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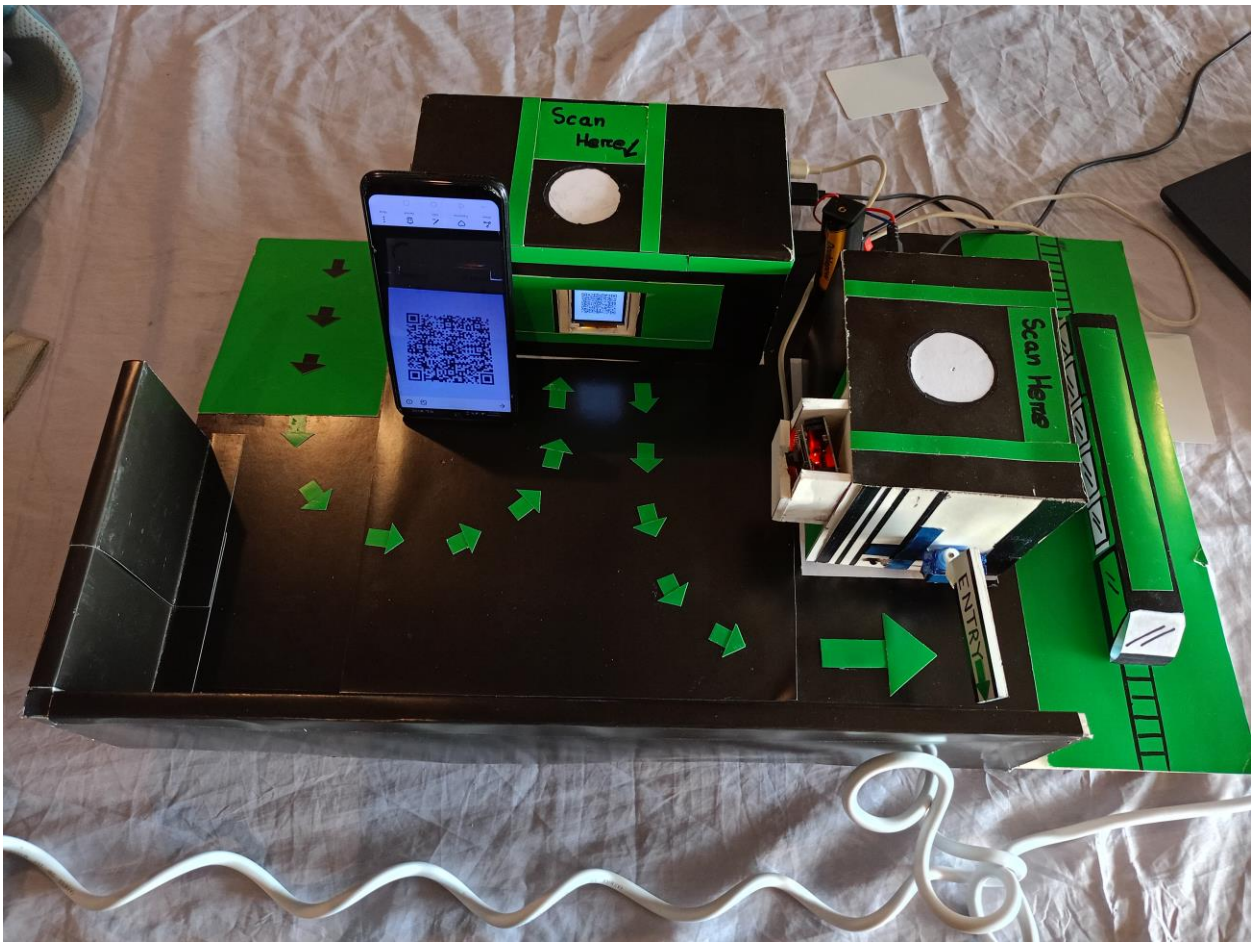


Smart Metro Gate Access System Using ESP32

Abstract

The **Smart Metro Gate Access System Using ESP32** is a decentralized and intelligent access control system designed to ensure uninterrupted metro station operation during network or server failures. The system integrates **QR code** and **RFID-based** authentication mechanisms, supported by **infrared sensors** and **servo motors** for automated gate control. Built on multiple **ESP32 microcontrollers**, it operates locally without requiring an internet connection, maintaining efficiency, reliability, and security. The project demonstrates how embedded systems and IoT devices can deliver low-cost, resilient, and scalable transportation solutions for developing urban infrastructures.

1. Introduction

Modern metro gate systems depend on centralized servers for ticket validation and gate control. While efficient under normal conditions, they are vulnerable to service disruption during network or power failures. The July 2024 student movement in Bangladesh highlighted this issue when multiple metro gates malfunctioned due to ticketing server outages, resulting in severe congestion and safety risks.

To address these challenges, this project presents a **Smart Metro Gate Access System** that functions entirely offline, powered by **ESP32 microcontrollers**. By combining **local ticket generation**, **RFID/QR-based authentication**, and **automated gate actuation**, the system ensures uninterrupted access management even during network disruptions.

2. Motivation

The motivation for this project stems from the need for a **reliable, low-cost, and autonomous metro gate system**. The central failures of Dhaka Metro exposed the fragility of server-dependent systems. Our goal is to design a solution that:

- Operates independently of internet or centralized databases.
- Provides fast, secure, and flexible access verification.
- Can be easily replicated in developing countries with limited resources.

The system contributes toward building **resilient public infrastructure** that can withstand emergency situations and promote smoother transportation experiences.

3. Objectives

1. Develop a dual-authentication metro access gate using **QR code** and **RFID card** technology.
2. Design an **offline validation architecture** that functions without internet dependency.
3. Integrate **IR sensors** and **servo motors** for fully automated gate control.

4. Implement secure **HMAC-SHA256 encryption** for ticket integrity and time-based expiry.
5. Create a **scalable framework** suitable for multi-gate installations in metro networks.

4. System Overview

The system operates through a **local Wi-Fi network** established by an **ESP32 main server**. All communications between devices occur over this network, allowing decentralized control. The architecture comprises three core units:

(a) ESP32 Server Unit

- Acts as the local Access Point (AP) and database server.
- Hosts a **web-based ticket management interface** for administrators.
- Generates unique, time-limited QR code tickets.
- Handles validation and communicates with the gate controller.

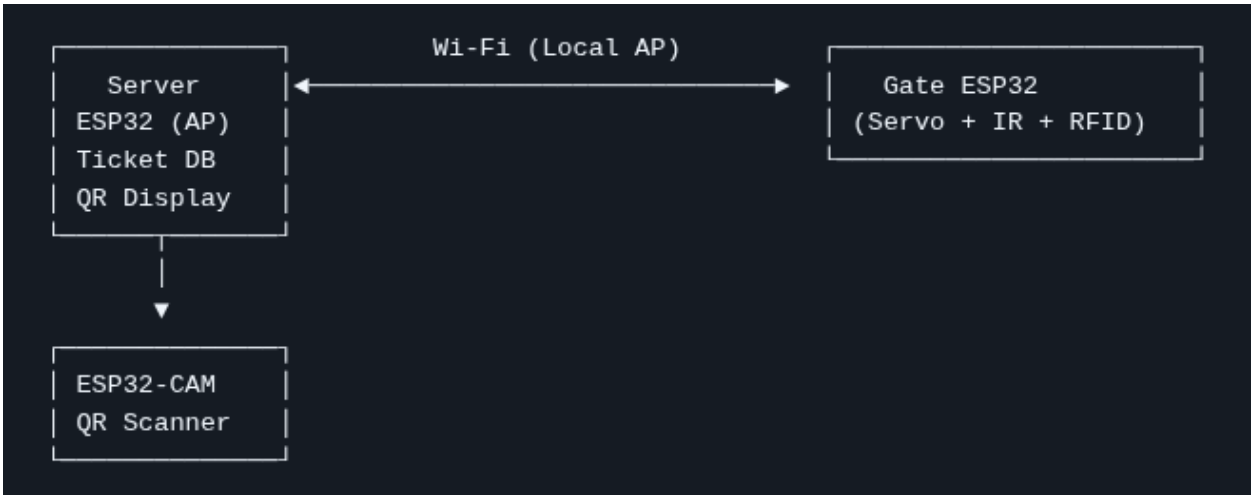
(b) Gate Control Unit (ESP32-S3)

- Controls **servo motors** for gate operation.
- Uses **dual IR sensors** to detect passenger movement and ensure safety.
- Receives validation commands wirelessly from the server.

(c) ESP32-CAM and PN532 RFID Reader

- The **ESP32-CAM** scans QR codes displayed by passengers.
- The **PN532** module reads RFID cards as an alternative access method.
- Both send encrypted authentication data to the server for validation.

System Architecture Diagram:



5. Features

1. **Dual Authentication System:** Passengers can authenticate using QR code or RFID card.
2. **Offline Operation:** The system works without internet connectivity.
3. **Automated Gate Control:** IR sensors trigger gate opening and closing through servo motors.
4. **Secure Ticket Validation:** HMAC-SHA256 ensures data integrity and prevents reuse.
5. **Time-Bound Access:** Tickets expire automatically after 10 minutes.
6. **Scalability and Modularity:** Additional gates can be integrated easily under the same local network.

6. Hardware Components

Component	Quantity	Description
ESP32-S3 Dev Module	2	Controls servo motors and IR sensors for gate operation

ESP32-CAM	1	Scans QR codes and communicates with the server
ESP32 Dev Module (Server)	1	Hosts Wi-Fi AP and manages ticket database
PN532 RFID Module	2	Reads and writes RFID cards
2.4-inch TFT Display (ILI9341)	1	Displays generated QR codes
Servo Motor	1	Opens and closes the gate barrier
IR Sensors	2	Detects passenger movement and position
PVC Board	3	Provides structural support
Wires and Soldering Components	—	Electrical connections between modules

7. Software Requirements

- **Development Environment:** Arduino IDE
- **Programming Language:** C++
- **Primary Libraries:**
  - Adafruit PN532 (for RFID communication)
  - ArduinoJson (for data serialization)
  - ESP32Servo (for motor control)
  - Adafruit BusIO and DMA NeoPixel (for efficient communication and display control)

8. Working Principle

The system begins with **ticket generation** on the ESP32 server, which produces a secure token encoded as a QR code and stored locally. Passengers can either scan the QR code or use an RFID card for access.

1. **Detection:** When a passenger approaches, the IR sensors detect their presence.
2. **Validation:** The scanned QR code or RFID UID is sent to the server for verification.
3. **Authorization:** If valid, the gate controller receives an open command via Wi-Fi.
4. **Gate Operation:** The servo motor rotates 90° to allow entry and then closes automatically after detection of passage.

5. **Security:** Expired or used tickets are deleted from memory to prevent unauthorized reuse.

9. Advantages

1. Operates reliably **without internet or centralized servers**.
2. **Low-cost and power-efficient**, suitable for developing regions.
3. **Dual authentication** increases system reliability.
4. **Local validation** minimizes latency and network dependency.
5. **Enhanced security** with time-bound, encrypted access tokens.
6. **Scalable and modular**, adaptable to various gate systems.

10. Limitations

1. Limited **RFID reading range** due to PN532 hardware constraints.
2. Lack of **centralized synchronization** between multiple gates.
3. **Hardware fragility** when mounted on temporary platforms.
4. **Memory constraints** of ESP32 may limit large-scale deployment.
5. Requires periodic manual maintenance for long-term use.

11. Future Enhancements

1. Integration of **cloud-based central synchronization** for multi-gate systems.
2. Development of a **mobile application** for digital ticket management.
3. Implementation of **long-range RFID/NFC** modules.
4. **Hardware enclosure design** for permanent deployment.
5. Addition of **visual displays and audio feedback** for improved user experience.

12. Conclusion

The **Smart Metro Gate Access System Using ESP32** provides an innovative and resilient approach to public transport access control. Its offline operation, dual authentication, and local processing ensure reliability during network failures and emergencies. The system's modularity, scalability, and cost-effectiveness make it a practical model for modernizing metro and transport systems in developing countries. With future improvements in synchronization and durability, it can serve as a foundation for large-scale smart transit infrastructure.

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