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RFID-Based Attendance System: Design, Implementation, And Performance Analysis Using ESP32 Microcontroller With RC522 RFID Module And I2C LCD Display

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Abstract: In most colleges and schools, attendance is still taken using roll calls or written registers. This method takes time and sometimes leads to mistakes, and students may also give proxy attendance**.**

Because of these problems, an RFID-based attendance system is developed in this work using ESP32, MFRC522 RFID reader, and a 16x2 I2C LCD display.
The system works by scanning RFID cards that operate at 13.56 MHz. Each card has its own unique ID. When a card is placed near the reader, the ID is read using SPI communication and then checked with the IDs already stored in the system. If the ID matches, access is allowed, otherwise it is denied. The result is shown on the LCD screen immediately.

The hardware and software parts were implemented using Embedded C in Arduino IDE. During testing, the system was able to read cards correctly within a small distance of around 0–30 mm. The response time was also quick, usually within about 200 milliseconds.

From the results, the system is simple, reliable, and low in cost, so it can be used easily in real environments. In future, this system can be improved by adding Wi-Fi, storing data in the cloud, and creating a web page to view attendance records.

Keywords: RFID, ESP32, Attendance System, MFRC522, SPI, I2C LCD, Embedded Systems, Arduino IDE

INTRODUCTION

The proliferation of Internet of Things (IoT) technologies and low-cost embedded systems has opened transformative possibilities across numerous domains, including industrial automation, smart homes, healthcare, and education.
Among the most practically significant applications is the automation of attendance management in educational institutions and corporate organizations. This paper presents the design and implementation of an RFID-based attendance system using the ESP32 microcontroller, the RC522 RFID reader, and a 16x2 I2C LCD display. The system is designed to overcome the fundamental weaknesses of manual attendance methods by providing instantaneous, contactless, and tamper-resistant identification of individuals.

1.1 Background and Motivation

Radio Frequency Identification (RFID) is a wireless communication technology that uses electromagnetic fields to automatically identify and track tags attached to objects. An RFID system fundamentally consists of two components: a reader (or interrogator) and a tag (or transponder). The reader emits radio waves, and the tag, when within range, responds by transmitting its stored data, typically a unique identifier (UID). This technology has found widespread adoption in supply chain management, library systems, toll collection, and access control due to its non-contact operation, speed, and reliability. The application of RFID to attendance management is a natural extension, as each individual can be assigned a unique RFID card, and their presence can be automatically logged upon scanning. This eliminates the need for time-consuming manual roll calls and mitigates the risk of proxy attendance, a persistent challenge in traditional systems.

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1.2 The Limitations of Manual Attendance Systems

Traditional attendance methods like paper registers are still used in many places, but they have several problems. Writing attendance manually takes time, and it also requires extra effort later to organize or check the data. There is also a risk of losing records if the paper is damaged. Even when attendance is entered into spreadsheets, it still depends on manual input, so mistakes can happen and proxy attendance is still possible. Also, this kind of data is usually stored locally, so it is not easy to access it instantly or manage it from one place. Because of these reasons, there is a need for a system that can record attendance automatically and give results in real time.Traditional attendance methods like paper registers are still used in many places, but they have several problems. Writing attendance manually takes time, and it also requires extra effort later to organize or check the data. There is also a risk of losing records if the paper is damaged. Even when attendance is entered into spreadsheets, it still depends on manual input, so mistakes can happen and proxy attendance is still possible. Also, this kind of data is usually stored locally, so it is not easy to access it instantly or manage it from one place. Because of these reasons, there is a need for a system that can record attendance automatically and give results in real time.

PROBLEM STATEMENT

In this project, the aim is to design and build a simple and low-cost RFID-based attendance system. The system should be able to read RFID cards properly within a useful distance, check whether the scanned card is valid by comparing its UID with stored data, and show the result clearly on an LCD display. It should also be reliable, consume less power, and be flexible enough so that more features like internet connectivity can be added later.

TECHNICAL CHALLENGES

One of the main challenges faced was related to SPI communication between the ESP32 and the RFID module. Since the setup was done on a breadboard, loose connections sometimes caused unstable data transfer. Also, the SPI pins of ESP32 are different from boards like Arduino UNO, so proper configuration was necessary.

Another issue was related to power supply. The RC522 module works only at 3.3V, and giving 5V can damage it permanently. So care had to be taken to ensure correct voltage levels throughout the circuit.

There was also a challenge in setting up the I2C LCD. The display requires a correct address (like 0x27 or 0x3F), and if the address is wrong, the display will not work, which made debugging a bit difficult.

Finally, the system had to respond quickly. From scanning the card to showing the result, everything needed to happen almost instantly, so the code had to be kept simple and efficient.

CONTRIBUTIONS

This project provides a complete working model of an RFID attendance system using ESP32. It includes proper circuit connections for both SPI and I2C devices. The software part is also implemented clearly using Embedded C in Arduino IDE, covering card detection, UID reading, comparison, and display output. The system was tested multiple times to check accuracy and response time. In addition, the project also discusses its limitations and suggests future improvements like adding Wi-Fi and cloud storage.

RELATED WORK

Earlier RFID attendance systems mainly used microcontrollers like Arduino UNO and stored data locally. These systems proved that RFID can be used for attendance, but they lacked features like online access and real-time monitoring.

Later, with the introduction of ESP32 and ESP8266, systems started using Wi-Fi to send attendance data to cloud platforms. Some projects even connected the system to Google Sheets for easy access. These improvements solved many limitations of older systems.

There are also biometric systems like fingerprint and face recognition. These systems provide better security, but they are more expensive and require more processing power. They are also affected by environmental conditions. Compared to them, RFID systems are simpler, faster, and more affordable, which makes them suitable for many institutions.

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This project mainly focuses on building a strong base system with proper hardware setup and working logic, which can later be extended with advanced features.

METHODOLOGY

The system is designed in a simple step-by-step manner. The ESP32 acts as the main controller and connects to the RFID reader using SPI and to the LCD using I2C.

When a card is brought near the reader, the system detects it and reads its UID. This UID is then compared with the stored data. If it matches, the system shows “ACCESS GRANTED”; otherwise, it shows “ACCESS DENIED” on the LCD. At the same time, the result is also printed in the serial monitor for checking.

The hardware components were selected based on cost, performance, and ease of use. The ESP32 was chosen because it supports 3.3V devices and also has built-in Wi-Fi for future upgrades. The RC522 module is commonly used for RFID applications and works well within a short range. Passive RFID cards are used since they do not need a battery. The 16x2 LCD with I2C reduces wiring complexity by using only two pins.

3.3 MODULE 1: SPI COMMUNICATION AND RFID CARD READING

The SPI (Serial Peripheral Interface) protocol is a synchronous, full-duplex, master-slave communication bus. In this system, the ESP32 acts as the master and the RC522 as the slave. Four lines are used: MOSI (Master Out Slave In) fordata from ESP32 to RC522, MISO (Master In Slave Out) for data from RC522 to ESP32, SCK (Serial Clock) generated by the ESP32 master, and SS/SDA (Slave Select) driven low by the master to activate the RC522. A fifth line, RST (Reset), provides hardware reset functionality. The MFRC522 library abstracts the low-level SPI registerread/write operations, providing high-level functions for card detection (PICC_IsNewCardPresent) and UID reading

Table 1: SPI Wiring: RC522 RFID Module to ESP32.

RC522 Pin	ESP32 Pin	Protocol Function
SDA (SS)	GPIO 5	Slave Select (Chip Select)
SCK	GPIO 18	Serial Clock
MOSI	GPIO 23	Master Out Slave In
MISO	GPIO 19	Master In Slave Out
RST	GPIO 4	Reset
GND	GND	Ground Reference
3.3V	3.3V	Power Supply

Table 2: I2C Wiring: 16x2 LCD Display to ESP32.

LCD Pin	ESP32 Pin	Protocol Function
VCC	3.3V (or VIN)	Power Supply
GND	GND	Ground Reference
SDA	GPIO 21	I2C Data Line
SCL	GPIO 22	I2C Clock Line

Algorithm 1: UID Byte-by-Byte Comparison.

```
FUNCTION VerifyUID(scannedUID[], authorizedUID[]):
    FOR i = 0 TO 3:
        IF scannedUID[i] != authorizedUID[i]:
            RETURN FALSE        // Access Denied
    RETURN TRUE                 // Access Granted
```

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3.5 LCD FEEDBACK DISPLAY

This module is used to display messages to the user using a 16x2 LCD with I2C communication. The I2C protocol is a simple way to connect devices using only two wires, called SDA (data line) and SCL (clock line). Because of this, it reduces the number of connections needed compared to normal LCD wiring.

Each LCD module has its own address, usually either 0x27 or sometimes 0x3F, depending on the type of I2C adapter used. To control the display, the LiquidCrystal_I2C library is used, which makes it easier to initialize the LCD, clear the screen, move the cursor, and print messages.

The display works in three basic conditions. When no card is detected, it shows a default message like "Scan Card..." so that the user knows the system is ready. When a valid card is scanned, the LCD shows "ACCESS" on the first line and "GRANTED" on the second line. If the card is not valid, then it displays "ACCESS" and "DENIED" instead.
After showing the result, the system waits for about 2 seconds so the user can read the message. Then it goes back to the default screen and waits for the next card. This makes the system simple and easy to understand for users.

Table 3: Software libraries used in the system implementation.

Library	Author/Source	Function
SPI	Built-in (Arduino)	Hardware SPI bus communication
MFRC522	GithubCommunity	RC522 RFID reader abstraction
Wire	Built-in (Arduino)	Hardware I2C bus communication
LiquidCrystal_I2C	Frank de Brabander	16x2 LCD control via I2C

EXPERIMENTAL SETUP AND RESULTS

This section describes the empirical analysis of the implemented RFID attendance system. We first detail the , then present the results for UID read accuracy, system response latency, and reliability over extended operation.

4.1 Testing Procedure

The system was tested following a structured protocol: (1) The RFID test sketch was uploaded to the ESP32 to read and record the raw UID of the test card via the Serial Monitor at 115200 baud. The obtained UID (e.g., '47 BF D5 05') was then hardcoded into the main system firmware. (2) The complete system code was uploaded. (3) A series of scan tests were performed: 50 scans with the authorized card and 50 scans with an unauthorized card. For each scan, the result(Granted/Denied) displayed on the LCD and printed on the Serial Monitor was recorded. (4) The scan-to- display latency was measured using Serial Monitor timestamps.

4.2 UID Read Accuracy

The UID read accuracy was evaluated over 100 total scan attempts (50 authorized, 50 unauthorized). The results are presented in Table 4. The system achieved a perfect 100% accuracy rate, correctly identifying the authorized card in all 50 attempts and correctly rejecting the unauthorized card in all 50 attempts. No false positives (unauthorized card granted access) or false negatives (authorized card denied access) were recorded. This result is consistent with the deterministic nature of the UID comparison algorithm and the high reliability of the MFRC522 hardware at close range (0-30mm).

Table 4: UID Verification Accuracy Results across 100 scan trials.

Metric	Authorized Card (50 Trials)	Unauthorized Card (50 Trials)
True Positive (Granted)	50	-
True Negative (Denied)	-	50
False Positive	0	0
False Negative	0	0
Accuracy	**100%**	**100%**

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4.3 SYSTEM RESPONSE LATENCY

The response latency, defined as the time elapsed from the moment the card is placed on the reader to the moment the result is displayed on the LCD, was measured across 20 scan events. The results are summarized The total mean pipeline latency was found to be approximately 185 milliseconds, well within the sub-500ms target for perceived real-time responsiveness. The bulk of this latency is attributable to the RFID card reading and anti-collision process, which accounts for the SPI data transfer and the electromagnetic coupling time. The UID comparison itself is computationally negligible.

4.4 RELIABILITY AND EDGE CASES

Processing Stage Mean Latency (ms) Card Detection & UID Read (SPI) ~150 UID Comparison Algorithm <1LCD Display Update (I2C) ~30 Serial Monitor Print ~4 Total Pipeline Latency ~185 Beyond the standard test protocol, several edge cases were evaluated. (1) Rapid Successive Scans: When the same card was tapped rapidly without fully removing it from the reader's field, the system correctly de-bounced and did not produce duplicate reads, as the MFRC522 library's PICC_IsNewCardPresent function only triggers on a new card entering the field. (2) Range Testing: The system reliably read cards at distances from 0 mm (contact) up to approximately 25-30 mm. Beyond 30 mm, read failures became frequent, which is consistent with the RC522's specified operational range. (3) Extended Operation: The system was run continuously for 4 hours, during which periodic scans were performed. No instability, memory leaks, or crashes were observed, confirming the robustness of the firmware for continuous deployment.

DISCUSSION

This section summarizes the key findings of the implementation, candidly acknowledges the system's current limitations, and outlines a strategic roadmap for future development.

4.5 KEY FINDINGS

1. Hardware Compatibility: The ESP32's native 3.3V logic level was confirmed to be a critical advantage for direct, reliable interfacing with the RC522 module. This eliminates the need for voltage level shifters that would be required with 5V boards like the Arduino UNO, simplifying the hardware design and reducing potential points of failure.
2. Deterministic Accuracy: The 100% UID verification accuracy achieved across all 100 test trials validates the reliability of the byte-by-byte comparison algorithm in conjunction with the MFRC522 hardware. For the well-defined task of matching a fixed-length identifier, this deterministic approach is both simpler and more reliable than probabilistic methods.
3. Real-Time Performance: The measured total pipeline latency of approximately 185 ms confirms that the system meets the real-time feedback requirement. The user experiences the scan result as instantaneous, which is essential for a positive user experience in a deployment scenario.

Table 5: Mean latency per processing stage.

Processing Stage	Mean Latency (ms)
Card Detection & UID Read (SPI)	~150
UID Comparison Algorithm	<1
LCD Display Update (I2C)	~30
Serial Monitor Print	~4
Total Pipeline Latency	**~185**

4.6 Limitations

This study has four primary limitations:
1. Single-Card Database: The most significant limitation is that the current implementation only stores a single authorized UID hardcoded in the firmware. This is impractical for any real-world deployment involving multiple users. Scaling to a multi-user system requires either on-device storage (EEPROM/SD card) or a network-connected database.
2. No Persistent Data Logging: The system displays the result and prints to the Serial Monitor but does not log attendance records with timestamps to any persistent storage medium. Without logging, the system functions as an access control device, not a true attendance management system.

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3. No Network Connectivity: Despite using the Wi-Fi-capable ESP32, the current implementation operates entirely offline. The significant potential of the ESP32's networking capabilities remains untapped.
4. Breadboard Prototype: The system is assembled on a breadboard, which is suitable for prototyping and testing but is not robust enough for permanent deployment. Loose jumper wire connections can be a source of intermittent failures in a production environment.

4.7 FUTURE WORK

Future development is planned across five strategic tracks to address the identified limitations:
1. Multi-Card Student Database: The immediate next step is to implement support for multiple RFID cards. This can be achieved by storing a lookup table of UIDs and associated student names either in the ESP32's non-volatile EEPROM or on a microSD card module interfaced via a second SPI bus.
2. Wi-Fi and Cloud Integration: Leveraging the ESP32's built-in Wi-Fi, attendance data (UID, name, timestamp) can be transmitted over HTTP/HTTPS to a cloud backend. Google Sheets via Google Apps Script is a cost-effective and accessible option, as demonstrated in recent literature. Alternatively, a dedicated database such as Firebase or a custom MySQL/PostgreSQL server can be used.
3. Buzzer and Relay Integration: Adding a piezo buzzer for auditory feedback (distinct tones for granted/denied) and a relay module for controlling an electromagnetic door lock would extend the system into a full access control solution.
4. Web Dashboard for Attendance Tracking: A web-based dashboard can be developed to provide administrators with real-time attendance visualization, analytics, and exportable reports. This could be hosted on the ESP32 itself (as a lightweight web server) or on an external server.
5. PCB Design and Enclosure: For permanent deployment, the breadboard prototype should be migrated to a custom Printed Circuit Board (PCB) and housed in a 3D-printed or commercially available enclosure.

CONCLUSION

In this paper, an RFID-based attendance system was designed and tested using the ESP32, MFRC522 RFID module, and a 16x2 I2C LCD display. From the testing we carried out, the system was able to correctly verify UIDs in all 100 trials, and the response time was around 185 milliseconds, which is fast enough for real-time use. The hardware setup, including both SPI and I2C connections, along with the working of the UID verification and software flow, were explained clearly as part of this work.

At the moment, the system works as a simple standalone model that reads one card at a time. However, it was built in such a way that it can be improved later without much difficulty. Since the ESP32 already supports Wi-Fi and Bluetooth, the system can be extended into a cloud-based attendance system that can handle multiple users. Overall, this project shows that it is possible to build a low-cost and reliable attendance system using easily available components, and it can also serve as a starting point for more advanced IoT-based applications in the future.

Table 6: Summary of edge case and reliability testing.

Test Case	Expected Behavior	Result
Rapid successive scans	No duplicate reads	PASS
Read at 0 mm (contact)	Successful read	PASS
Read at 15 mm	Successful read	PASS
Read at 30 mm	Marginal / Successful	PASS
Read at 40 mm	Failure expected	FAIL (Expected)
4-hour continuous operation	No crash/instability	PASS
Wrong I2C address (0x3F)	No LCD output	Confirmed
Correct I2C address (0x27)	LCD displays correctly	PASS

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7. Important Notes

Table 7: Critical design and deployment notes for the RFID attendance system.

#	Note	Severity
1	RC522 must be powered with 3.3V only. 5V will damage the module.	CRITICAL
2	Ensure correct SPI wiring (MOSI, MISO, SCK, SS) specific to the ESP32 pinout.	HIGH
3	RFID card/tag must be 13.56 MHz (ISO 14443A). 125 kHz tags are incompatible.	HIGH
4	LCD I2C address may be 0x27 or 0x3F. Use an I2C scanner sketch to confirm.	MEDIUM
5	Adjust LCD contrast using the onboard potentiometer on the I2C backpack.	LOW
6	Use the Serial Monitor at 115200 baud for debugging UID reads.	LOW

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