An Open Hardware RFID Inventory Management System

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I. Executive Summary

RFID stands for Radio Frequency Identification. It uses radio waves to wirelessly track objects. In inventory management, unlike bank cards which use similar technology for secure transactions, RFID tags are attached to items for tracking. A reader emits radio waves that are picked up by the tag, which transmits a unique identifier (UID). This allows for quick and accurate tracking of items, like updating stock levels in real-time. Imagine library books with RFID tags. When a book is returned, the librarian simply scans it with a reader, automatically updating the library's database. For some applications in retail or inventory management it is easier to use handheld RFID tag readers. Paired with the software, person scanning the RFID tags in certain area can check whether all items are present and haven't been replaced or stolen.

This project studies the possibility of using a low-cost RFID reader for cost-effective multi-purpose tracking applications. The project explores the integration of RFID and GPS modules into an ESP32 microcontroller. The developed system offers a potential low-cost alternative to existing handheld readers. The functionality of the system is evaluated through real-world testing in various scenarios. The results show that the system is capable of providing satisfactory functionalities at a low cost.

II. Introduction

Radio Frequency Identification (RFID) is a technology widely used in the area of security and Internet of Things (IoT) tracking. An RFID tag contains a unique identifier, that is applied to inventory management solutions [1]. The market research revealed that existing Ultra-High Frequency (UHF) RFID readers, also known as RFID data terminals [2], pose significant expenditures, especially for small businesses. Prices ranged from USD$450 to USD$2500 for devices offering largely similar functionalities. These existing solutions typically comprise an Android interface, an RFID reader component, and manufacturer-developed software for managing scanned tag data. A perfect example of such system is CipherLab 1861, manufactured by CipherLab [3].

This paper proposes a novel approach that leverages cloud technologies and a mobile device software to significantly simplify and improve upon existing solutions. The proposed system prioritizes user convenience by offering a "turnkey" solution that eliminates the need for complex configurations involving PCs, terminals, and .NET SDKs. This includes measurements of GPS accuracy, server response times, power consumption, and RFID-specific metrics. Additionally, the paper compares our system with similar solutions, presents system schematics, and explores potential encryption implementations. Moreover, it publicly offers a number of software tools developed during the research[1].

To develop the system, an ESP32-WROOM microcontroller, a NEO-6M GPS module, and an Invelion R200 RFID reader were chosen due to their availability, ease of use and low cost. Overall, the contribution of this research is:

- Integration of the R200 RFID reader and a NEO-6M GPS tracker with the ESP32 microcontroller.
- Development of an open-source software system for inventory management.
- Evaluation of the efficiency and applicability of the system for the needs of inventory management.

This paper begins by presenting the hardware and software architectures of the system. This includes simplified hardware schematics and algorithm structure for decision-making process of the device. Experiments and evaluation of experimental results are then performed to provide the quantifiable results to gauge the efficiency of the system.

III. Background and Related Work

After market research mentioned in the Introduction section of the paper, we decided to pivot the project. Our study investigates the application of the R200 UHF RFID reader, manufactured by Invelion LTD, for a cost-effective multi-purpose tracking system. The research explores the integration of the R200 with a NEO6M GPS module and an ESP32 microcontroller. A web application is developed using the NextJS framework to facilitate data visualization and control. The resulting system offers a potential low-cost alternative to existing handheld readers, following further development. As most of the background information was already present in the Introduction, this section of the paper focuses more on key findings and potential limitations of our system.

[1] GitHub Repositories:

- https://github.com/zhany-bek/ecoton_rfid
- https://github.com/zhany-bek/ecoton-inventory/

A. Key Findings

The proposed solution offers a significantly lower hardware cost (USD $67) compared to commercially available inventory management systems, such as CipherLab 1861 [3]. The cost breakdown (in USD) is:

- $54 for Invelion RFID R200 reader.
- $4 for ESP32-WROOM microcontroller.
- $9 for NEO-6M GPS module.
- $1 per UHF RFID tag.

This represents a cost reduction factor of 3.73 compared to CipherLab and similar data terminals. The cost can be decreased even further if the modules were built as a single device and in large quantities. Notably, the proposed solution achieves a greater reading and writing range compared with CipherLab, 2.30m and 1.0m, respectively. However, it is acknowledged that commercial solutions might offer faster software operation and direct connection to PC and enterprise software. We believe that if our system was developed further with better hardware, plastic casing and own software, we can still manage price less than $150. This is affordable, can be sold as a DIY kits and overall can be good solution for Small and Medium Businesses (SMB). For comparison purposes, here are some of the most similar products on the market with their retail price in USD:

- $67 - Proposed.
- $1245 for CipherLab 1861.
- $431 for SRK9U RFID.
- $849 for Zebra RFD2000.
- $1310 for Bunker and Elsherbeni [4].

One of the similar open hardware inventory management system is Modular Integrated RFID System for Inventory Control Applications proposed by Ross Bunker and Atef Elsherbeni [4]. Their hardware is based on Raspberry Pi, and the UDP-HTTP server is located in the same local network as the device, which includes an RFID reader and other components for scanning purposes. The end product is a large handheld prototype, with an estimated cost of USD $1310, which incurs significantly higher cost than the proposed solution. Additionally, their system operates without the GPS tracking module, which means that the location should be set manually.

B. Limitations and Considerations

The effective reading range and the efficiency of RFID systems are limited by physical properties such as the maximum output power of the reader, the coupling efficiency between the reader and the tag, tag power consumption, and the size of the tag. Sorrels, Want and Kamoun identify additional parameters affecting reading range, including tag modulation depth, reader signal-to-noise ratio, tag power-conversion efficiency, reader antenna tuning, and reader filter quality [2], [5], [6]. In our system, potential operational speed limitations are primarily due to the R200 module's ability to read all tags without repetition. Improvements can be made through the use of larger ceramic antennas, optimized reading angles, refined power consumption management, and higher quality RFID tags and readers.

Data security is prioritized using the Firebase ESP client library, which encrypts communication between the ESP32 microcontroller and the Firebase back-end using TLS. Output data is also encrypted before transmission, protecting sensitive information such as Firebase and Telegram keys. While the Telegram bot is restricted to the administrative interface, implementing additional key management practices would be beneficial. It is important to note that the protection against channel threats on RFID transmission signals described by Figueroa Lorenzo et al. [7] is not implemented in the proposed system. Further improvement of reader connection security can include randomized communication protocols that do not allow obtaining the data contained in the tag or even prohibits foreign readers to read the tag. This ensures that the tag tracking is impossible to perform. Additionally, as Faouzi Kamoun stated in his work [6], data security has to be integrated on all communication layers of the RFID technology. Thus, a Pharaday cage can be used to protect tags in the operating environment.

For a broader system integration, developing a specialized mobile application for direct communication with the ESP32 would eliminate the dependency on a third-party platform and improve the system UI and responsiveness, as well as security. Improvements to the proposed system is largely dependent on the use-case. For example, adopting more structured approach to the inventory management logic as it was described by Ting [8] on the case of manufacturing enterprises can be extremely efficient.

IV. Project Approach

A. Hardware Architecture

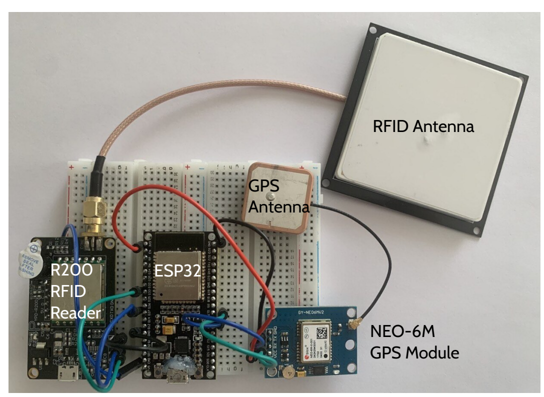

Fig. 1. Prototype version of the proposed system.

The prototype of the device is presented in Fig. 1. The hardware consists of the following items:

- An ESP32-WROOM-DA microcontroller.
- A NEO-6M GPS module.
- An R200 UHF RFID Reader module.
- A 7x7cm RFID antenna with 0-3m reading range.

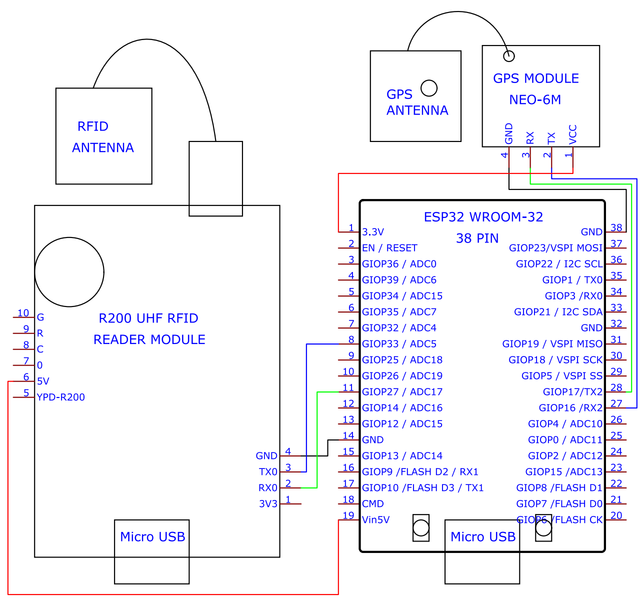

Fig. 2. EasyEDA Hardware Schematic

- A GPS antenna

The connection scheme is presented in Fig. 2. ESP32-WROOM-DA serves as a main module connected to RFID and GPS modules for further transfer of the received data via Wi-Fi connection to Firebase. The GPS module is supplied by a 3V3 pin and UART TX/RX pins are connected to ESP32's pins 16(RX), 17(TX) respectively for serial communication. RFID module is supplied by a 5V pin and its UART TX/RX pins are connected to ESP32's default serial connection pins 9(RX) and 10(TX). This configuration ensures a seamless parallel operation of both the GPS module and the RFID reader.

B. Software Architecture

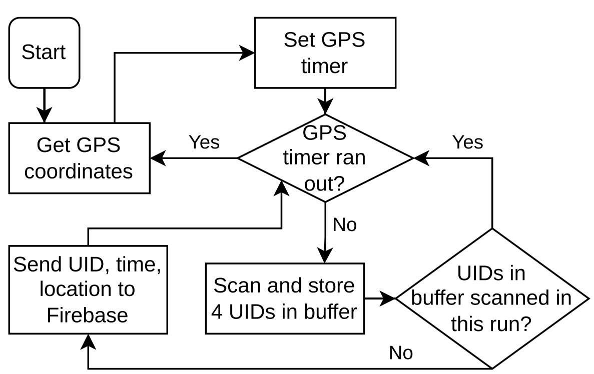

Fig. 3. System Logic Block Diagram

The system starts its operation by getting GPS coordinates. Two approaches of attaining the GPS data are explored: using the NEO-6M GPS module or by interacting with the user through a front-end interface. NEO-6M is a low-cost GPS tracking module, which is often applied to the IoT, healthcare [9] and positioning solutions [10]. For the simplicity of the development and interaction, a Telegram bot is acting as a front-end interface for the system's user during operation. With the latter, the user is expected to send Telegram's built-in location attachment, which provides the system with the latitude and the longitude values. The location is necessary per security requirements to verify that the products' RFID tags were scanned at the company's storage facilities or expected delivery locations. Telegram has been chosen to be used, because it eliminates the use of third-party apps during development, while offering a wide variety of tools, such as GPS location messaging, that are useful for the development.

Once the coordinate variables are set, the system starts a GPS timer, during which the R200 UHF RFID scanner is enabled. For each scanning iteration, the scanner reads several presented tags (the amount may vary), saving the frames containing their Unique IDs (UIDs) into a buffer. The number of tags read in a single iteration depends on the buffer's size and the delays set within the R200 library. For the purposes of this demonstration, the scanner can read up to 4 tags at a time.

The system then sends the UIDs to the Firebase Realtime Database after verifying that they correspond to the company's inventory items. The system keeps track of the 20 most recently sent UIDs, which allows the system to avoid redundant communication with the cloud database on the following iterations. Decreased amount of requests results in a lower delay between scans and an increase in the battery life of the device.

Once the GPS timer runs out, the system requires the user to acquire GPS coordinates again to continue scanning tags. It is assumed that the time allotted for the scan is sufficient to cover an entire storage facility, so the system resets the array of recently sent UIDs.

V. Project Execution

As stated previously, the initial goal of this project was to develop a system incorporating RFID tags resistant to harsh weather environments. However, a major issue with this direction would have been a focus on finding insulation materials and developing tag protection measures using them. This type of work does not correspond to the requirements of the Computer Science major.

Due to this and further research into cost-efficiency issues of using RFID in stock management, we decided to shift focus towards developing a cost-effective, open-source RFID-based inventory management system.

During the Fall 2023 semester, the overall architecture of the system was much simpler with no GPS module and only an RFID scanning module connected to an ESP32 microcontroller. Said RFID module was a cheaper and less effective model as well, being able to read 1 tag at a time at a maximal distance of 5-10 cm. In Spring 2024, we were able to find the currently used model, which effectively balances cost-efficiency and better performance.

In terms of GUI, in Spring 2024, we changed the web app development framework from Django to NextJS, since the latter offers a more streamlined front-end development experience. Additionally, Firebase handles most of the system's back-end operations, making the use of Django - a primarily back-end framework - less efficient than NextJS.

VI. Evaluation

A. Reading Range Measurements

The stability of the readings of the R200 UHF RFID scanner was investigated at various distances up to the maximum reading range of 3 meters, which was provided in the datasheet of the device. The results of the evaluation can be seen in the list below.

- 30 – 100 cm – Feasible.
- 100 – 150 cm – Feasible.
- 150 – 200 cm – Feasible.
- (Max.) 292 cm – Feasible.

The results indicate that the R200 UHF RFID meets factory specifications with a 10% margin of error. The reading range and reliability decrease with longer distances, resulting in a narrower cone of reading RFID tags. Stable readings were consistently obtained at distances between 30 cm and 100 cm, with the scanner successfully acquiring a tag's UID on every iteration of the main loop. However, at distances of 100 cm to 150 cm, the stability of readings varied depending on the tag's placement relative to the scanner. Placing the tag directly in front of the scanner within a 30-degree cone provided similar performance to the previous distance range. This trend continued at distances of 150 cm to 200 cm, but even with optimal tag positioning, several unsuccessful readings occurred. This issue worsened with increasing distance. The maximum range at which the scanner could read RFID tags was found to be 292 cm. Based on these measurements, it is recommended to scan tags within a range of up to 100 cm. While a more powerful R200 antenna could extend this range, it is unnecessary for inventory management purposes.

B. GPS evaluation

The first approach of acquiring the GPS data, as stated in Section IV, was to use the NEO-6M GPS module. This approach was tested in different scenarios, which can mainly be divided into 2 categories: indoors and outdoors locations. There have been 40 total trials of GPS location with NEO-6M, 20 for indoors and 20 for outdoors, respectively.

The average location time for the outside locations was approximately 47.75 seconds. Since inventory management can take a significant time, a time of under 1 minute for the preparation process is deemed appropriate.

Due to the technical limitations of the NEO-6M GPS module, indoors experiments did not yield any successful location identification, where each of the experiments was held up to 30 minutes. The experiments were held in a different types of structures ranging from an apartment building to a hangar-like structure that is similar to a warehouse. Since NEO-6M required at least 3 satellites transmitting positional data, majority of the indoor areas will have identical results. Future work may assess more powerful GPS antennas to assess their efficiency indoors.

Due to the limitations of the hardware, it was decided to use the communication over Telegram to acquire the GPS data from the user's mobile device. This approach eliminates the waiting time for the GPS module to make a satellite connection outdoors in between scanning sessions, which enhances the user experience significantly.

C. Power Consumption Evaluation

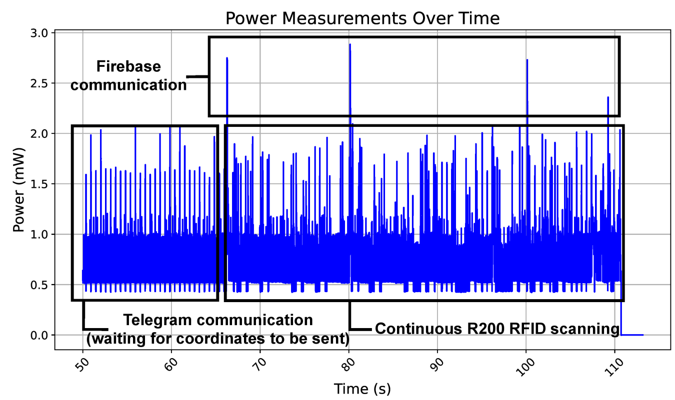

Fig. 4. Power Consumption Measurements

The measurements of power consumption of the system over time are showcased in Fig. 4. Peaks in power consumption occur during communication over the WiFi with the Firebase Realtime Database and with the user over Telegram. The values for the former reach up to 3 mW and around 2.0-2.3 mW for the latter. While the R200 RFID scanner is active, significant fluctuations in power consumption can also be observed. In this mode, the device is expected to be operational for up to 4 hours while being powered by a 2500mAh battery.

VII. Conclusions & Possible Future work

Due to the high cost of existing RFID inventory management systems, this paper proposes a more efficient open-hardware RFID system using open hardware and software components. The system allows for the collaboration and customization to meet specific needs of small to medium size businesses with unique inventory management challenges. This flexibility and affordability is a major benefit. Another advantage is the real-time access to the inventory data enabling users to make real-time decisions about restocking and resource allocation, potentially leading to smoother operations and fewer stockouts.

In the future, we intend to explore additional implementation details to improve energy efficiency and security. We also plan to develop an Android application to transfer to the RFID reader GPS data but also act as an intermediate point between the reader and the Internet when no WiFi is available. The future holds exciting possibilities for improvement in the RFID hardware, development of user-friendly software, and overall system optimization. However, most companies in the CIS region rely on vendors for inventory management systems. The idea of a cost-effective, self-managed system might need some time to gain traction in this market.

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