International Journal of
DATA SCIENCE AND IOT MANAGEMENT SYSTEM
Peer Reviewed, Referred & Indexed Journal
ISSN: 3068-272X www.ijdim.com Original Research Paper

AI-Enabled Metro Access System Using ESP32 for Monitoring and Multi-Layered Passenger Authentication

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Abstract

In metro stations, railway terminals, airports, and high-density public transit hubs, there is a critical requirement for systems that can provide fast, secure, and automated passenger authentication while minimizing congestion and preventing unauthorized access. These environments demand multi-layered verification, real-time monitoring, and efficient gate control mechanisms to ensure smooth passenger flow and enhanced security. Traditional ticketing and access systems rely on manual verification or basic card-based entry, which are prone to misuse, duplication, long queues, and lack of real-time monitoring. Furthermore, conventional systems do not integrate biometric authentication or intelligent surveillance, reducing their effectiveness in handling modern transportation challenges. To address these limitations, the proposed smart metro access system utilizes the ESP32 microcontroller to develop an intelligent and automated access control solution. The system integrates RFID-based smart card identification, fingerprint biometric authentication, and an ESP32-CAM for real-time image capture and monitoring, ensuring multi-factor authentication. Upon successful verification, a servo motor controls the gate to allow entry, while an LCD display provides passenger information and system status. Unauthorized attempts trigger buzzer alerts, enhancing security. IoT integration enables remote monitoring, centralized data management, and analytics for metro authorities. This smart system improves passenger flow efficiency, enhances security, reduces waiting time, and supports the development of intelligent and connected urban transportation systems.

Keywords: Biometric Authentication, Intelligent Transportation System, Internet of Things, Metro Access Control, RFID Identification, Smart Ticketing, Surveillance Systems, Urban Mobility

1. Introduction

The rapid expansion of urban metro systems and the continuous rise in passenger volume have significantly increased the demand for efficient and secure access control mechanisms [1]. Globally, metro systems handle billions of passengers annually, making them one of the most critical components of urban transportation. At the same time, smart transportation technologies are projected to grow at over 16% annually, driven by the need for automation, security, and seamless mobility [2]. In high-density environments such as metro stations, railway terminals, airports, and public transit hubs, there is a strong requirement for systems that ensure fast passenger authentication, smooth flow management, and enhanced security [3]. These systems must be capable of handling large crowds while minimizing delays and preventing unauthorized access.

Traditional ticketing and access control systems rely on manual verification or basic card-based mechanisms. While these systems are widely used, they are often inefficient in handling high passenger volumes, leading to long queues and congestion during peak hours [4]. Additionally, card-based systems are vulnerable to misuse, duplication, and unauthorized sharing, compromising security. Conventional setups also lack real-time monitoring and centralized control, limiting the ability of authorities to track passenger movement and respond to suspicious activities [5]. The absence of biometric authentication and intelligent surveillance further reduces their effectiveness in modern transportation environments.

In real-time scenarios, these limitations result in several critical challenges affecting both efficiency and security [6]. High passenger density can lead to crowding, delays, and inconvenience, especially during peak travel times [7]. Unauthorized access and ticket misuse can cause revenue losses and security risks. The lack of real-time monitoring and alert mechanisms prevents quick detection of suspicious behavior or system failures. Furthermore, inefficient gate control systems can disrupt passenger flow and reduce overall operational efficiency [8]. These challenges highlight the need for an intelligent, AI and IoT-based access control system that incorporates multi-factor authentication, real-time monitoring, and automated gate operation, ensuring enhanced security, reduced congestion, and improved passenger experience in modern urban transportation systems.

2. Literature Survey

Civitas [9] proposed an analysis of vehicle access regulation implementation, focusing on policy frameworks and practical deployment strategies in urban areas. Fransen et al. [10] proposed a taxonomy of sustainable mobility strategies that classified urban vehicle access regulations based on functional and operational characteristics.

Macário et al. [11] proposed an analysis of sustainable urban logistics solutions across different scales, emphasizing the need for tailored strategies in city environments. The authors in [12] proposed recommendations for urban logistics innovation, focusing on policy adoption, technological integration, and efficiency improvement in city transport systems.

The authors in [13] proposed a policy framework for the new European Union urban mobility strategy, addressing sustainability, accessibility, and efficiency in transportation systems. Roca-Riu et al. [14] proposed a dynamic delivery parking system that optimized parking space allocation in urban areas to reduce traffic disruptions. Burns et al. [15] proposed a dynamic parking reservation system for delivery vehicles to improve accommodation and reduce congestion. The system enhanced efficiency through reservation-based allocation.

Mackowski et al. [16] proposed a parking space management system using dynamic performance-based pricing to optimize utilization and reduce congestion. The authors in [17] proposed Industry 4.0 concepts focusing on digital transformation, automation, and integration of advanced technologies in industrial systems.

Breque et al. [18] proposed Industry 5.0 concepts emphasizing sustainability, human-centric design, and resilience in industrial systems. Merchan et al. [19] proposed an overview of megacity logistics focusing on best practices, innovative strategies, and technology trends for last-mile delivery. De Marco et al. [20] proposed a classification and benchmarking of city logistics measures based on empirical analysis of urban transport strategies.

3. Proposed System

Figure 1 illustrates the architecture of the AI smart metro access system built around the ESP32, which serves as the central controller for authentication and access management. The system integrates multiple input modules such as RFID for smart card identification,

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fingerprint sensor for biometric verification, and ESP32-CAM for real-time monitoring and image capture. A regulated power supply ensures stable operation. The ESP32 processes authentication data and controls output devices including an LCD display, buzzer alerts, a servo motor for gate control, and IoT connectivity for remote monitoring. This system ensures secure, automated, and efficient passenger entry into metro stations.

Step 1: Power Supply Initialization: The regulated power supply provides stable DC voltage to the ESP32 and all connected modules, ensuring uninterrupted system operation.

Step 2: RFID-Based Passenger Identification: The RFID reader scans the smart card carried by the passenger. Each card contains a unique ID linked to passenger details in the system database.

Step 3: Biometric Authentication using Fingerprint Sensor: After RFID verification, the fingerprint sensor performs biometric authentication to confirm that the cardholder is the authorized user, enhancing system security.

Step 4: Visual Monitoring using ESP32 CAM: The ESP32-CAM captures real-time images of passengers during authentication. This data can be used for security verification, surveillance, and record keeping.

Step 5: Data Processing by ESP32: The ESP32 processes all authentication inputs and verifies whether access should be granted based on stored credentials and system logic.

Step 6: Gate Control using Servo Motor: If authentication is successful, the ESP32 activates the servo motor to open the gate, allowing the passenger to enter the metro station.

Step 7: LCD Display Output: The LCD displays real-time messages such as authentication status (access granted/denied) and system notifications for user guidance.

Step 8: Buzzer Alert System: In case of unauthorized access or authentication failure, the buzzer is activated to alert security personnel and nearby users.

Step 9: IoT-Based Remote Monitoring: The ESP32 transmits access logs and system data to a cloud platform via IoT. This enables metro authorities to monitor passenger entries, analyze data, and manage the system remotely.

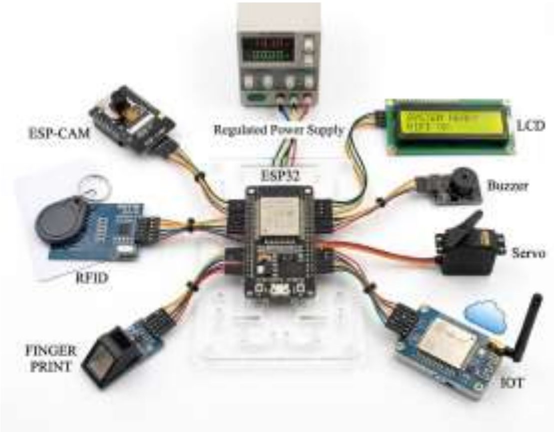

Figure 1. AI-Enabled Metro Access System.

3.1 Working Procedure

The proposed AI Smart Metro Access System as shown in Figure 2 is designed to provide a secure and automated passenger entry system for metro stations using advanced authentication technologies. The system integrates RFID identification, fingerprint biometric authentication, camera monitoring, and IoT connectivity to ensure that only authorized passengers can access metro platforms. The entire system is controlled by the ESP32 microcontroller, which acts as the central processing unit responsible for managing all system operations.

The system consists of several input devices that are used to authenticate passengers. An RFID reader module is used to scan smart cards carried by passengers. Each RFID card contains a unique identification number that is associated with passenger information in the system database. In addition to RFID verification, a fingerprint sensor is used to

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perform biometric authentication. This ensures that the person using the RFID card is the authorized owner, thereby improving security.

To further enhance security and monitoring, an ESP-CAM module is integrated into the system. The camera captures images of passengers during the authentication process, which can be used for security verification and record keeping. If the authentication process is successful, the system allows entry through an automated gate mechanism controlled by a servo motor.

The system also includes an LCD display that provides real-time information such as authentication status and system messages. A buzzer is used to generate alert signals when unauthorized access attempts are detected. Furthermore, the system integrates IoT technology, which allows metro authorities to monitor passenger entry data remotely through internet-based platforms. This improves system management and security monitoring.

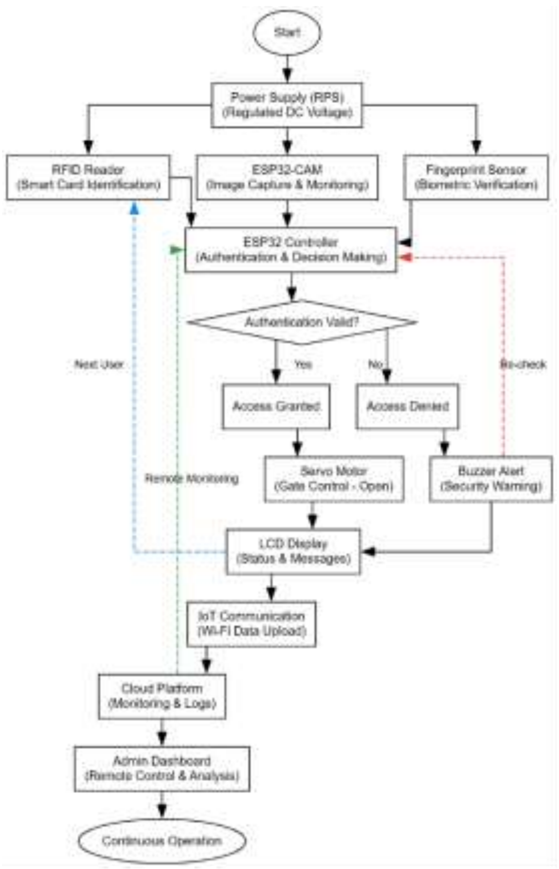

Figure 2. Proposed Flowchart.

Figure 3 illustrates the circuit diagram of an AI-based smart metro access system designed for secure, automated passenger entry management. The system is powered by a regulated power supply unit consisting of a step-down transformer, bridge rectifier, filter capacitors, and a 7805-voltage regulator to provide a stable +5V output. The ESP32 microcontroller serves as the central control unit, interfacing with multiple authentication modules such as an RFID reader for card-based access and a fingerprint sensor for biometric verification. A keypad and servo motor are integrated to control gate operation based on authentication results. An IoT camera module enables real-time surveillance and AI-based monitoring of passenger activity. The system also includes a 16×2 LCD to display user status and instructions, and a buzzer for alert notifications during unauthorized access attempts. This integrated design enhances security, reduces manual intervention, and ensures efficient crowd management in modern metro systems.

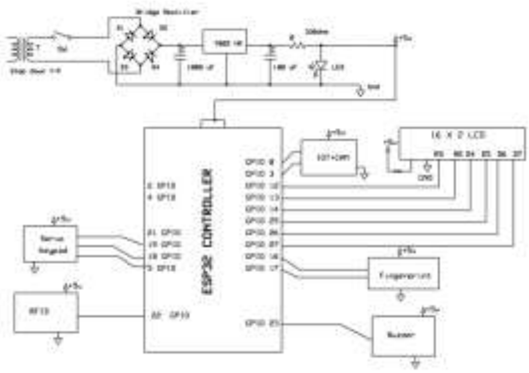

Figure 3. Circuit Diagram of AI-Based Smart Metro Access System Using ESP32.

4. Results and Discussion

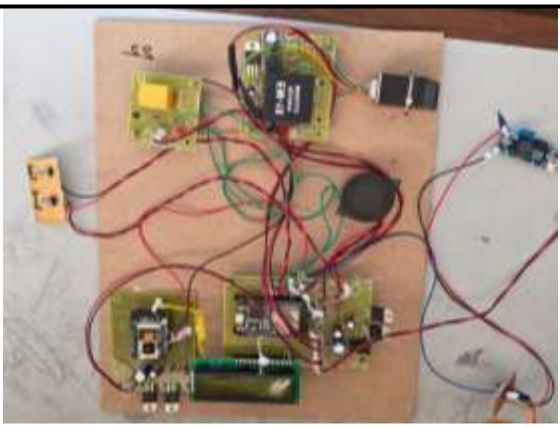

Figure 4. Hardware Implementation of AI Smart Metro Access System

Figure 4 shows the hardware prototype of the AI Smart Metro Access System developed using the ESP32 microcontroller. The system integrates modules such as RFID reader, fingerprint module, servo motor, buzzer, and LCD display for passenger authentication and gate control. The ESP32 processes the data from input devices and controls the access mechanism.

Figure 5 shows the LCD display indicating the initialization and operational status of the AI Smart Metro Access System. The LCD provides real-time information such as system messages, authentication status, and access confirmation for passengers.

Figure 6 shows the IoT web server interface where authentication records are stored and monitored. The server logs details such as fingerprint status, card validation status, and date/time of access attempts. This allows metro authorities to remotely monitor and manage passenger access activities.

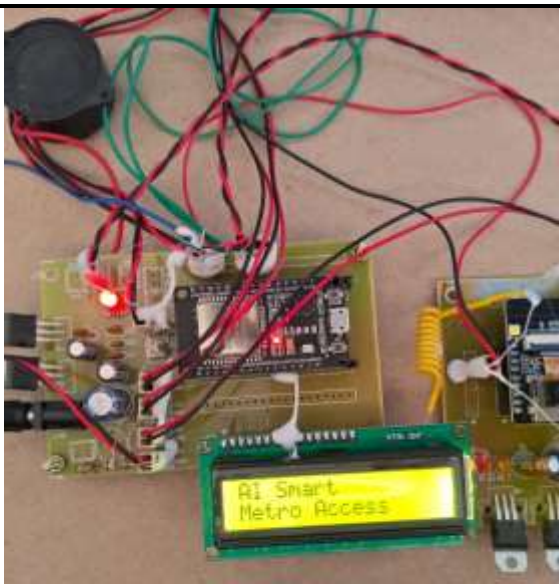

Figure 5. LCD Display Output of AI Smart Metro Access System

S.No	Status	Card_Details	Date
1	FP_Not_Found	—	2026-02-10 15:19:13
2	FP_Not_Found	—	2026-02-10 15:18:38
3	Invalid_Card	—	2026-02-10 15:09:08
4	Invalid_Card	—	2026-02-10 12:06:43
5	FP_Not_Found	—	2026-02-10 11:42:43
6	FP_Not_Found	—	2026-01-31 19:11:13

Figure 6. IoT Web Server Monitoring Output

5. Conclusion

The proposed AI smart metro access system offers an advanced and efficient solution for modern public transportation by integrating multi-factor authentication, automation, and IoT connectivity. By combining RFID-based identification, fingerprint biometric verification, and ESP32-CAM-based monitoring, the system ensures secure and reliable passenger authentication while minimizing unauthorized access. The automated gate control using a servo motor enables smooth and fast passenger flow, reducing congestion and waiting time in high-density transit environments. Real-time feedback through the LCD display and immediate alerts via buzzer further enhance system responsiveness and user awareness. Additionally, IoT integration allows centralized monitoring, data analytics, and efficient management by authorities. This system overcomes the limitations of traditional access methods by providing a secure, intelligent, and scalable framework. Finally, it enhances operational efficiency, strengthens security, and supports the development of smart, connected, and user-friendly urban transportation systems.

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