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IoT-Based RFID-Enabled Crowd Management and Child Safety System

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***Abstract*---Large public gatherings in places such as temples, festivals, and events present significant crowd management and child safety challenges. This paper proposes an IoT-based RFID-enabled system that assigns unique RFID cards to individuals and tracks their movement across predefined zones using RFID readers interfaced with an ESP32 microcontroller. A parent-child association mechanism enables quick child recovery during separation. Real-time data is transmitted to the ThingSpeak cloud platform for monitoring and analytics. LED and buzzer alerts provide immediate feedback, while NTP synchronization ensures accurate timestamping. The system offers a scalable, cost-effective alternative to manual supervision.**

Keywords---*RFID, IoT, crowd management, child safety, ESP32, ThingSpeak, real-time tracking*

I. INTRODUCTION

The rapid increase in population and the growing frequency of large-scale gatherings in public places such as temples, festivals, and events have significantly intensified the challenges associated with crowd management and public safety. Among these challenges, maintaining orderly movement within crowded environments and ensuring the safety of vulnerable individuals, particularly children, have become critical concerns. Conventional methods that rely heavily on manual supervision are often inefficient, prone to human error, and lack real-time responsiveness, which can lead to confusion, delays, and even hazardous situations.

With the advancement of Internet of Things (IoT) technologies, there is a growing opportunity to develop intelligent systems capable of automating monitoring and control processes in crowded environments. Integrating IoT with Radio Frequency Identification (RFID) provides an effective solution for tracking individuals and managing crowd flow. The proposed system assigns a unique RFID card to each individual, tracks movement across zones via ESP32 microcontrollers, implements a parent-child association mechanism, and transmits all data to the ThingSpeak cloud platform for visualization and decision-making.

The primary purpose of this project is to design an intelligent system that enhances crowd management efficiency while ensuring the safety of children in densely populated environments. The system establishes a reliable parent-child linkage mechanism, ensuring that the location of a child can be quickly determined through the parent's identification, thereby reducing panic, confusion, and response time during separation incidents. Furthermore, the integration of IoT, RFID technology, and cloud-based data management presents a scalable and cost-effective solution for modern crowd control and safety applications.

II. RELATED WORK

Previous research indicates that conventional crowd control techniques primarily rely on manual supervision, surveillance cameras, and basic entry management systems. Several studies have highlighted the inefficiency of manual monitoring in large gatherings, where human error and delayed decision-making can lead to overcrowding and safety hazards. Wireless sensor networks have been explored for crowd density estimation, but they generally lack the capability to track individual identities, making them less suitable for locating missing children.

RFID-based systems have been widely studied for identification and access control, providing fast and contactless identification. However, most existing implementations are limited to attendance tracking or simple access management and do not extend to continuous tracking across multiple zones or integration with real-time cloud analytics. GPS-based child

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tracking systems, while offering accurate outdoor positioning, often face challenges such as high power consumption, satellite dependency, and reduced accuracy in indoor or densely crowded areas.

IoT-enabled crowd management systems integrating microcontrollers, wireless communication, and cloud platforms have improved remote monitoring capabilities but often omit individual-level parent-child association. The proposed system bridges this gap by integrating RFID-based identification with IoT-enabled communication and cloud storage, while introducing a parent-child linking mechanism that provides real-time tracking, improved safety, and efficient crowd control within a unified framework.

III. SYSTEM DESIGN

A. System Architecture

The system follows a five-layer architecture: (1) Input Layer -- parents and children carry unique RFID cards linked during registration; (2) Sensing Layer -- MFRC522 RFID readers at strategic zones detect card UIDs via SPI interface; (3) Processing Layer -- ESP32 microcontroller identifies cardholder role, updates child location, triggers alerts, and formats data for cloud transmission; (4) Communication Layer -- ESP32 built-in Wi-Fi transmits data to ThingSpeak; (5) Output Layer -- Red LED (child scan), White LED (parent scan), buzzer alerts, and ThingSpeak dashboards for real-time monitoring.

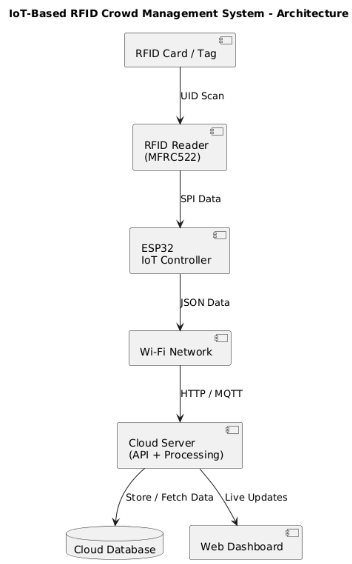

Fig. 1. IoT-Based RFID Crowd Management System Architecture

B. Modules

- Registration Module: Issues unique RFID cards; links child UIDs to parent UIDs in the database.
- RFID Scanning Module: Readers at zone checkpoints continuously detect cards and forward UIDs to ESP32.
- Parent-Child Linking Module: On child scan: displays child and parent details, updates child location. On parent scan: retrieves child's last known location for rapid recovery.
- Alert Module: Red/White LEDs and buzzer provide immediate visual/auditory feedback on every scan.
- Cloud Module: ThingSpeak receives, stores, and visualizes movement data, queue lengths, and parent-child associations in real time.
- Queue Management Module: Analyzes zone-wise movement data to estimate queue lengths and guide crowd control decisions.

C. Data Flow

Devotee scans RFID card → RFID reader captures UID → ESP32 processes UID and updates location and parent-child mapping → ESP32 triggers LED/buzzer alerts → Processed data transmitted to ThingSpeak → Real-time visualization and analysis on the cloud dashboard. This structured and automated approach ensures that real-time tracking, crowd management, and child safety operations are efficiently integrated within a unified IoT-enabled framework.

IV. SYSTEM REQUIREMENTS

A. Hardware Requirements

The hardware components are selected to ensure accurate RFID detection, real-time alert signaling, cloud communication, and reliable operation. Table I summarizes the key hardware components and their roles in the system.

TABLE I. HARDWARE COMPONENTS

Component	Description
ESP32 Microcontroller	Central processing, built-in Wi-Fi, GPIO support
RFID Reader (MFRC522)	Zone-based RFID card detection via SPI
RFID Cards/Tags	Unique ID per individual; child linked to parent
Red LED	Visual indicator for child scan
White LED	Visual indicator for parent scan
Buzzer	Auditory confirmation on every RFID scan
5V DC Power Supply	Powers all system components
Wi-Fi Router/Access Point	Cloud data transmission via ESP32

B. Software Requirements

The software stack enables seamless integration between the hardware, IoT devices, and cloud platform. Table II summarizes the key libraries and tools used for system development, data processing, and visualization.

TABLE II. SOFTWARE LIBRARIES AND TOOLS

Library / Tool	Purpose
Arduino IDE	Firmware development environment for ESP32
Embedded C/C++	Microcontroller programming language
MFRC522.h	RFID module interface library
SPI.h	Serial Peripheral Interface communication
WiFi.h	ESP32 Wi-Fi network connectivity
ThingSpeak.h	Cloud platform integration library
time.h (NTP)	Real-time timestamp synchronization

C. Project Prerequisites

Successful deployment requires: stable Wi-Fi connectivity for ESP32-to-cloud communication; predefined RFID zone placement ensuring all entry and exit points are covered; pre-registration of all RFID cards with parent-child associations in the database; consistent 5V DC power supply; hardware calibration and testing of RFID readers prior to deployment; ThingSpeak channel setup with API key and dashboard configuration; and an operating environment free from excessive electromagnetic interference.

V. IMPLEMENTATION

A. Technology Stack

The system leverages ESP32 as the central IoT controller, responsible for reading RFID data, processing role identification, triggering LED/buzzer alerts, and transmitting structured data to ThingSpeak. RFID (Radio-Frequency Identification) technology using MFRC522 readers provides non-contact, fast, and reliable individual identification. Wi-Fi connectivity ensures real-time cloud transmission without extensive cabling. ThingSpeak serves as the IoT analytics platform, providing real-time dashboards for movement patterns, parent-child associations, and queue statistics. NTP protocol ensures accurate timestamping for all scan events.

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Embedded C/C++ firmware is developed in Arduino IDE, integrating RFID scanning, role identification, alert control, NTP time fetching, and ThingSpeak data transmission. Parent-child associations are encoded in arrays within the firmware, mapping child UIDs to corresponding parent UIDs and names. The red LED activates for child scans and the white LED for parent scans, while the buzzer provides audible confirmation for every successful scan.

B. Sample Code Overview

The core firmware initializes the ESP32, RFID reader, LEDs, buzzer, Wi-Fi connection, and ThingSpeak client during setup. The main loop continuously polls for new RFID cards using PICC_IsNewCardPresent() and PICC_ReadCardSerial(). Upon detection, the UID is assembled from the card bytes and converted to uppercase. The system iterates through the childUIDs[] array to determine if the scanned card belongs to a child, triggering the red LED; otherwise it checks parentUIDs[], triggering the white LED. The buzzer activates for every scan. NTP time is fetched using configTime() and getLocalTime(), and the assembled data (UID, role, parent name, child name, timestamp) is transmitted to ThingSpeak using setField() and writeFields(). A 15-second delay ensures compliance with ThingSpeak rate limits.

VI. RESULTS AND DISCUSSION

A. System Performance

The system was prototyped and tested using ESP32 and MFRC522 modules. RFID card detection was accurate across all tested zones with sub-second response time. Parent-child associations were correctly retrieved in all test cases, with the child's last known location displayed upon parent card scan. LED and buzzer alerts functioned correctly, differentiating parent and child scans reliably. Data was successfully transmitted to and visualized on ThingSpeak with minimal latency. Queue length estimation provided actionable insights for congestion control. The system demonstrated reliable operation under simulated multi-user scenarios, confirming its viability for real-world deployment.

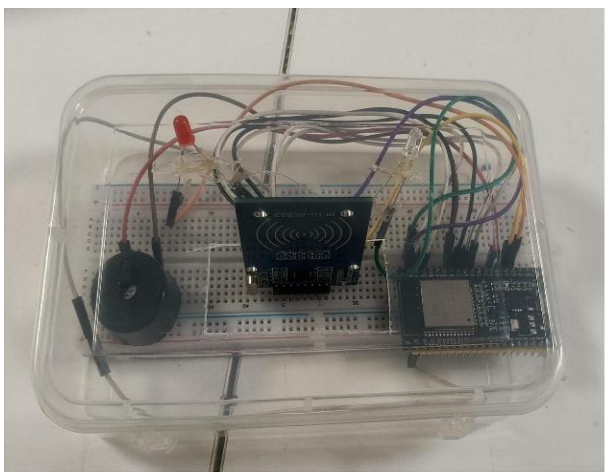

Fig. 2. Prototype Hardware Implementation

B. Output Screenshots

Child RFID Scan -- When a child's card is scanned, the Red LED illuminates, the buzzer beeps, and the serial monitor shows: Scanned UID: XYZ789 | Role: Child | Child Name: Sam | Parent Name: John | Current Location: Zone 2 | Timestamp: 14:35:22. Parent RFID Scan -- When a parent's card is scanned, the White LED illuminates and the serial monitor displays: Scanned UID: ABC123 | Role: Parent | Parent Name: John | Child Name: Sam | Last Known Location: Zone 2 | Timestamp: 14:36:05.

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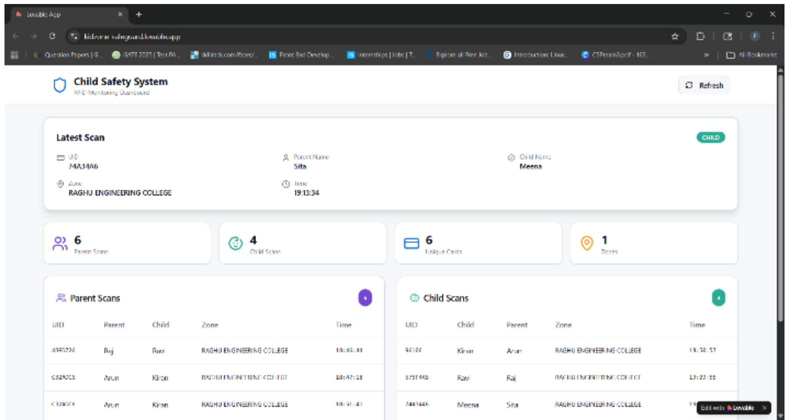

C. Cloud Dashboard (ThingSpeak)

Every RFID scan is transmitted to ThingSpeak in real time. Table III shows a sample data log captured from the ThingSpeak platform during system testing.

TABLE III. SAMPLE THINGSPEAK DATA LOG

UID	Role	Parent Name	Child Name	Zone	Timestamp
XYZ789	Child	John	Sam	Zone 2	14:35:22
ABC123	Parent	John	Sam	Zone 2	14:36:05
LMN012	Child	Alice	Emma	Zone 1	14:37:11

Real-time graphs on the ThingSpeak dashboard display the number of scans per zone over time, providing insights into crowd density and peak hours. Role-based color-coded indicators allow quick monitoring of child versus parent scans. The dashboard also highlights child location when a parent scans, enabling rapid recovery in separation scenarios.

VII. SYSTEM TESTING

System testing verifies that all hardware, software, and cloud components operate cohesively under real-world conditions. The following testing types were conducted:

- Unit Testing: Individual modules tested in isolation -- RFID reader UID detection, ESP32 role identification logic, LED/buzzer alert mechanisms.
- Integration Testing: Combined RFID detection with ESP32 processing; verified ESP32-to-ThingSpeak communication and complete scan-to-alert-to-cloud workflow.
- System Testing: Real-time tracking of multiple children and parents across different zones; simulated high-density crowd scenarios for response time and reliability.
- Performance Testing: Multiple simultaneous RFID scans; ThingSpeak cloud update interval monitoring under load.
- Usability Testing: Clarity of LED and buzzer alerts; ease of retrieving child locations using parent card scans.
- Reliability Testing: Network downtime behavior; missing or duplicate RFID scan handling to assess fault tolerance.

Through systematic testing, the system demonstrated robustness, scalability, and reliability, confirming that it can operate effectively in high-density public spaces while enhancing child safety and crowd management.

VIII. CONCLUSION AND FUTURE WORK

This paper presented an IoT-based RFID-enabled crowd management and child safety system integrating ESP32 microcontrollers, cloud-based analytics, and a parent-child association mechanism. The system automates individual tracking, reduces manual supervision dependency, and provides real-time alerts and data visualization. Key accomplishments include enhanced child safety through immediate parent-child identification, automated crowd monitoring via zone-wise queue length calculation, real-time LED and buzzer alerts, and cost-effective scalable design using low-cost hardware and open-source software.

Future work includes: integration of GPS/BLE for precise indoor-outdoor tracking; AI-powered predictive crowd analytics using machine learning; companion mobile applications for parent notifications and emergency alerts; multi-venue coordination for large-scale deployments; wearable smart badges replacing RFID cards for enhanced durability and continuous tracking; and solar-powered RFID readers for sustainable outdoor operation. These enhancements aim to evolve the system into a fully integrated smart public safety solution.

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