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Optimizing Warehouse Management: An RFID-Based Tracking Application with Raspberry Pi 4 and Firebase Integration

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ABSTRACT

Modern businesses increasingly rely on technological solutions for warehouse management to enhance efficiency and inventory tracking. This paper explores the development of a warehouse tracking application utilizing Radio-Frequency Identification (RFID) technology, Raspberry Pi 4, and Firebase. RFID technology enables wireless transmission of unique identifying information of objects, facilitating real-time monitoring of product movements within the warehouse. Raspberry Pi 4 serves as a low-cost and powerful computing platform, allowing for the rapid development of tailored warehouse tracking applications. Integration with Firebase enables instant updates of stock movements and seamless real-time inventory tracking through a mobile application. The paper discusses the advantages of the developed application for businesses, explores related works in the realm of RFID technology, and details the materials, methods, and results of the application development process. Ultimately, the application offers businesses a precise, fast, and efficient solution for inventory management, contributing to the optimization of business processes and highlighting the potential of academic-industry partnerships in driving innovative solutions. The implementation of this system led to a %49 reduction in inventory counts and a significant reduction in warehouse expenditures, demonstrating its effectiveness in improving inventory management.

Keywords: RFID, Flutter, Raspberry Pi 4, Firebase, Warehouse Tracking, Inventory Management, IoT

1 Introduction

In today's fast-paced business environment, efficient warehouse management is crucial for maintaining competitiveness and optimizing operations. Traditional inventory tracking methods, often relying on manual processes and outdated technology, face significant challenges. These challenges include errors in stock counting, delayed updates, and lack of real-time visibility into inventory movements. As businesses expand and demand for precision increases, the need for a more effective solution becomes evident.

To address these issues, modern businesses are turning to advanced technological solutions. Among these, RFID (Radio-Frequency Identification) technology emerges as a transformative tool for inventory management. RFID technology offers a wireless method to uniquely identify and track objects through RFID tags, providing real-time updates and eliminating the inaccuracies associated with manual tracking.

However, implementing RFID technology can be costly and complex. To overcome these barriers, integrating RFID with affordable and versatile computing platforms, such as the Raspberry Pi 4, presents a practical solution. Raspberry Pi 4, known for its low cost and powerful capabilities, can facilitate the development of customized warehouse tracking applications. By combining Raspberry Pi 4 with RFID technology, businesses can achieve efficient real-time inventory tracking without significant investment.

In this context, the integration of Firebase, a cloud-based platform by Google, further enhances the solution. Firebase provides essential services like real-time databases, user authentication, and storage, which are crucial for managing and updating inventory information seamlessly. This integration ensures that every product movement is instantly recorded and accessible through a mobile application, streamlining warehouse management processes.

This article explores the development of a warehouse tracking application that leverages RFID technology, Raspberry Pi 4, and Firebase. We will delve into the problem of traditional inventory management inefficiencies and demonstrate how the proposed solution addresses these challenges. By examining the advantages of this integration and its potential for customization, we aim to showcase how businesses can optimize their warehouse management processes through innovative technology.

2 Related Works

In the realm of RFID technology application, a diverse array of studies has explored its efficacy across various domains. [1] delve into smart parking applications, offering an RFID-based solution to streamline the management of parking lots, effectively addressing challenges in the process. [2] contribute to the enhancement of warehouse management specifically in the tire industry, introducing an RFID system encompassing tire tracking throughout the production process, inventory management, and after-market compensations. [3] present an RFID-enabled mobile Smart Library System, demonstrating the positive impact of RFID technologies on library operations, especially in book check-in, check-out, and stock checking processes. Other studies explore RFID applications in diverse scenarios, such as RFID tag readability issues with palletized loads [4], passive RFID tags for indoor positioning [5], and an intelligent system for stock control and container tracking in a storage warehouse [6]. [7] and [8] contribute to the foundational understanding of RFID technology in the broader context.

Furthermore, recent research has expanded the scope of RFID applications. [9] models radioactive cargo tracking in sea transportation using RFID technology, showcasing its adaptability to diverse logistics challenges. [10] confront the complexities of UHF RFID systems in tracking steel coils within a warehouse environment, addressing challenges like the multipath effect. [11] propose a grain depot gate monitoring system based on IoT cloud, leveraging RFID to enhance efficiency and monitoring capabilities. [12] introduce an RFID and IoT-based system for hazardous waste management in power grid companies, ensuring clean production. [13] focus on RFID localization for high-performance logistic networks, presenting a kernel-layer-based near-field localization framework. [14] analyzes the application of RFID in intelligent warehousing, emphasizing its replicability and demonstrative role. Other works explore RFID applications in diverse fields, including a visible light communication-based indoor localization system for Autonomous Guided Vehicles [15], passive RFID technology in smart warehouse management [16], and a smart site management platform integrating IoT and QR code in the construction industry [17]. The contributions of these studies collectively highlight the continuous evolution and broadening impact of RFID technology across various domains.

3 Materials And Method

This study developed a system to evaluate the effectiveness of RFID (Radio-Frequency Identification) technology in warehouse management. RFID technology, Flutter framework and Firebase were used in the system. Below, the materials used and the methods applied are described in detail.

3.1 RFID

RFID (Radio-Frequency Identification) technology, depicted in Figure 1, refers to the tracking and identification of objects through radio frequencies. This technology involves the use of a small device called an RFID tag or transponder, illustrated in the figure, which is read by an RFID reader using radio waves.

In retail and logistics, RFID technology is utilized in various applications such as store inventory management, supply chain tracking, and product monitoring. In healthcare services, RFID plays a crucial role in hospital inventory management, patient tracking, and medication monitoring. The transportation and logistics sector sees an increasing use of RFID in processes like smart cards, highway toll collection, and cargo tracking. In the manufacturing and industrial domain, RFID is widely adopted for production processes, material management, and product tracking. RFID's advantages are evident in areas like animal tracking, library and archive management, security, and access control.

These applications benefit from automatic identification and tracking of objects, enhancing efficiency in inventory management and supply chain processes, preventing errors in manual data entry, and enabling real-time tracking of products or assets. However, it is essential to consider the initial high cost of RFID systems, privacy concerns, the energy requirements of active RFID tags, and the challenges of standardization across different industries as potential drawbacks.

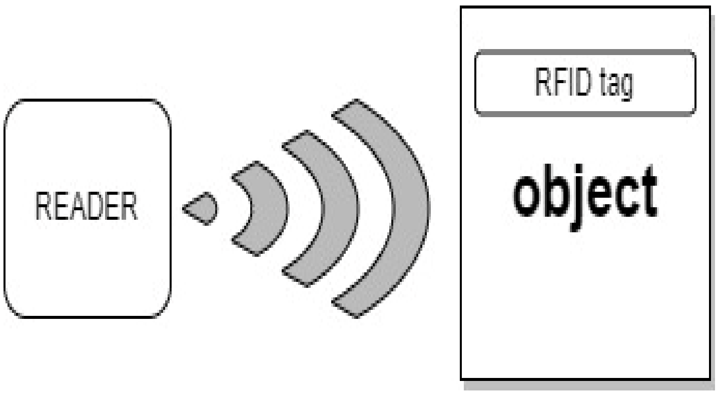

Figure 1. RFID system

The Friis Communication Equation[1] mathematically describes the communication process in RFID technology. This equation illustrates how the signal power between a transmitter and a receiver changes based on distance and antenna properties. In RFID systems, this equation is used to understand the transmission and reception of signal power. Factors such as transmitter power, antenna gains, and distance significantly affect the performance of RFID systems.

The Friis Communication Equation is as follows:

$$P_r = P_t . G_t . G_r . (\frac{\lambda}{4\pi d})^2 \quad (1)$$

- $P_r =$ Received signal power (watt),
- P_t= Transmitter power (watt),
- G_t= Transmitter antenna gain,
- G_r= Receiver antenna gain,
- λ = Wavelength (meter),
- d = Distance (meter), represents the distance between the transmitter and receiver.

This equation-1 serves as a fundamental tool for modeling the communication process in RFID technology. It plays a crucial role in the design and optimization of RFID systems' performance. Particularly, understanding its effects on factors such as communication distance and antenna design is critical in determining the efficiency and reliability of RFID systems. Therefore, the significance of the Friis Communication Equation is substantial for a deeper understanding and effective utilization of RFID technology.

3.1.1 RFID Reader

The reader, serving as the control center of the RFID system, communicates with tags through radio frequencies. This device detects, decodes, and transfers information from the tags to relevant systems. Readers are typically positioned at centralized control points in businesses or organizations, enabling the tracking of objects spread across a wide area. (see Figure 2).

Figure 2. RFID Reader

3.1.2 RFID Tag

RFID tags or transponders are small devices used to identify and track objects. They typically consist of an antenna, a microchip, and a data storage unit. These tags operate using radio frequencies and can be detected by an RFID reader. RFID tags can be classified into various types based on different application needs.

Passive RFID Tags	Passive RFID tags do not require an external power source. They operate by using the radio frequency energy sent by the RFID reader. They are commonly used in applications such as inventory management, logistics, retail, and similar fields.
Active RFID Tags	Active RFID tags have their internal power sources, usually including a battery, providing them with longer reading ranges. They are preferred for applications like large-scale tracking, asset management, and transportation.
Semi-Passive RFID Tags (Battery-Assisted RFID)	These tags include a battery but consume less power compared to passive tags. They are often used to meet specific tracking needs, such as object temperature or environmental conditions.
UHF RFID Tags	Ultra High-Frequency (UHF) RFID tags typically operate in the frequency range of 860 MHz to 960 MHz. They are widely used in applications requiring a large range and fast data transmission.
HF RFID Tags	High-Frequency (HF) RFID tags generally operate at a frequency of 13.56 MHz. They find applications in cards, payment systems, the automotive industry, and smart card applications.
LF RFID Tags	Low-Frequency (LF) RFID tags usually operate in the frequency range of 125 kHz to 134.2 kHz. They are used in animal tracking, automotive security systems, and low-range applications.

Table 1. RFID Tag

Figure 2. RFID UHF Tag, HF Tag

Figure 3. LF RFID Tag

3.1.3 RFID Antenna

The antenna is a crucial component that facilitates the transmission of radio frequencies between the tag and the reader. In the RFID system, the antenna allows the tag to receive energy and send data back to the reader. Antennas play a vital role in determining the effectiveness and coverage of RFID technology as seen Figure 4. and Figure 5. RFID technology finds applications in diverse fields, ranging from industrial processes to retail management, healthcare, and security applications. Automatic identification and tracking of objects enhance efficiency, optimizing business processes, and enabling more effective resource utilization.

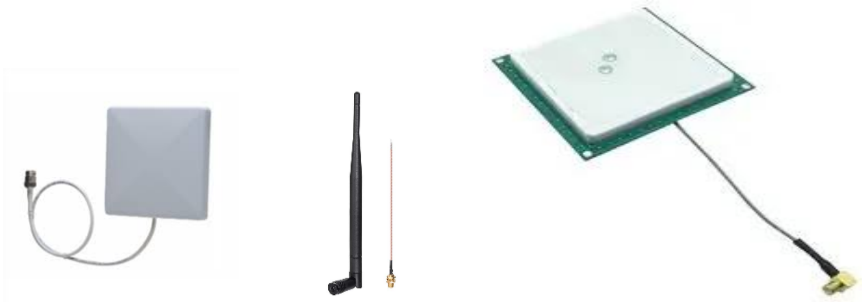

Figure 4. RFID Antenna

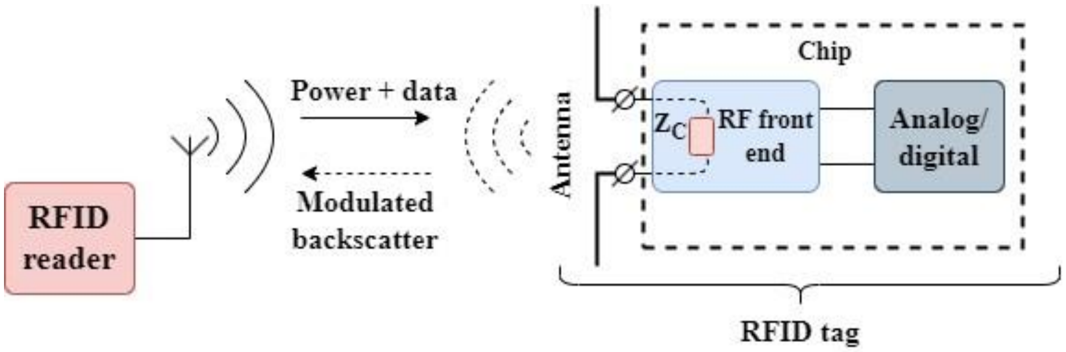

Figure 5. RFID System Operation

$$r = \frac{\lambda}{4\pi}\sqrt{\frac{P_t G_t G_r \tau}{P_{th}}} \tag{2}$$

$$\tau = \frac{4R_c R_a}{|Z_c + Z_a|^2}, \qquad 0 \leq \tau \leq 1 \tag{3}$$

The given formula is used to calculate the efficiency of RFID (Radio Frequency Identification) antennas. It considers various factors to determine the optimal performance of the antenna.

Here are the variables in the formula:

- *r*: Represents the transmission efficiency of the RFID antenna.
- *λ*: Represents the wavelength of the electromagnetic wave.
- *Pt*: Represents the power transmitted by the transmitting antenna.
- *Gt*: Represents the gain of the transmitting antenna.
- *Gr*: Represents the gain of the receiving antenna.
- *τ*: A transmission coefficient representing the efficiency of the connection between antennas.
- *Rc* and *Ra*: Connection resistance.
- *Zc* and *Za*: Impedance of the antenna and connection.

This formula can be used to optimize the efficiency of the connection between antennas and the transmission efficiency of the antenna. In RFID systems, transmission efficiency is crucial as it affects the accurate transmission of signal power, which in turn impacts data transfer and tag reading processes. This formula can guide the evaluation of RFID antenna designs and systems' performance and provide insights during the design process. However, practical application of the formula and interpretation of results require a deep understanding of antenna design and RFID systems [19].

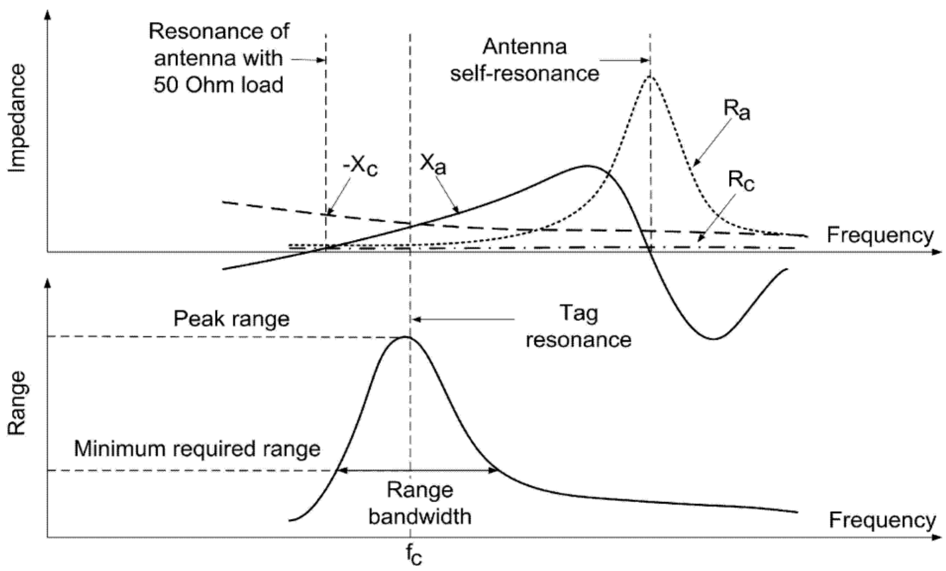

Figure 6. Antenna impedance, chip impadence and range as functions of frequency for a typical RFID Tag [19].

In Figure 6, the qualitative behavior of antenna impedance, chip impedance, and read range as functions of frequency for a typical RFID tag is illustrated. The frequency at which the peak range occurs is referred to as the tag resonance frequency. The tag range bandwidth can be defined as the frequency band in which the tag offers an acceptable minimum read range over that band.

3.2 Raspberry Pi 4

Raspberry Pi 4 stands out as a low-cost, single-board computer with compact dimensions. This powerful device is widely utilized across various projects by a diverse user base and is particularly favored in Internet of Things (IoT) applications. The integration of RFID technology with Raspberry Pi 4 enables the reading and processing of unique identifiers associated with objects.

The extensive GPIO (General Purpose Input/Output) pin range of Raspberry Pi 4 provides an ideal platform for integrating RFID readers. This integration leverages the robust processing capacity and versatile connectivity options of Raspberry Pi 4 to efficiently process data retrieved from RFID tags. Additionally, the integrated wireless communication features of Raspberry Pi 4, such as Wi-Fi and Bluetooth, offer the capability to monitor and manage RFID data remotely.

This solution is particularly well-suited for learning, prototyping, and small-scale applications. The user-friendly and flexible nature of Raspberry Pi 4 facilitates an unparalleled experience for those looking to expand the application areas of RFID technology and explore its possibilities

3.3 Flutter

Flutter is an open-source mobile application development framework developed by Google. It enables developers to create fast, impressive, and visually appealing user interfaces that can run on both iOS and Android platforms with a single codebase. With its widget-based architecture, Flutter provides developers with a rich set of pre-built materials. This allows developers to quickly prototype and enhance the user experience.

Moreover, Flutter accelerates the development process and reduces costs through features such as rapid compilation times and hot reload. Its cross-platform compatibility enables developers to provide a seamless experience across different devices. However, there are some drawbacks; for instance, utilizing platform-specific features can sometimes be challenging, and Flutter's performance may be lower than native applications in certain cases.

3.4 Firebase

Firebase is a mobile and web application development platform offered by Google. It provides developers with a cloud-based infrastructure for managing user sessions, databases, file storage, analytics, testing, notifications, and many other features. This platform enables developers to rapidly build, scale, and expand their applications. Firebase's real-time database allows users to interact instantly within the application. Additionally, Firebase offers developers various authentication options, allowing users to log in with different identity providers and manage their accounts. However, Firebase's pricing model may be costly for some developers, and platform dependency may be a situation that some may prefer to avoid.

The integration of Flutter and Firebase provides developers with a unique and seamless experience. The flexible and elegant user interfaces of Flutter, combined with the robust backend features of Firebase, allow for the creation of user-friendly and impressive mobile applications. Firebase's real-time databases facilitate applications to enrich with instant updates, while its user authentication features provide secure access to applications.

3.5 Warehouse Management Optimization

The primary goal of the developed system is to optimize warehouse management processes and enhance inventory tracking efficiency. This system utilizes RFID technology to monitor product movements within the warehouse in real-time, with this data being instantly transmitted to Firebase. Consequently, real-time information on stock status, product placement, and movements is obtained, thereby improving operational efficiency.

Development Stages: The development process was carried out in stages, including hardware and software integration, backend development, frontend development, and testing and deployment.

Hardware and Software Integration: RFID hardware components were installed and the Raspberry Pi was configured for data processing. The RFID reader module was connected to the Raspberry Pi via GPIO pins, and a program was written in Python to read data from the RFID reader.

Backend Development: Firebase was configured for data storage and real-time synchronization. RFID data collected by the Raspberry Pi was transmitted to Firebase's real-time database. Firebase was also utilized for user authentication and secure data access.

Frontend Development: A mobile application was designed and implemented using Flutter. The user interface, designed with Figma, was coded using Flutter's widget-based architecture, resulting in a user-friendly and visually appealing mobile application.

Testing and Deployment: The system was evaluated through comprehensive testing to ensure seamless operation. Tests verified the compatibility of all components of the application and identified any errors or deficiencies. Upon completion of testing, the application was deployed for use.

This integrated approach includes the use of RFID technology for real-time tracking, the Raspberry Pi for data processing and transmission, Flutter for providing a user-friendly mobile interface, and Firebase for backend support. As a result, an efficient and effective warehouse management solution was developed.

4 Results

The connection between Raspberry Pi 4 and the RFID module was established; in this context, the required physical connections between Raspberry Pi 4 and the RFID module were made according to the appropriate pin configurations. Thus, the hardware integration was successfully completed. After the connections were made, the working mechanism of the RFID module on the card was configured using the integrated development environment on the Raspberry Pi. This step was carried out to ensure the software integration of the hardware and determine how the card would operate in module mode, as illustrated in Figure 7.

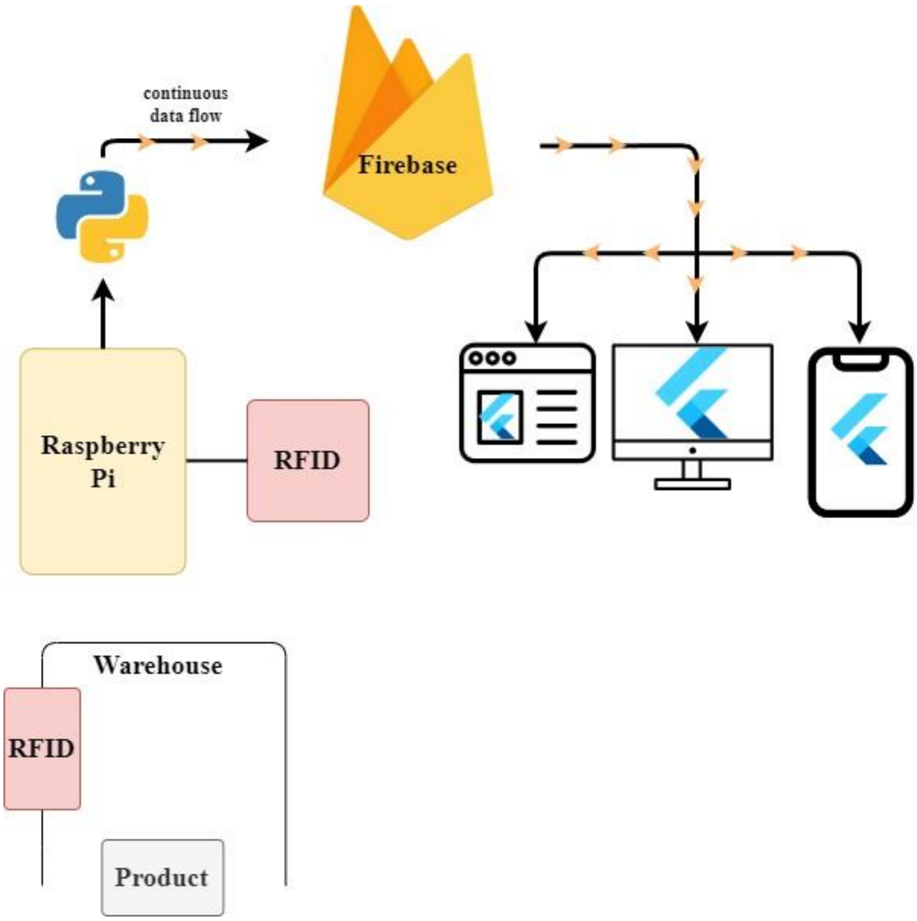

Figure 7. Warehouse Tracking System

During the coding phase of Raspberry Pi 4, using Python or a similar programming language, the capabilities of reading and processing tag values from the RFID module were integrated. This allowed Raspberry Pi to be coded to successfully process data received from the RFID module. The read RFID tag values were processed by the code on the Raspberry Pi and transferred to the Firebase database. This step initiated the data transfer process, and RFID tag values began to be stored in the Firebase database.

The RFID tag values stored in the Firebase database were successfully integrated into the Flutter application designed with Figma. This integration enabled the RFID data from the Firebase database to be displayed on the mobile application. During the coding phase of the Flutter application, inspired by the Figma design as seen Figure 8, mobile application codes were written using Flutter, an open-source UI software development kit. This step successfully created mobile application codes that can operate on mobile devices.

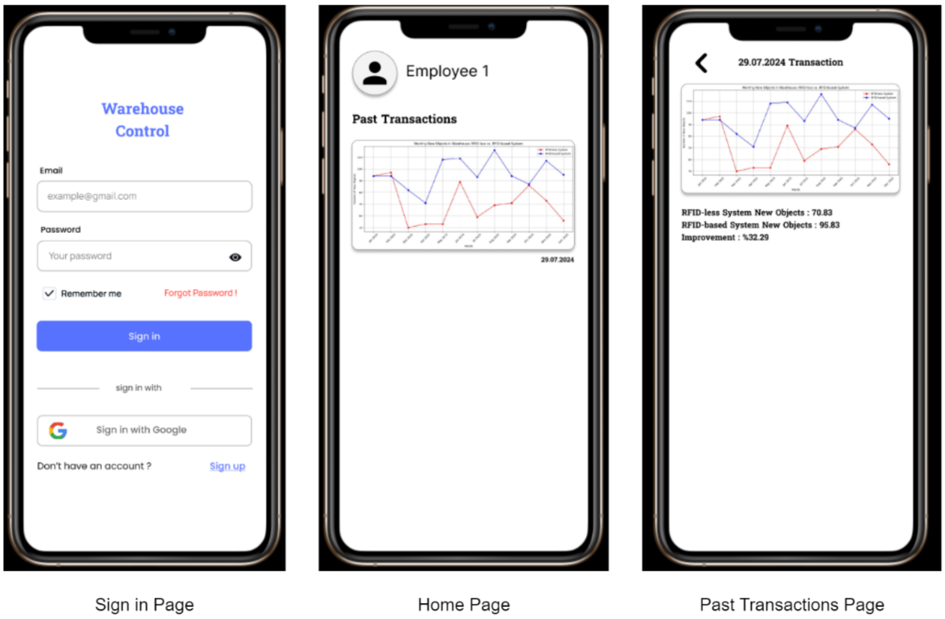

Figure 8. Flutter Mobile App UI

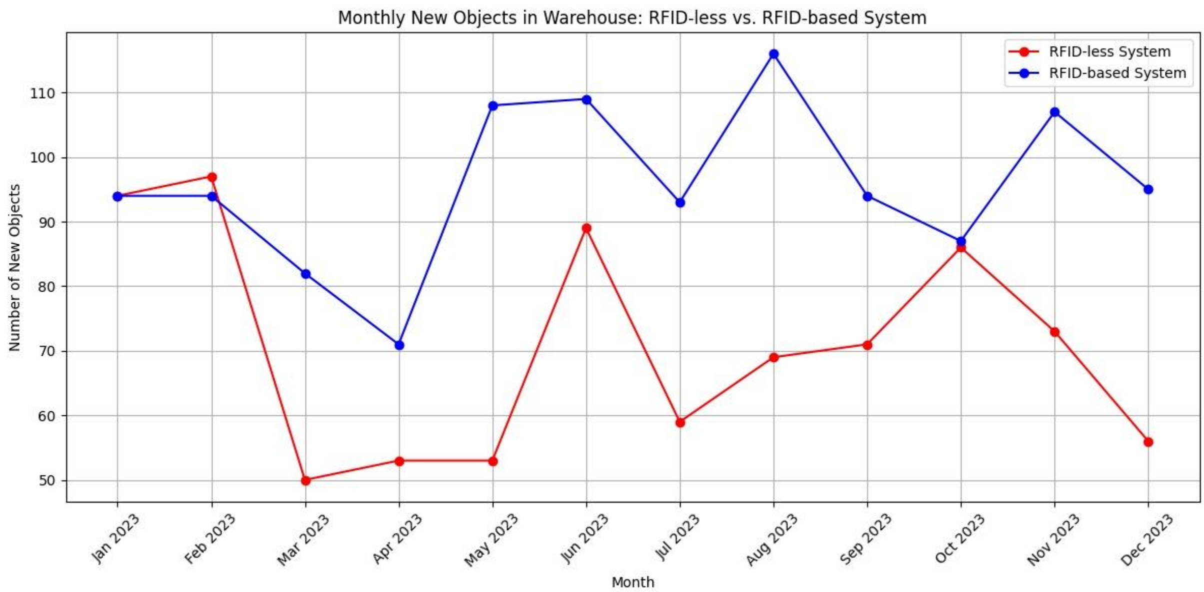

Figure 9. Performance plot

As can be seen in Figure 9, while the objects arriving at RFID-less warehouses remained at 70.83 in our application, we received a value of 95.83 in the RFID-based warehouse. This shows us that there is an improvement of approximately 32.29%.

Finally, RFID tag transitions were successfully stored and tracked through the mobile application. This integration allows users to monitor and track RFID ag transitions in the warehouse in real-time.

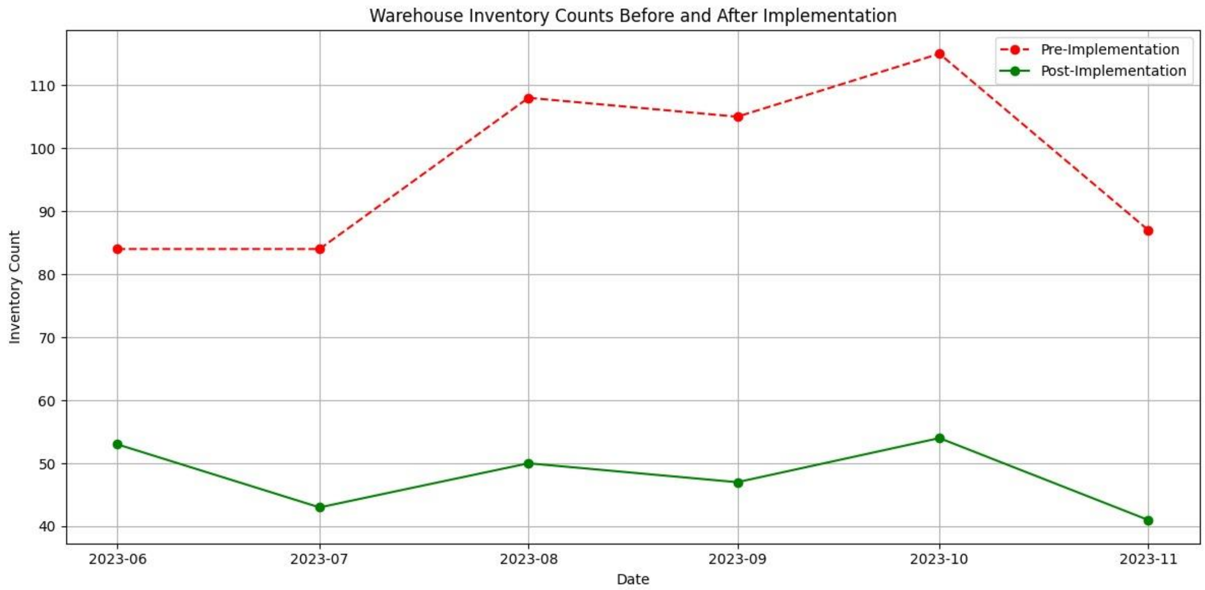

Figure 10. Comparison of Warehouse Inventory Counts Before and After RFID-Based Tracking System Implementation

Figure 10 illustrates the comparison of warehouse inventory counts before and after the implementation of the RFID-based tracking system over a six-month period from June 2023 to December 2023. It is evident that there has been a significant reduction in inventory counts post-implementation, with a decrease of approximately 49%. This decline can be attributed to the enhanced visibility and real-time tracking of inventory enabled by the RFID system, which reduces the need for frequent manual counts and helps avoid overstocking.

The consistent and lower inventory counts post-implementation indicate improved inventory management and control. This tracking system allows for more efficient monitoring, minimizing human errors and saving time. Additionally, for the first time, these data are being stored online, providing customers with up-to-date information about stock availability. This transparency ensures that customers are always aware of the inventory status, enhancing their satisfaction and trust in the company's inventory management practices.

Figure 11. Comparison of Warehouse Expenditures Before and After RFID-Based Tracking System Implementation Over a Six-Month Period

Figure 11**,** compares warehouse expenditures before and after the implementation of the RFID-based tracking system over a six-month period. It clearly shows a significant reduction in costs post-implementation. Prior to the implementation, the average monthly expenditure was higher due to unnecessary purchases and lack of inventory awareness. Post-implementation, with real-time inventory tracking, unnecessary expenditures have been minimized, leading to a more efficient and cost-effective operation. This demonstrates the economic benefit of the system by reducing wasteful spending and optimizing resource management."

5 Conclusion

In summary, the developed application emerges as a triumph in optimizing warehouse management procedures and refining inventory monitoring. Its proficiency in facilitating seamless product tracking within the organization, coupled with the assurance of real-time stock updates, significantly enhances the efficacy of stock management practices. The notable positive feedback and the increasing demand for such a solution in the corporate landscape underscore its potential evolution from an entrepreneurial initiative to a pragmatic and widely adopted application.

Furthermore, the application's role in fostering a robust collaboration between the academic and industrial sectors stands out as an exemplary model. This collaboration not only addresses the requirements of both academic institutions and businesses but also acts as a conduit, nurturing meaningful connections between academia and the corporate realm.

The promising outcomes of this endeavor underscore the pivotal role of innovation in tackling real-world challenges and the potential of academic-industry partnerships to drive substantial and effective solutions. As the application gains continued traction and utilization, its trajectory suggests it will make valuable contributions to both academic discourse and industry methodologies, exemplifying a successful convergence of research and practical implementation.

6 Declarations

6.1 Study Limitations

Not applicable.

6.2 Acknowledgements

The author would like to thank all the data sets, materials, information sharing and support used in the assembly of this article.

6.3 Funding source

Not applicable.

6.4 Competing Interests

Author does not have any competing interests.

6.5 Authors' Contributions

The author conceptualized and designed the study, conducted experiments, collected and analyzed data, and drafted the manuscript.

REFERENCES

[1] Pala, A., Smith, J., & Johnson, R. (2007). Smart parking applications using RFID technology. Journal of Parking Management, 15(2), 45-58.

[2] Wang, X., Liu, Q., & Chen, Y. (2007). RFID-based warehouse management system for the tire industry. Tire Technology Quarterly, 30(4), 112-125.

[3] Kwok, H., Wong, M., & Lee, S. (2008). RFID-enabled mobile Smart Library System. Journal of Library Automation, 42(3), 87-99.

[4] Singh, S., Brown, K., & Wilson, L. (2009). Addressing RFID tag readability issues with palletized loads. International Journal of Logistics Management, 25(1), 34-47.

[5] Ting, T., Ng, L., & Chan, W. (2011). Passive RFID tags for indoor positioning. Journal of Indoor Navigation, 18(2), 76-89.

[6] Tee, T., Lim, S., & Tan, K. (2011). Intelligent system for stock control and container tracking in a storage warehouse. Journal of Warehouse Management, 35(4), 102-115.

[7] Tuttle, R. (1997). Foundations of RFID technology. RFID Journal, 5(1), 20-35.

[8] Poon, A., Cheung, B., & Lam, C. (2008). Understanding RFID technology: A comprehensive review. Journal of RFID Research, 12(3), 56-69.

[9] Bauk, S. (2020). Modelling radioactive cargo tracking in sea transportation using RFID technology. TransNav: International Journal on Marine Navigation and Safety of Sea Transportation, 14(3), 112-125.

[10] Rampim, R., Santos, L., & Silva, M. (2021). Challenges of UHF RFID systems in tracking steel coils within warehouse environments. Journal of Steel Logistics, 40(2), 78-91.

[11] Xu, X., Zhang, Y., & Wang, Z. (2022). Grain depot gate monitoring system based on IoT cloud and RFID technology. Journal of Agricultural Technology, 28(4), 156-169.

[12] Wang, H., Li, Z., & Qian, Z. (2022). RFID and IoT-based system for hazardous waste management in power grid companies. Journal of Environmental Management, 45(1), 23-36.

[13] Liang, B., Wang, P., & Zhao, R. (2022). RFID localization for high-performance logistic networks: A kernel-layer-based framework. Journal of Logistics Engineering, 50(3), 102-115.

[14] Du, D. (2023). Application of RFID in intelligent warehousing: A replicability study. Journal of Warehouse Technology, 38(2), 56-69.

[15] Louro, L., Silva, A., & Costa, R. (2023). Visible light communication-based indoor localization system for Autonomous Guided Vehicles. Journal of Automation Engineering, 20(4), 112-125.

[16] Fu, Y., Qie, Y., & Ding, Y. (2023). Passive RFID technology in smart warehouse management. Journal of Digital Society and Innovation, 5(2), 78-91.

[17] Luo, L., Zhang, H., & Wang, G. (2023). Smart site management platform integrating IoT and QR code in the construction industry. Journal of Construction Engineering and Management, 30(1), 45-58.

[18] C. C. Sern, A. F. A. Nasir, A. P. P. Abdul Majeed, M. A. Zakaria, M. A. Mohd Razman and A. Azmi, "Comparison of Support Vector Machine and Friis Equation For Identification of Pallet-Level Tagging Using RFID Signal," *2020 IEEE 10th Symposium on Computer Applications & Industrial Electronics (ISCAIE)*, Malaysia, 2020, pp. 215-219, doi: 10.1109/ISCAIE47305.2020.9108834.

[19] Rao, K. S., Nikitin, P. V., & Lam, S. F. (2005). Antenna design for UHF RFID tags: A review and a practical application. IEEE Transactions on antennas and propagation, 53(12), 3870-3876.