DESIGN AND IMPLEMENTATION OF A SMART DIGITAL ATTENDANCE SYSTEM USING FINGERPRINT BIOMETRICS AND ESP32 MICROCONTROLLER

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ABSTRACT
The greatest challenge today for any event or academic management is efficient attendance tracking. A major limitation of current systems is their trade-off. Manual methods often lead to mistakes and allow for proxy attendance. On the other hand, automated token-based systems, such as RFID, incur ongoing costs and require physical tokens. The paper discusses the design, construction, and implementation of a Smart Digital Attendance Device (SDAD), which is a low-cost portable stand-alone system for biometric recognition based on fingerprints during attendance with a manual alphanumeric entry system as a backup option. This is built around an ESP32 microcontroller integrating an S120R optical fingerprint sensor for enrollment and verification, an SSD1306 OLED display for user interface, a DS3231 Real-Time Clock (RTC) for accurate timestamping, and a micro-SD card module for non-volatile data storage. The system utilizes a Li-ion battery and has a power management unit for extended length of time in the field. Detailed descriptions of hardware architecture, software state machine, and user interface navigation design that is driven by minimal buttons are provided. Results indicate that the device recorded a 95% first-trial success in fingerprint enrollment, with data logged reliably in SD storage, and a precise time-keeping mechanism. The SDAD is thus a strong, offline way of managing attendance in connectivity poor to non-internet areas such as classrooms, workshops, and corporate meetings, compared to manual systems, thus becoming a feasible alternative to an online biometric terminal.

Keywords: *Attendance System, Biometrics, Fingerprint Recognition, ESP32, Embedded Systems, Offline Data Logging.*

1. INTRODUCTION
Recording and managing attendance is, in fact, the very first administrative task of any educational institution, corporate house, or even an event. The typical methods of manual attendance-recorded analogues like handwritten sign-in sheets tend to be ineffective, too tedious for processing, and prone to errors and malpractice such as proxy attendance (Abdulkarim, 2017). Automated attendance systems, such as RFID or QR code-based systems, have attempted to solve these problems, but they have substitutes and limitations on their own (Lowry, 2021). RFID systems necessitate the issue of purchasing and maintaining physical tags/cards for each user, which will incur recurring costs and a loss or forgetfulness risk (Hossain, 2020). For QR code-dependent systems, it is essential to have access to smartphones and a dependable internet connection for both generation and scanning; not all citizens have either access or are able to use them (Memane *et al*., 2022).
Undoubtedly, fingerprint recognition biometric systems form a convincing solution since they fixedly attach attendance to a unique individual and eliminate the possibility of proxy attendance or physical tokens (Patel *et al*., 2019). The decreasing cost, along with the increasing reliability of fingerprint sensors, enables them to be equipped in more embedded applications. However, many of the biometric attendance systems are high in cost setup for networked terminals or complex software unsuited for offline, portable use in resource-constrained environments (Chowdhury, 2023).
This work bridges this gap by presenting the design and implementation of a self-contained, offline Smart Digital Attendance Device (SDAD). The core objective was to develop a portable, low-power, and cost-

effective terminal that utilizes fingerprint biometrics as the primary authentication method, supplemented by a manual ID entry system. The system is designed to operate independently of network connectivity, storing all data locally on a micro-SD card for later retrieval and analysis.

2. LITERATURE REVIEW

Several studies have been conducted into implementations of automated attendance systems. The RFID-based systems are the most widely documented and include, for instance, an RFID-based attendance system that automatically logs student's details (Oyebode, 2019). However, the much talked about setback here is that it requires each user to possess a tag. Just like that, Zhang (2014) made use of a system implemented on QR codes using smartphones, which is efficient but again is dependent on those smart gadgets plus an internet data package which is unfeasible in some places.

The uniqueness of the biometric systems has been the reason for their preference. (Rahman *et al*., 2020), gave an all-inclusive analysis of fingerprint biometrics for access control, thus stating that it stands out in security above both knowledge-based passwords and possession-based cards systems. The integration with embedded systems is facilitated by very powerful microcontrollers. The newest favorite is the ESP32, according to (Espressif Systems, Apr. 2025), as its dual-core processor, Wi-Fi/Bluetooth capabilities, and rich peripheral set have made it popular for IoT projects.

Previous works like (Adewumi, 2019) have built attendance systems using Arduino and fingerprint sensors but often lack a polished user interface, robust data management, or portability. This work advances the state-of-the-art by integrating a complete system-on-a-chip (ESP32) with a high-contrast OLED, a precise RTC, and a file-system-based data storage architecture into a single, battery-operated portable device. This integration, coupled with a carefully designed state-machine-based user interface, offers a user experience and operational reliability that surpasses many prior art systems.

3. MATERIALS AND METHOD

The SDAD was realized through a structured approach encompassing hardware design, software development, and system integration.

3.1. System Hardware Design

The hardware architecture shown in Figure 1 is built around the ESP32-WROOM-32 microcontroller, which acts as the central processing unit.

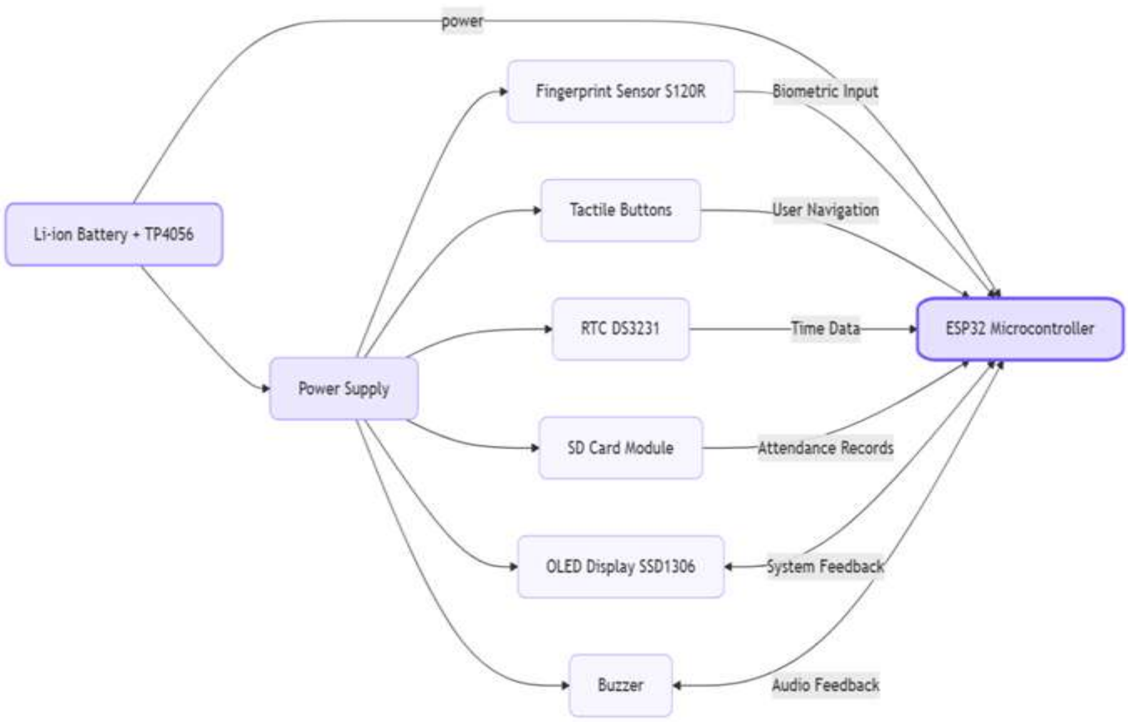

Figure 1: Block Diagram of the SDAD System [created with mermaid code on the mermaid website - https://mermaid.live/]

i. **Microcontroller Unit (MCU):** The ESP32 was selected for its computational power, low power consumption features, and integrated support for multiple communication protocols including I²C, SPI, and UART, which are essential for peripheral interfacing (Espressif Systems, Feb. 2025).

ii. **Power Supply Unit:** A 3.7V 2000mAh Li-ion battery provides power. A TP4056 charging module manages battery charging via USB. A DC-DC boost converter steps the voltage up to a stable 5V, which is then regulated to 3.3V for the ESP32 and other components, ensuring stable operation throughout the battery's discharge cycle.

iii. **Fingerprint Sensor:** The S120R optical fingerprint sensor (UART interface) is used for capturing and verifying fingerprints. It has an internal database to store templates and performs matching operations onboard, reducing the processing load on the ESP32 (Kulkarni *et al*., 2022).

iv. **Display Module:** A 0.96-inch SSD1306 OLED display (128x64 pixels, I²C) provides a high-contrast user interface with low power consumption.

v. **Input Unit:** A 5-way navigation switch (Left, Right, Up, Down, OK) plus a dedicated Clear button provides all user inputs.

vi. **Real-Time Clock (RTC):** The DS3231 precision RTC module (I²C) maintains accurate date and time even when the main system is powered off, ensuring all logged attendance records are correctly timestamped (Khan *et al*., 2018; Khan *et al*., 2021).

vii. **Data Storage:** A micro-SD card module (SPI interface) provides persistent storage for all system data, including administrator profiles, event details, and attendance logs.

viii. **Audible Feedback:** A piezoelectric buzzer provides audio feedback for key presses, successful actions, and errors.

The schematic diagram illustrating the interconnections between all components is shown in Figure 2.

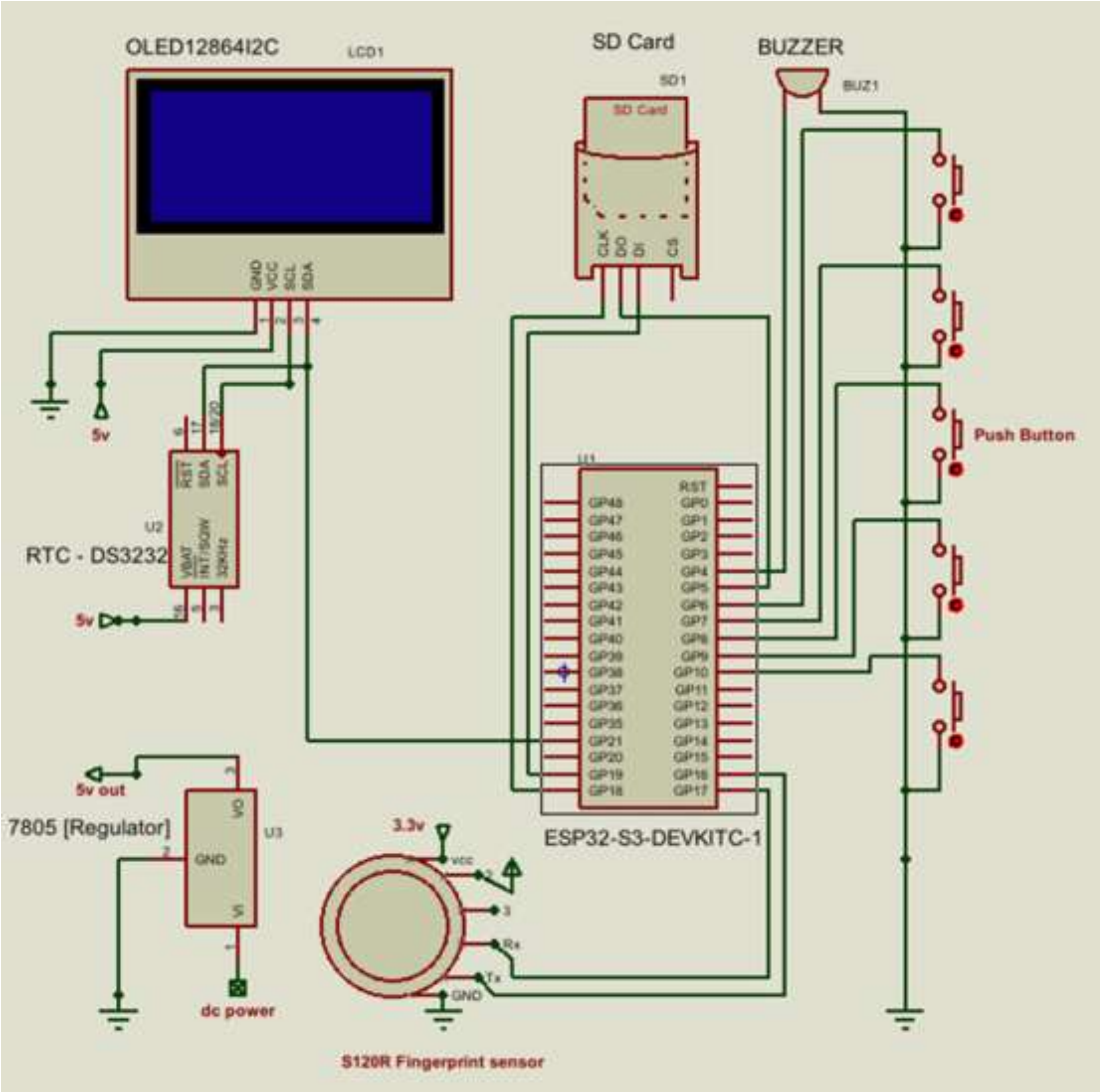

Figure 2: Circuit Schematic Diagram of the SDAD (the pin mapping table, source code (on request) and additional photos of the device are presented in appendices A, B and C respectively)

3.2. System Software Design

The software was developed in the Arduino IDE (C/C++) and structured modularly for maintainability. The key libraries employed include U8g2 for the OLED, Adafruit_Fingerprint for the sensor, RTClib for the RTC, and the built-in SD library.

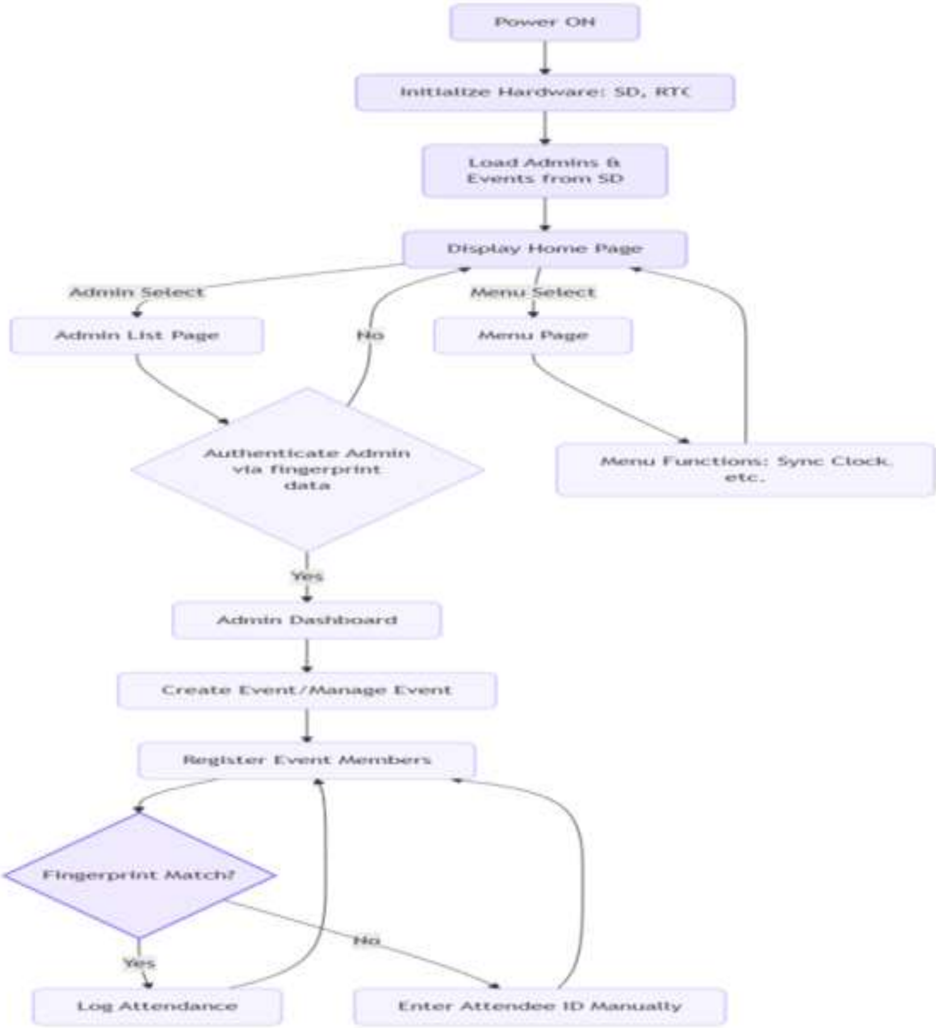

Figure 3: Program flowchart of the whole system [created with mermaid code on the mermaid website - https://mermaid.live/]

i. **Program Flow:** The system operation is governed by a finite state machine. The main flow is as follows:
   a. *Power On → System Boot & Diagnostics (RTC, SD, Sensor, OLED, Buzzer)*
   b. *Load existing admin profiles and fingerprint mappings from the SD card.*
   c. *Display Home Screen with current time and main options (Admin, Menu).*
   d. *User navigates to either authenticate as an admin or access the menu.*
   e. *Authenticated admins can create events and register attendees via fingerprint or manual ID.*
   f. *All attendee entries are appended with a timestamp to the active event's log file on the SD card.*

ii. **User Interface & Navigation:** The UI is organized into distinct states (e.g., HOME, MENU, ADMIN_DASHBOARD). The navigation buttons transition between these states. A custom character scroll input system was implemented for text entry (e.g., naming admins, events, entering IDs). The user scrolls through a character set with Up/Down, selects with OK, and moves to the next character with Right.

iii. **Fingerprint Processing:** The enrollment process involves capturing a fingerprint image three times to generate a reliable template. The template is stored in the sensor's memory, and its ID is mapped to a user name in a text file (fingerprint_map.txt) on the SD card. Authentication involves scanning a finger; the sensor returns an ID, which is then mapped to the corresponding name.

iv. **Data Management:** The SD card is organized in a hierarchical folder structure:

/Admins/
/Admin_Name_1/
fingerprint_map.txt
/Event_Folder_1/
attendees.txt
/Event_Folder_2/
attendees.txt
/Admin_Name_2/
...

This structure simplifies data retrieval and analysis.

4. RESULTS

The constructed prototype and its key functionalities are shown in the figures (Figures 4 - 7). The system was rigorously tested.

Figure 4: Clock Synchronization Test Figure

Figure 5: Home screen (*time + ADMIN / MENU buttons*)

Figure 6: Menu screen (show Beep *ON/OFF*).

Figure 7: Admin dashboard (CREATE / LOGOUT)

4.1. Functional Testing

All core subsystems were tested successfully upon boot, as summarized in Table 1.

Table 1: System Boot Diagnostic Results

Test Component	Status	Remarks
Real-Time Clock (RTC)	OK	Time accurately retrieved and maintained.
SD Card Storage	OK	Files and directories read/written correctly.
Fingerprint Sensor	OK	Communication established; enrollment & Verification functional.
OLED Display	OK	All UI elements rendered clearly.
Buzzer	OK	Audible feedback confirmed.

a. **Fingerprint Enrollment & Verification:** The system achieved an average first-try enrollment success rate of approximately 95%. Failures were typically due to poor finger placement or overly dry/oily fingers and were resolved by prompting the user to retry. Verification time was consistently under 1 second.
b. **Data Integrity:** All created events and registered attendees were successfully logged in the correct .txt files on the SD card. The file structure was maintained, ensuring data was easy to locate and export.
c. **Clock Synchronization:** The manual time sync feature functioned correctly. The new time set by the user was accurately written to the DS3231 RTC and reflected on the home screen.

4.2. User Interface

The UI was found to be intuitive and functional despite the display size constraints.

Figure 8: Enter event name screen (char-entry box)

Figure 9: Sync clock editor (hour/min selector)

4.3. Discussion

The SDAD successfully meets its design objectives. Its strengths are evident in its:

a. **Complete Offline Operation:** Makes it ideal for environments with poor or no network coverage.
b. **Dual Authentication Mode:** Biometric precision with a manual backup ensures no user is left unregistered.
c. **Portability and Low Power Consumption:** Battery operation allows for deployment anywhere.

However, some limitations were identified:

i. **Power Sequencing:** An intermittent boot issue was observed, requiring a specific power-on sequence. During testing, the system wouldn't always start properly unless powered in a particular order. The root cause was unstable startup voltage timing for modules like: Fingerprint sensor, SD card module, Display and RTC. Recommendation was adding a **power management IC (PMIC)** or proper sequencing capacitors/regulators so the ESP32 boots cleanly every time. For the option of a Proper Power-on sequence, the following method should be implemented:

   a. V3.3 stable hold before release: **≥ 200 ms**
   b. Firmware delay before peripheral init: **300–500 ms**
   c. SD card extra settle time: **200–500 ms** before mounting
   d. Peripherals retry spacing: **200–300 ms**, up to 3 attempts

   Total time from input power to full ready state: **~0.8 — 1.5 s** (typical)

ii. **Input Speed:** The scroll-based text entry, while functional, is slower than swiping an RFID card. This limitation was reviewed and considered not comparable as the two systems, during sign in, are as fast as one another. For RFID, you just touch with your Card, and for SDAD, you touch with your finger to sign in. This makes the system more suitable for small to medium-sized groups rather than high-throughput scenarios.
iii. **Sensor Limitations:** The optical fingerprint sensor can struggle with certain finger conditions, a known limitation of the technology.

Compared to existing systems, the SDAD eliminates the cost of tokens (RFID) and the dependency on networks and smartphones (QR codes), offering a robust and self-contained solution.

5. CONCLUSION AND RECOMMENDATIONS

This paper detailed the design and construction of a functional, low-cost, and portable Smart Digital Attendance Device. The SDAD effectively leverages fingerprint biometrics and embedded systems technology to automate attendance recording, providing a reliable and secure alternative to manual methods and token-based systems. Its offline operation makes it particularly valuable for use in rural educational institutions, workshops, and meetings where internet connectivity is unreliable or unavailable.

For future work, the following enhancements are proposed:

i. **Wireless Connectivity:** Leveraging the ESP32's integrated Wi-Fi/Bluetooth to enable real-time data sync with a cloud server or a mobile phone for instant report generation.
ii. **Enhanced Power Management:** Implementing a hardware-based automatic power-on/power-off circuit to solve the boot issue and further extend battery life.
iii. **Alternative Biometrics:** Exploring integration of facial recognition modules to provide multi-modal biometric authentication.
iv. **Improved UI:** Replacing the button matrix with a small touchscreen to significantly speed up manual data entry.

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APPENDICES

Appendix A: Pin Mapping

Prototyped on perfboard; wiring follows the pin mapping table shown in Table 2. Buttons are wired with pull-ups. For production, recommend a small PCB with connector pads for battery, SD, fingerprint and display.

Table 2: The pin mapping table

Component	Signal	ESP32 Pin	Notes
OLED Display (I2C)	SDA	GPIO 21	Default ESP32 I2C SDA
	SCL	GPIO 22	Default ESP32 I2C SCL
Fingerprint Sensor (S120R)	TX → ESP32 RX	GPIO 16	UART2 RX
	RX ← ESP32 TX	GPIO 17	UART2 TX
SD Card Module (SPI)	MISO	GPIO 19	SPI default
	MOSI	GPIO 5	SPI default
	SCK	GPIO 18	SPI clock
	CS	GPIO 23	Chip Select (SD_CS)
Buttons (5 total)	OKAY	GPIO 6	Pulldown or pull-up depending on logic
	RIGHT	GPIO 7	Navigation
	LEFT/BACK	GPIO 8	
	UP/NEXT	GPIO 9	
	DOWN	GPIO 10	
Buzzer	Signal	GPIO 4 (D4)	With series resistor / transistor recommended
RTC DS3231 (I2C shared)	SDA	GPIO 21	Shared with OLED
	SCL	GPIO 22	Shared with OLED
Fingerprint Power	Vcc	5 V	Needs stable supply
SD Module Power	Vcc	3.3 V or 5 V	Use logic-level safe module only!

Appendix B: Full Source Code (Available upon request).

Appendix C: Additional Photographs of the System.