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Design and Implementation of a Smart RFID-Based Library System Using ESP32

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Abstract

Recent advancements made in automated technologies have created major changes in previous library management systems. The aim of the Smart Library System is to provide improved efficiency, accuracy, and security in the management of books throughout the entire borrowing and returning process, as well as throughout the entire process of maintaining an accurate inventory of books. Each book has an RFID tag embedded within it while each registered user of the smart library system has an RFID card associated with him/her. When a user scans their RFID card to check out a book, the RFID tag on the book generates machine-readable data that is automatically uploaded to a central RFID-based computer program through a central RFID "controller" using a microcontroller that contains an Integrated Wi-Fi module so that all checkout and return transactions are immediately stored for users who do not require a user to register with the smart library system at the time of check out or when a user actually returns a book, returns scars the system. Additionally, the system utilizes the ESP32 microcontroller for real-time data transmission and cloud-based monitoring, enabling librarians to track inventory remotely. The proposed system reduces human intervention, minimizes errors, and enhances operational transparency. Furthermore, it supports faster book identification, automated alerts for overdue books, and efficient database management. This integrated approach ensures a scalable, cost-effective, and user-friendly solution suitable for modern digital libraries and educational institutions.

Keywords: RFID; ESP32; Smart library system, IoT (internet of things), cloud computing

INTRODUCTION

Recent advancements in technology have significantly changed how different industries use traditional library sys- tems, including Library Management Systems (LMS). Li- braries have mainly used manual methods or barcodes to identify items, which take more time to process, can produce human mistakes, and can be inefficient for processing large amounts of material and users [1]. As the number of libraries grows, there is a need for better and more efficient automated library management systems. Recently, RFID technology has been developed as a useful tool to provide automated identi- fication and tracking of items [2]. Unlike barcodes, RFID tech- nology does not require an unobstructed line of sight when scanning, and multiple items can be scanned at the same time, improving the speed at which items can be processed and the convenience of processing items. FID technology can be integrated with new and improved microcontrollers to provide real-time processing information and more intelligent library systems [3].

The most common microcontroller being used in embedded systems is the ESP32 because of its low

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cost, high-speed processing, and built-in Wi-Fi and Bluetooth capabilities. These benefits make it the best choice for developing IoT-based smart systems. The ESP32 microcontroller will be the foundation upon which the connected library system will be developed, providing support for monitoring items without being present, synchronization of the database between the library's database and users' databases, and a better overall experience for users when working with the library . This thesis will present a completed design and implementation of a smart RFID library management system [4]. The digital age has seen a sharp rise in the need for automated and intelligent systems to process high volumes of data and transactions; this is especially true for libraries. Most of today's library management systems continue to rely on manual records or use a barcode system to perform their function [5].

METHODOLOGY

A smart library system is created using ESP32 microcon- troller in order to automate the management of books and identify users. The system will utilize an RFID reader module interfaced with ESP32 controller, a database system, and a user interface to facilitate viewing transactions conducted by users and managing the ordering process of books. The overall design of the system is documented using a block diagram (Figure1) , which specifies how the system's hardware components and software modules are interrelated. To facilitate communication between the RFID reader and the ESP32 controller, the SPI protocol (SPI) is being used to transmit unique identification tags contained within the library card and book. Upon success- ful implementation of the RFID reader and controller system in a functional state, a user will be able to scan the RFID tag from either the library card or the book itself. When the RFID reader reads the raw identification number (ID) from the library card or book, the ESP32 will receive the information via the SPI protocol and process it. The processing of the RFID tag number will include verifying the tag number against an ID number stored within the database of registered users and a list of available books.

If the RFID tag number is found within the database of registered users or available books, the ESP32 will complete the additional functions related to issuing and/or returning books based upon the validation procedure specified in the EMS of the library system. In addition to data validation, the controller will utilize Wi-Fi to send and receive real-time data through a cloud or local server that will facilitate efficient record-keeping of transactions and books. Embedded C/C++language for the development of the software conforms to the Arduino IDE and provides the logic necessary to process and authenticate the RFID tag and complete any further actions related to processing and maintaining books and/or users.

Implementation

In order to create the smart RFID-based system the use of ESP32 microcontroller will work as the main processor with RFID reader module (for example MFRC522 reader) connected via SPI. This will allow wireless identification of users through library card and books with the tags using the embedded C/C++ programming language by using Arduino IDE to develop your software with the correct libraries for both the RFID communication and Wi-Fi connection [6]. Once the RFID tag has been scanned by the reader, the tag's ID is sent to the ESP32 for identification and a decision is made based on the programmed logic as to whether the user or book is located with the scanned tag. Then, according to that decision, either the book is issued or returned. The final outcome will be dependent on the type of transaction recorded for each of the user's records in the database through Wi-Fi; whether the database is located on site or on the cloud. The system will have a web-based administrator or application to keep track of book availability, user activity, and transaction histoy.

RFID (Radio Frequency Identification) is a wireless tech- nology employed to identify an object using electromagnetic fields. It is an electronic components device (microcontroller) that uses Wi-Fi, allowing connection via Wi-Fi for IOT ap- plications. An RFID tag identification procedure begins by

scanning the RFID tag by a reader, which has a tag ID that then gets sent to the ESP32 for verification against a database record for that RFID tag ID. Once the scanned RFID tag ID has been verified, the appropriate transaction, e.g., issuing or returning a book, is executed, and the transaction record is updated to reflect this transaction. The ESP32 does this through use of its internal Wi-Fi module to provide communication with either a local database or a cloud-based database, ensuring up-to-date and accurate records [7].

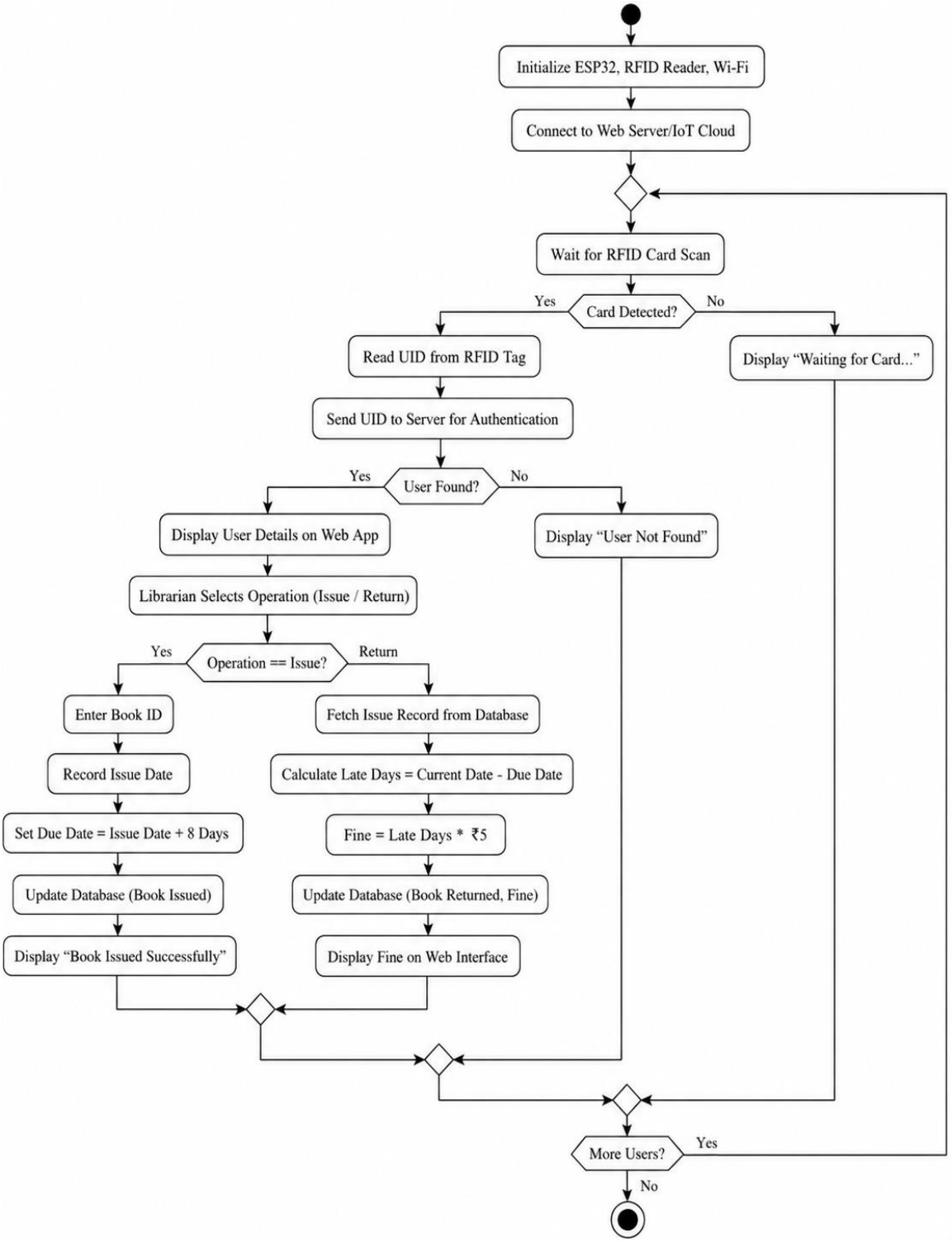

Figure 1. Flowchart of library management system.

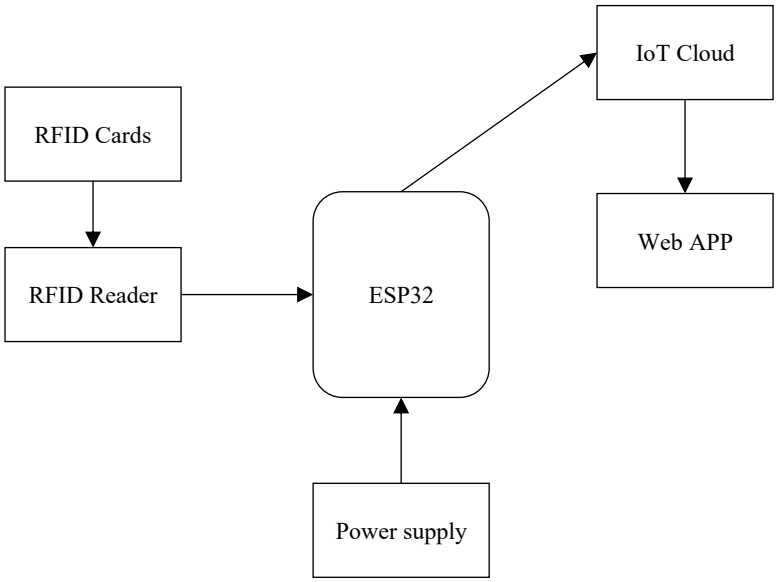

Figure 2. Block diagram of IOT enabled library management system using RFID and ESP32.

Database Design and Implementation

A library system that uses RFID technology can be imple- mented through the use of a database platform for storage and management of user information, book information, and transaction information. A separate set of tables will be established for each of these types of information, and the tables will be linked together through a unique identifier such as an RFID tag when they are created. For example, if a user has an RFID tag and tries to scan the tag at the library, then the system will use the RFID tag's identifier to retrieve the corresponding information from the database regarding the user's status as a good standing member of the library or that the book that is in hand is a valid library book. Upon confirming that the user/book information are valid, then the system will update the transaction table to indicate if the book was issued or returned to the library and when this transaction occurred (timestamp). To ensure that records in the database can be retrieved quickly for reporting purposes and to facilitate efficient management of these records, the tables will be properly indexed and there will be established structured relationships among the tables. To store, retrieve, and manage library information in an effective manner, the database structure for the smart RFID library system is organized with multiple tables that relate to one another. These tables consist of at minimum a user table, a book table, and a transaction table. Each table would contain specific attributes such as, a user's ID, a book's ID, the RFID tag ID for the book (associated with the user's ID), the date the book was issued to the user (the issue date), and the date the book is returned (return date).

Authentication System Implementation

To limit access to library services for users who cannot be identified, an RFID-based smart library will have an Authentication System installed. Each user will receive a unique RFID tag that is recorded in a central database along with that user's other identifying information for later use. Upon the user scanning their RFID card to enter the library, the RFID reader scans that card and captures the unique tag ID to send to an ESP32 microcontroller where the unique ID will be processed. The ESP32 microcontroller then connects to a central database to determine if the scanned ID has been entered in the user database as shown in Figure 2.[8]

RFID-Based Book Tracking and Implementation

The RFID-based book tracking system uses RFID Tags installed on books as well as RFID Tags incorporated into user ID Cards for identification purposes. When the RFID Reader scans an RFID Tag on a Book or an ID Card within its scanning range, it transmits the data to an ESP32 Mi- crocontroller and to a Database (Office365). Once the Data is in the Database, it provides a status for the Book that determines how to handle the Book (i.e. check out or check- in). Thus the implementation of this system

will provide a method for tracking books in real-time, significantly reducing the amount of manual labor involved, increasing the speed of the Library System, increasing the accuracy of the Library System, and providing a significant advantage by enabling contactless transactions through the use of RFID.

System Testing and Implementation

Testing the full integrated system during the system testing phase is done in order to verify that the entire system(s) are working as designed. This entails testing all functionality within the complete application including hardware compo- nents (e.g., RFID tags) by passing them through the corresponding application, communicating to and from an ESP32 microchip to verify proper data communication, and executing the entire operation of all associated components (i.e., book issuing and returning) without any errors. Additionally, mon- itoring all displayed output on the user displays to ensure correct output. Once testing has been completed all found issues are resolved and corrected through the debug process. This is vital to ensure the overall system will work properly after it is implemented in the production environment.

System Security and Data Management

When it comes to IoT based systems, security and data management are critical pieces of the puzzle. Within this system, the user and book data are stored in a structured database, which enables organised storage and easy re- trieval of the data. There are also authentication mech- anisms to restrict access to only those users who have been granted permissions, protecting the library from unauthorised access and keeping sensitive information safe. The ESP32 processes data from RFID tags that are validated before reaching the library management system. This permits to maintain the integrity of the system by confirming that valid RFID tags are used to issue and return books to and from the library. In addition, when books are issued or returned, data is updated immediately in real-time so that information regarding issued and returned books is accurate at all times. Data handling techniques are employed throughout the system to prevent data duplication and/or loss. The library management system is designed to provide reliable access to the library and improve the reliability of the library management process by enforcing controlled access, data validation and error handling procedures [9]. This gives users a feeling of safety while using the library and allows for a more efficient library management process

System Operation

To initiate the system, a user places an RFID tag (that is linked with a book or ID card) into range of the RFID reader. The reader scans the RFID tag, capturing the tag's unique identifier. This information is then sent to an ESP32 microcontroller to process further. Upon receiving the infor- mation, the ESP32 processes the data and references the stored database to see if the tag represents a book or a user. Using this information, the system can determine the current state of the book, whether it is available or has been issued to a user. If available, the system will update the database to mark the book as issued to the user. Conversely, if the item has already been issued, the book's status will be updated to indicate that it has been returned. All of these operations are accomplished automatically, with no manual intervention. The output of the operation is displayed on an output screen (book status and user information).

RESULT AND DISCUSSION

The proposed IoT-based Library Management System using RFID and ESP32 was successfully implemented and tested under various conditions. The system demonstrated efficient performance in all operations, including RFID tag scanning, data processing, and database updating. During testing, the system accurately identified RFID tags for both books and users, ensuring correct execution of book issue and return operations. The response time of the system was fast, as the RFID reader quickly captured the tag information and the ESP32 processed the data within a few seconds. Furthermore, the system showed high reliability and consistency, as all records were updated correctly in the database without any data loss or duplication. The automation of library processes reduced manual effort and minimized human errors, thereby improving overall operational efficiency. The system also provided a user-friendly experience by delivering quick and accurate results to users.

The success of the RFID-based library system, which uses an ESP32 microcontroller, has been established through per- formance evaluation on usability, accuracy, and reliability. The detection of RFID tags was shown to be reliable, and scanning both user and book IDs resulted in quick response times. The ESP32 microcontroller processed input data effectively and established reliable communication between the ESP32 and a central database over Wi-Fi, which allowed for real-time updates of book transactions, such as the issue and return of a book. The automation of these transactions greatly reduced the amount of work needed to be done by hand, reduced the number of mistakes made by people, and improved efficiency in the way libraries operate. Results indicate that the RFID technology provided an efficient and contactless way for peo- ple to identify themselves within a library, greatly enhancing the user experience and decreasing wait times. The design of the library's database provided efficient use of storage space, quick access to database records, and accurate record keeping of transactions. The authentication portion of the RFID system provided an additional layer of protection for library users by restricting access to library services to only those who have registered. The performance of the RFID system was affected by the stability of the network, and slowdowns occurred from time to time due to poor Wi-Fi connectivity. Finally, the lack of funds to purchase all hardware components needed to set up an RFID-based library system is a barrier that small libraries may face.

Authentication System Result

The system has been verified to work with both the normal login and the RFID based login methods. Both methods were tested thoroughly, with normal logins allowing for proper verification of user credentials through hashed password com- parison, rejecting users with invalid credentials and giving access to users with valid credentials upon completion of authentication and redirection to the appropriate dashboard assigned by role. The RFID login method also functioned properly, with the 2-minute session-based authentication window working correctly. The process of tapping an RFID card caused the ESP32 to capture the UID from the card and transmit that UID to the server. The server would then match that UID up against all registered users in the system and automatically complete the authentication process. Users had access to their dashboard within seconds after logging in, creating a more convenient process for users while also maintaining a secure login process. The timeout mechanism also ensured that users were not able to continue using the system once their session has expired.:

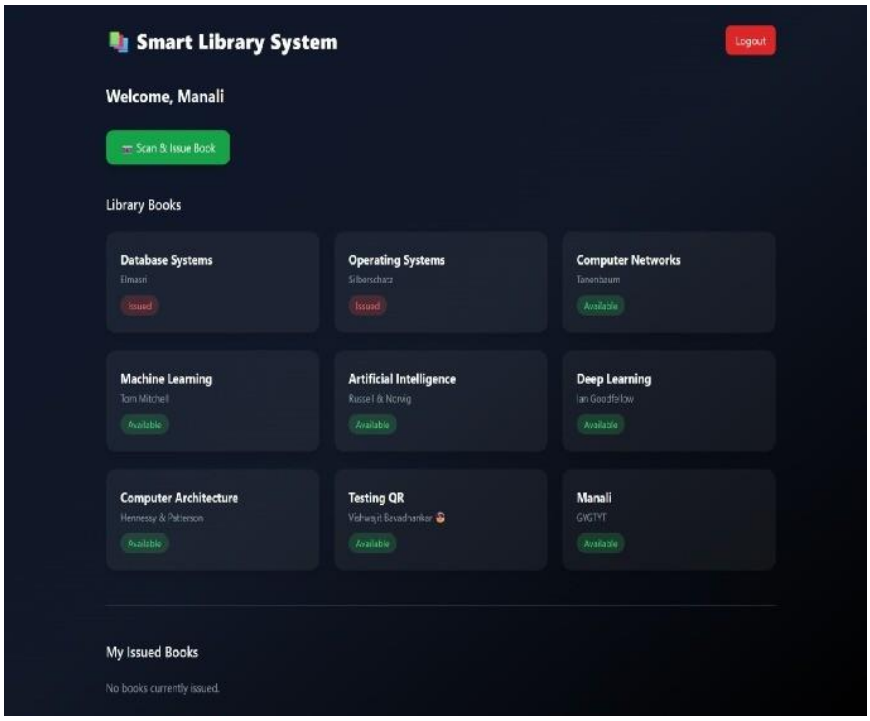

Figure 3. Book issued displayed on student panel.

QR Based Book Issue and Result

In the course of testing, the generation of QR codes and the ability to scan them were accurate with regards to func- tionality. The system was able to record information on a newly entered book into the database by an administrator and generate a QR code associated to the unique id of the book These QR codes are stored in a static directory, and used the camera based scanner for recognition. Students were able to scan the QR codes and the system was able to validate if there is an available book prior to issuing [10]. If the book is available and the person has a student privilege, an issue record was created. After a book has been issued using RFID technology, students can view their current book or typing in from the student dashboard of the system is called The Student Dashboard (Figure 3). The dashboard displays real-time information on all of the books that have been issued to the student based on their RFID identity. Typical information displayed includes students' name or number, title of the book, issue date, current status of the book and will indicate when it is due (at the time of issue plus 8 days later). Therefore, this confirms that the transaction was successfully completed and that the book information has been updated in the main MySQL database through RFID authentication and the use of the ESP32 - Internet of Things Integration.

Admin Pannel Result

In terms of monitoring and managing the library system efficiently, the administrator panel had all those capabilities. An administrator could quickly add a new book to the system, generate a QR code for that book, and keep the digital inventory updated. In Figure 4, The dashboard allowed administrators to see in real-time a list of books currently on the shelf, find out which books are overdue, and track any fines accumulated by students for overdue books. The section showing issue records allowed administrators to view the complete transaction details on each book issued: student name, book title, date issued, date due, date returned, and calculated fine due. Having this organized display provided transparency within the system and enabled administrators to oversee the library system easily. Students were unable to access any of the restricted functions of the administrator part of the system through the implementation of role-based access control mechanisms. Therefore, the security of the system was improved. Additionally, the system was designed to be responsive, providing instantaneous transactions without the requirement of manually refreshing the page or re-syncing the data with the database.

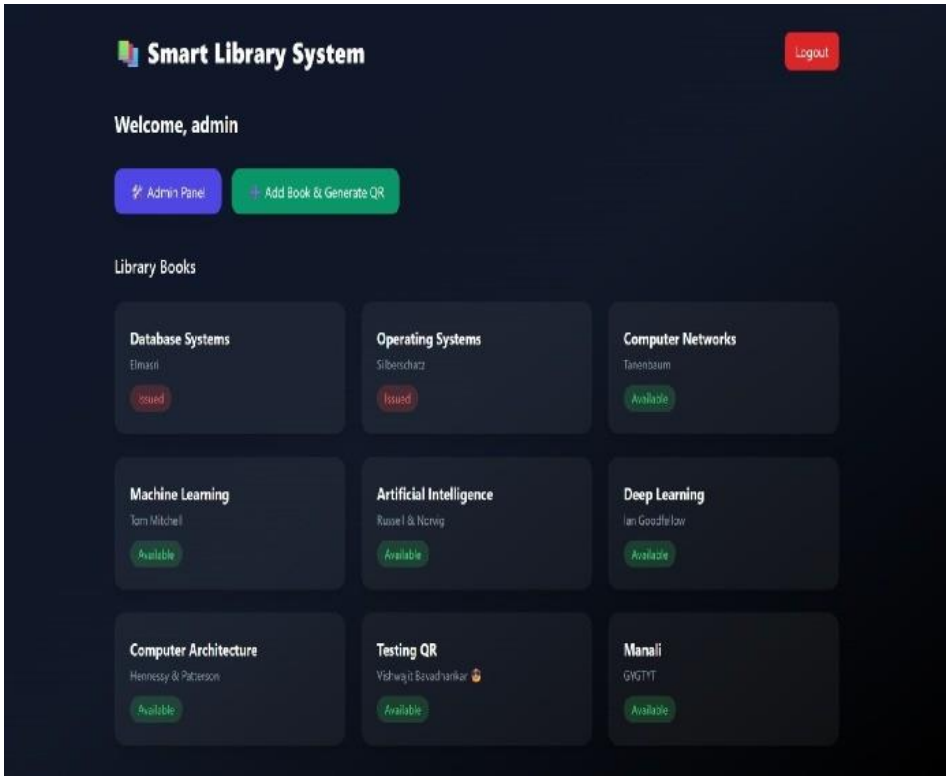

Figure 4. Fine calculation.

CONCLUSION

The implementation of an RFID-based Library Management System (LMS) using the ESP32, as demonstrated by the re- search presented in this paper, is proof of a successful applica- tion of IoT technologies for automating library processes that are traditionally completed without automation. The system combines hardware devices and software/database support in order to efficiently perform the functions of identification (of books), issuing, and returning books. After conducting the implementation and testing, it was shown that this system has high reliability and high accuracy for handling real-time data. Because of the use of RFID technology, there is no need to maintain records manually making traditional libraries more efficient through reducing human error and speeding up the process. The ESP32 microcontroller uses the data from the RFID reader to process data for the sequence of events that occur when books are issued and returned to the library, which maintains consistency of the data in the database, providing quality management of the data. The LMS provides an interface to users that allows for easy interaction with these three functions, as well as well-structured data. The user will notice a high speed response time from the LMS interface as well as through interactions with

FUTURE SCOPE

The RFID-based Library Management System utilizing the ESP32 platform has many opportunities for future improve- ment and adding more features. It can be further developed in terms of functionality, and scalability along with making the user experience more convenient. Some examples of additional enhancements that can be made in the future include: Devel- oping a Mobile Application: The mobile application will allow users to check the availability of books, current status of the book(s) being issued and when books are due to be returned from anywhere. Implementing a Cloud-Based Database Sys- tem: Upgrading to a cloud-based database will provide remote access to data and better data management capabilities at larger libraries. Adding Advanced Security Features: Adding features such as user authentication, password protection, and encrypted communication will improve the security of the system. Increasing Flexibility Through Barcode and QR Code Support: In order to provide more options, the RFID-based Library Management System can be expanded to include bar- code or QR code scanning in addition to the RFID technology. Automating Fine Calculation for Overdue Books: Adding the ability to automatically calculate the fine amount due when a book is returned late will decrease the amount of manual work involved. Integrating with Online Library Portals: Connecting the RFID-based Library Management System to online library portals will allow for tracking reservations for books, tracking history of books, and managing user accounts online. Scaling for Larger Libraries: As the RFID-based Library Management System can be designed to handle multiple users at one time and be able to work with large data sets, the system can be used in universities or large organizations.

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