diverse environments. Furthermore, the system must be able to transmit data over Wi-Fi to the application's database. According to these considerations, four main components are used in this RFID detection system: a middle-range (6 dBi) UHF Integrated Reader (HW VX6330K), an E18-80NK Infrared proximity sensor, an ESP32 Wi-Fi microcontroller, and an ESP32 DevKit Base expansion shield.

The RFID reader utilized in this system is the UHF Integrated Reader Electron HW VX6440K. This RFID reader has an IP54 rating for water resistance, enabling operation in both indoor and outdoor environments. This system employs the E18-80NK Infrared proximity sensor to achieve short-range detection with fast response times, thereby maximizing real-time detection. Additionally, this sensor is compatible with many microcontrollers, sending a digital signal directly to their GPIO pins without any processing. An ESP32 serves as a middleware, transmitting captured data to the database. The ESP32 receives data from the proximity sensor and the RFID reader, then sends it to an API that connects to the database. This process uses Wi-Fi to enable real-time data transmission from the ESP32. The connection between the RFID reader and the ESP32 uses the MAX3232 module, which acts as a level shifter for serial communication. The circuit diagram is shown in Figure 1, and the implementation is shown in Figure 2.

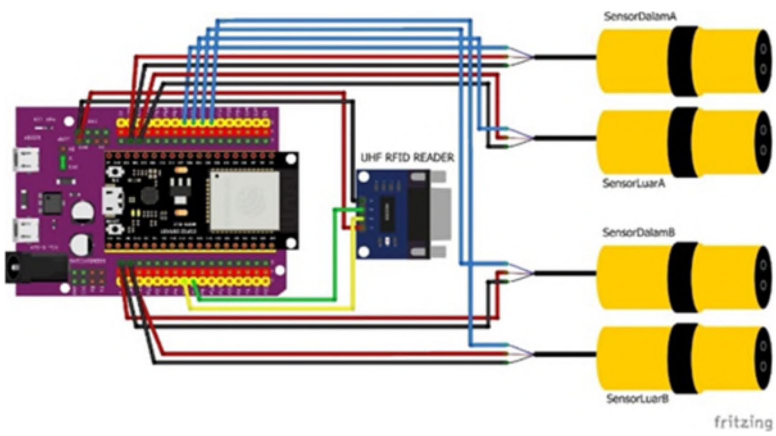

Figure 1 Circuit Diagram of The Developed System

Figure 2 Device Circuit Implementation

The series of devices is strategically placed with an RFID reader outside that continuously detects, and two proximity sensors in the door area. The system has two infrared sensors, one placed inside and one outside each room. The item's status (in/out) is determined by the order of infrared sensor activation, as shown in Figure 4. For clarity, the external proximity sensor is Proximity SensorLuar, and the internal proximity sensor is Proximity SensorDalam. If the order of detection is proximity SensorLuar before proximity SensorDalam, the item is detected as entering the storage area, and the database status is updated to “in”. In contrast, if proximity SensorDalam is first triggered, followed by proximity SensorLuar, then the item exits the storage area, and the status changes to “out”. A more detailed process for determining the status of goods (in/out) is presented in the following pseudocode.

```
/* Pseudocode to connect RFID Reader with ESP32 */
INITIALIZE Serial2 with 115200 baudrate
INITIALIZE pinProximity as INPUT
INITIALIZE pinLED as OUTPUT

FUNCTION setup():
    BEGIN communicate Serial2
    CONFIGURE pinMode for pinProximity and pinLED
    CONNECT to WiFi Network
END FUNCTION

FUNCTION loop():
    IF data is available from RFID Reader THEN
        READ data tag
        STORE ID tag to temporary buffer
    END IF

    IF sensor proximity is triggered THEN
        DETERMINE directions (enters/exit) according to detection
sequence
        SEND data tag with directions information to server
        CLEAR temporary buffer
    END IF
END FUNCTION
```

3.4. System Architecture and Workflow

The system employs a cloud-based architecture, with an ESP32 as the primary microcontroller, transmitting data to the database via an Application Programming Interface (API). The API accelerates and simplifies the data transmission process between IoT devices and the database. The RFID reader and proximity sensor are responsible for item detection, while the Android application facilitates real-time monitoring for users. The system architecture is as shown in the block diagram in Figure 3.

Figure 3 Block Diagram of Multi-object Inventory System

The system workflow is shown in Figure 4. The system begins with the detection of the RFID tag within the reader's range. At the same time, the system detects the activation of the proximity sensor to determine the item's direction of movement (in/out). The collected data, including detection time, storage location, and type of goods, will be temporarily stored. The data is then sent to an API that acts as an intermediary between the system and the database. If the submission fails, the system will continue attempting until it succeeds. Data stored in the database can be accessed directly by the Android application using the Firebase API key.

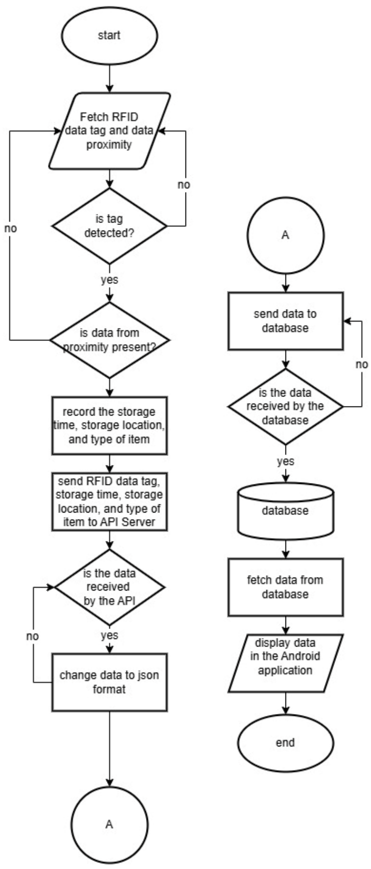

Figure 4 Multi-object Inventory System Flowchart

3.5. Application Interface Development

The application interface was developed in Kotlin using Android Studio as the integrated development environment (IDE). The application is designed with three main functions integrated into one cohesive system. First, the monitoring feature allows users to track item activity in real time and provides visibility into inventory movement. Second, the registration function provides a mechanism for registering new items into the system with the necessary detailed information. Third, the data management module facilitates the modification and updating of information for items already registered in the system.

The system can determine whether a detected RFID tag is registered in the inventory database. Unregistered tags will be labeled "unregistered." When such a tag is detected upon entry, the system displays a pop-up warning to alert the user. However, if an unregistered tag is detected during exit, the system records the event but does not trigger a warning. This means the system can distinguish between registered and unregistered tags but does not assess whether an item's movement is appropriate or authorized.

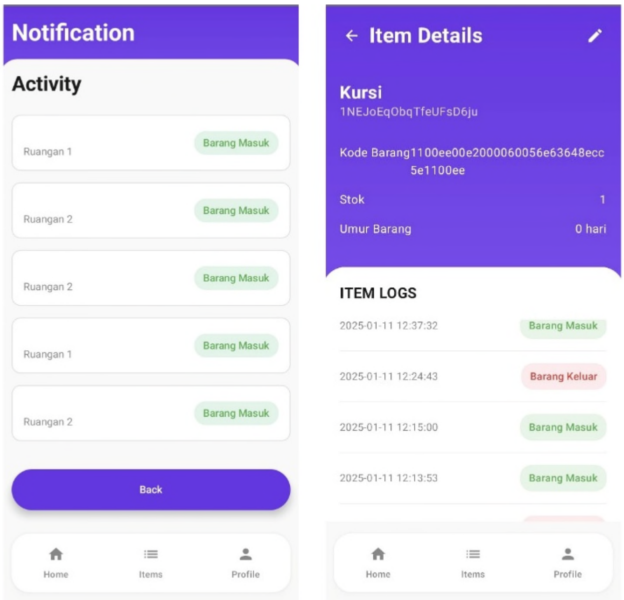

Figure 5 Example of Android Application Interface

As shown in Figure 5, the application provides intuitive visualization of incoming and outgoing goods data, comprehensive item details (type, location, activity records), warning notifications for unregistered tags at entry, and an item-locking feature to prevent unauthorized movement.

3.6. Data Sources and Data Collection Methods

Primary data comprises RFID tag-reading results at various distances and object counts, data transmission performance between devices and the database, and overall system response time. Secondary data includes technical component specifications (data sheets) and API documentation, including communication protocols.

Data were collected through systematic observation with predetermined parameters, using instruments to measure outcomes. Data are logged continuously in a spreadsheet, and distance measurements are taken with a tape measure.

3.7. Testing Method

Testing the Accuracy of RFID Detection against Distance and Number of Objects. The testing is conducted to analyze the performance of RFID detection as a function of distance and the number of objects. Several tests are conducted to assess the system's overall performance, including accuracy, test duration per attempt, and average time per distance. These tests are conducted with different detection distances from 1 meter to 3 meters, the number of tags from one to three tags in each detection distance, and it is tested 20 times for each combination of distance and tags. Below are the tests conducted to assess the system's performance:

1. Accuracy

Accuracy is calculated as the total number of successful detections divided by the total number of attempts for a specific combination of distance and number of tags. Below is the formula for calculating accuracy:

$$A = \frac{\sum_{i=0}^{n} N_{b(i)} - \sum_{i=0}^{n} N_{g(i)}}{n} \quad \text{Equation 1}$$

From equation 1, A is accuracy, $N_{b(i)}$ is the number of successful trials, $N_{g(i)}$ is the number of failed trials, and n is the total number of trials.

2. Data Transmission Time Testing

Data transmission time testing is conducted to assess the system's feasibility for real-time operation. Testing parameters include the time difference between tag detection and data reception in the database, the average delivery time under various conditions (distance and number of tags), and the fastest and slowest times for each testing scenario.

As mentioned, the test was conducted 20 times at specific distances and tag quantities. Time differences are averaged using the Millis function, which returns the time in milliseconds since device startup. More minor time differences indicate closer real-time operation. Below is the formula for calculating time per trial:

$$T_{(n)} = T_{p(n)} - T_{d(n-1)} \quad \text{Equation 2}$$

From equation 2, $\mathrm{T}_{(\mathrm{n})}$ is the total delivery time in the n-th trial, $\mathrm{T}_{\mathrm{p}(\mathrm{n})}$ is the system's active time during the delivery of the n-th trial, and $\mathrm{T}_{\mathrm{d}(\mathrm{n}-1)}$ is the system's active time during tag detection in the previous trial. From the equation, it indicates that, n is the current number of trials and $\mathrm{n} - 1$ is the previous trial.

After obtaining the total delivery time for each trial, the average trial time is calculated for each tag count and distance. The average delivery time is calculated with the equation below:

$$T_{avg} = \frac{\sum_{i=1}^{n} T_{(n(i))}}{n} \quad \text{Equation 3}$$

From equation 3, T_{avg} is the average time for distance trials and the number of tags $T_{(n(i))}$ is the total time of each trial, n is the number of trials, and i is the number of iterations.

The test is conducted manually, with multiple people assigned to specific tasks. Person 1 is assigned to hold the RFID tag in front of the RFID reader. Person 2 is responsible for triggering the proximity sensor, enabling the ESP32 to capture the tag ID from the RFID reader. Person 3 oversees that the data is sent to the database and updated in the application. Figure 6 depicts the detection position, while Figure 7 presents the actual implementation of the test.

Figure 6 Testing Method

Figure 7 Real Implementation of The Testing

4. Results and Discussion

This section presents the test results for the multi-object inventory system using the developed UHF RFID system. The testing was conducted to analyze two essential aspects of the system: (1) the accuracy of RFID detection in relation to distance and the number of objects, and (2) the data transmission time from the system to the database.

4.1. RFID Detection Accuracy Results

The accuracy detection test evaluated the system's ability to detect RFID tags across varying distances and object counts. Results are presented in Table 1.

Table 1 RFID Detection Accuracy and Testing Duration

Number of Items	Detection Range (m)	Testing Duration (mm:ss)	Accuracy (%)
1	1	00:42	100
	2	00:46	100
	3	00:49	100
	4	00:47	100
	5	01:17	100
2	1	03:17	94.74
	2	05:00	80.95

Number of Items	Detection Range (m)	Testing Duration (mm:ss)	Accuracy (%)
	3	04:37	90
	4	02:14	100
	5	02:11	86.36
3	1	04:05	37.5
	2	03:29	60
	3	05:03	34.61
	4	03:58	42.85
	5	05:56	5

Single-object detection achieved 100% accuracy across all tested distances (1-5 meters), demonstrating excellent performance for individual item tracking. Testing duration remained consistently low (≤77 seconds), indicating efficient processing for single-object scenarios. However, detection accuracy degraded when tested with multiple objects. When tested with two objects, the accuracy ranged from 80.95% (2m) to 100% (4m), with an average of 90.41%. On the other hand, when tested with three objects, accuracy drops dramatically from 60% (2m) to 5% (5m), with an average of 36.00%. A visualization of this accuracy degradation as a function of distance and the number of tags is shown in Figure 8.

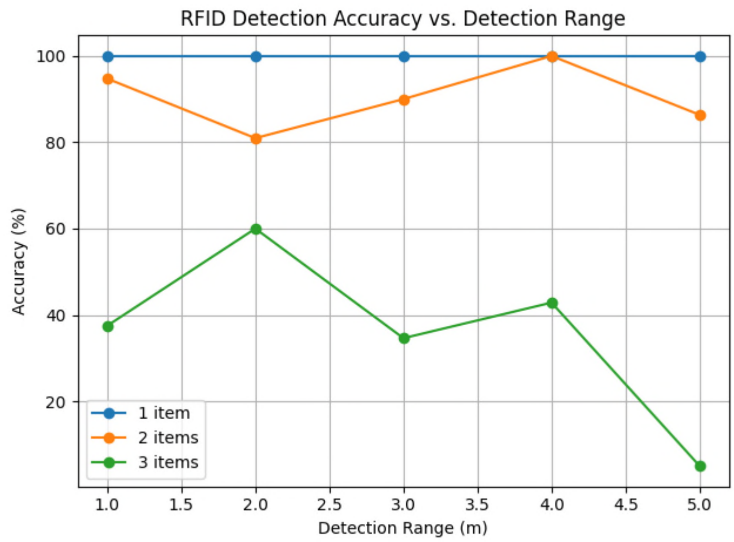

Figure 8 Accuracy vs. Detection Range for Different Numbers of RFID Tags

Detection time increased substantially with the number of objects, reaching up to 356 seconds for three objects at 5 meters. Anomalies occurred when RFID tags were read before the proximity sensor was activated, resulting in data truncation during transmission. The performance degradation in reading three UHF RFID tags at a distance of 5 meters is caused by a combination of weak radio frequency (RF) power received by the passive tags, which reduces backscatter capability; tag-to-tag interference triggering collisions despite the use of the EPC Gen2 anti-collision protocol; increased cycle time due to reduced signal-to-noise ratio (SNR) at longer distances; and power reflection loss and multipath effects from the environment that disrupt the synchronization of tag responses.

4.2. Data Transmission Time Results

Another critical aspect of system evaluation is the time required for data transmission from detection to database entry. Table 2 presents a comprehensive analysis of data transmission performance.

Table 2 Data Transmission Time Analysis

Number of Items	Detection Range (m)	Average Time (s)	Fastest Time (s)	Slowest Time (s)
1	1	1.62	1.31	1.83
	2	1.53	1.31	2.16
	3	1.61	1.33	2.09
	4	1.55	1.32	3.18
	5	1.54	1.32	1.82
2	1	6.05	3.64	11.07
	2	5.63	3.86	7.59
	3	6.83	5.41	12.95
	4	5.74	5.25	8.24
	5	5.54	3.58	6.90
3	1	10.23	3.47	20.57
	2	7.47	3.67	18.04
	3	6.30	3.57	13.80
	4	7.20	3.68	14.77
	5	5.68	3.46	10.13

Transmission times showed a strong correlation with object count: a single object was consistently fast, averaging 1.53-1.62 seconds, with a minimum of 1.31 seconds. Two objects experience a moderate delay, averaging 5.54-6.83 seconds and reaching a maximum of 12.95 seconds. However, three objects exhibit highly variable performance, with average durations ranging from 5.68 to 10.23 seconds and a maximum of 20.57 seconds.

Interestingly, lower accuracy at longer distances (e.g., 3 objects at 5m: 5% accuracy) resulted in shorter transmission times (5.68s average) because fewer successful detections required processing.

The primary cause of the extended delay was identified as internet connectivity instability, as the system relied on a 2.4 GHz mobile hotspot with signal strength fluctuating between –65 dBm and –82 dBm, as measured with inSSIDer. These fluctuations caused variable latency, packet loss, and retransmission delays during database synchronization. This indicates that network reliability strongly influences transmission latency, emphasizing the need for local buffering or offline synchronization mechanisms to maintain consistent system performance.

4.3. System Limitations and Challenges

RFID system performance is limited by low RF power and insufficient signal-to-noise ratio (SNR), as three UHF RFID tags have an effective reading range of less than five meters. Furthermore, the performance of the EPC Gen2 anti-collision protocol was degraded by tag-to-tag interference and collisions; despite the EPC's anti-collision mechanism, it is only effective over medium distances. Because some of the energy bounces back rather than reaching the RFID tag, environmental factors such as signal reflections, metallic surfaces, and RF interference also contribute to power reflection loss and multipath effects. Additionally, the system's dependence on an internet connection introduces vulnerabilities in data transmission.

5. Conclusions and Future Work

This study presents the development of an IoT-based multi-object inventory prototype that integrates UHF RFID technology, proximity sensors, and a mobile application. The system enables automatic tracking of item movement direction (in/out) through sequential sensor activation and provides real-time inventory monitoring via an Android interface.

Under controlled testing, the prototype demonstrated stable single-object performance, achieving 100% detection accuracy at distances of 1–5 meters and an average data transmission time of 1.53-1.62 seconds. However, performance degraded notably under multi-object conditions, with accuracy dropping to approximately 5% for three objects at five meters. These results indicate that the system operates reliably in low-density scenarios, but scalability remains constrained by hardware capacity and network stability.

Within its current configuration, the proposed system demonstrates potential applicability in low- to medium-intensity environments such as small warehouses, retail stores, and healthcare storage facilities. The integration of RFID and proximity sensors provides a practical foundation for automated inventory tracking; however, further comparative studies are required to quantitatively evaluate efficiency and cost-effectiveness relative to manual and other RFID-based systems.

Several constraints were identified, including ESP32 buffer limitations, distance-dependent read accuracy, network dependence, and tag-quality sensitivity. Future improvements should therefore focus on algorithm optimization to achieve more robust multi-object detection in high-density scenarios, as well as on hardware upgrades to higher-capacity microcontrollers or distributed processing architectures. Additionally, network reliability could be enhanced by implementing local data buffering or offline operation features. The integration of machine learning techniques may also contribute to predictive analytics, anomaly detection, and inventory forecasting. Moreover, expanding the mobile application to include augmented reality capabilities could enhance the visualization and user interaction aspects of the inventory process.

Comprehensive large-scale, long-term testing is recommended to validate the system's performance, reliability, and scalability under real operational conditions, thereby ensuring a more representative evaluation of its practical potential.

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