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Avoidance of Train Collision System

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Abstract: Train collisions are one of the critical safety concerns in railways, which could result from human error, signal failure, communication delay, or reduced line of sight owing to complex terrain. This paper proposes a low-cost intelligent TCPS designed using ESP32 microcontrollers, ultrasonic sensors, ESP-NOW wireless communication, and an automatic servo-based braking mechanism. The trackside unit constantly monitors the movement of the train through two ultrasonic sensors and calculates real-time distances for potential head-on collision detection. When the system identifies a threat, it issues an instantaneous emergency braking signal to the onboard units, which trigger the servo-driven brake assembly. Further, the proposed system is integrated with regenerative braking to recover the kinetic energy for recharging the lithium-ion battery supply present in the system. Experimental testing on a prototype railway track has shown high detection accuracy, quick wireless communication, and reliable automatic braking. The proposed system gives a scalable, modular, and energy-efficient alternative to conventional railway safety mechanisms that can be integrated with state-of-the-art signalling and AI-based prediction in future applications.

Keywords —Train safety, Collision prevention, ESP32, Ultrasonic sensor, Wireless communication, Regenerative braking, Automatic braking.

I. INTRODUCTION

Railways continue to be one of the most feasible and cost-effective mass transit systems, transporting millions of passengers and volumes of cargo daily. With the ever-increasing rail traffic density, assuring safe and continuous train movement has become an engineering challenge of the highest order. While there is considerable improvement in the state-of-the-art in signalling and control systems, collisions happen due to human failure, signal failure, delayed communication or the inability to monitor properly in challenging geographical layouts. High-profile accidents occurred in India: the Balasore triple-train collision (2023), the Vizianagaram rear-end collision, and the earlier incidents at Penukonda (2012) and Mathura (1995), all point to recurring vulnerabilities in the existing railway safety frameworks.

Conventional protection in railways is based on block signalling, interlocking, and Centralised Traffic Control-CTC. These systems basically use fixed infrastructure for regulating train movements along with long-range communications between station controllers and locomotives. Although robust, they also have some critical limitations:

1. Human interpretation dependency,
2. Signal transmission latency
3. An inability to detect local, on-track obstacles in real time, and
4. Reduced reliability in blind bends, single-track sections, and hilly terrain, where visibility is low and reaction time is very short.

Kavach, an indigenous modern ATP system of the Indian Railways, has empowered operational safety with speed limits and automatic application of brakes during signal violations. However, Kavach primarily operates over long-distance radio communications without localised sensing and energy-efficient braking. Independent train detection from centralised signalling by small-scale, low-cost decentralised systems is at a nascent stage of development. The proposed TCPS in this paper is a real-time, short-range, embedded electronics and wireless communication-based system. In it, dual ultrasonic sensors are installed trackside to detect the approach of two trains on a collision path.

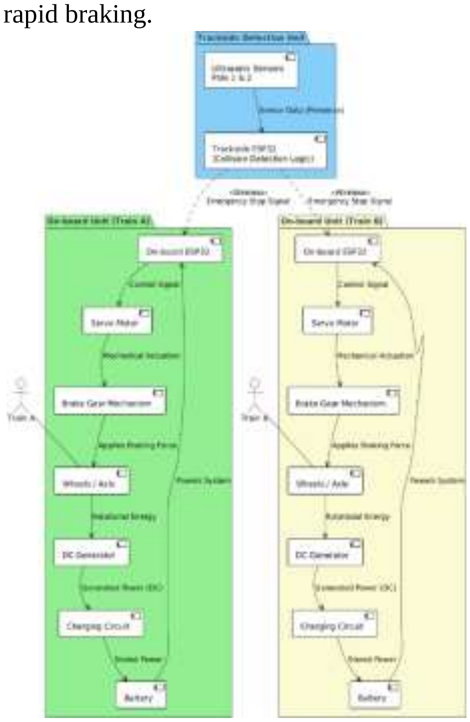
The ESP32 microcontroller will process the detection results and immediately broadcast an emergency stop command to the trains via ESP-NOW, an ultra-low-latency peer-to-peer wireless protocol. Upon receiving that signal, the on-board unit actuates a servo-driven braking mechanism to stop the train. The braking assembly is interfaced with a small DC generator to demonstrate regenerative braking in order to convert the deceleration energy into electrical power for on-board electronics.

II. SYSTEM ARCHITECTURE

The proposed Train Collision Prevention System will be a distributed, real-time safety framework, comprising three major subsystems:

- Trackside Detection Unit,
- On-board Emergency Braking Unit, and
- Wireless Communication Network.

While each subsystem performs an independent safety task, it works in concert with the other to detect collisions and initiate rapid braking.



Trackside Detection Unit

The Trackside Detection Unit works as the main sensing and decision-making block. It employs two ultrasonic sensors mounted on opposite sides of a single-track section. These sensors continuously measure the distance of approaching trains.

Key functionalities include:

Dual-Sensor Verification

Instead of relying on one sensor, two sensors are used to:

- Monitor in both directions of train movement.
- Reduce false triggers caused by animals, humans, or environmental noise.
- Confirm that two trains are present in the same track segment simultaneously.

Real-Time Decision Logic

- An ESP32 microcontroller processes distance values and executes a collision detection algorithm.
- A collision threat is detected when:
- Both sensors measure a train within the predefined danger threshold at the same time.

Emergency Command Trigger

- Upon detecting this condition,
- The ESP32 immediately generates an emergency stop signal,
- The signal is wirelessly broadcast to all on-board units within its vicinity.

The unit ensures local intelligence instead of fully depending on station control or long-range signalling.

On-board Emergency Braking Unit

- Each train comprises a compact on-board system, which is made of an ESP32 controller, servo motor, DC generator, TP4056 battery charger, and Li-ion battery.

Continuous Listening Mode

The ESP32 on board remains in a passive listening mode and waits for:

Emergency stop signals from the trackside unit, or

Direct communication from other trains, if extended to future versions.

Servo-Based Braking Mechanism

Upon receiving the emergency command:

- The ESP32 generates a PWM signal.

- The servo rotates to a predefined angle.
- A mechanical brake lever presses against the wheel of a train to commence immediate deceleration.

This ensures consistent, automated braking without human involvement, reducing reaction time significantly.

Wireless Communication Layer (ESP-NOW)

Reliability and timeliness of communication are key components of collision prevention.

In this respect, the system utilises ESP-NOW, a low-latency, peer-to-peer wireless protocol embedded in ESP32.

Key features of ESP-NOW:

- Latency < 10 milliseconds
- Does not need Wi-Fi routers or the internet.
- Supports broadcasting to multiple devices simultaneously
- Low power consumption
- High stability in local, short-range environments
- Role in the TCPS architecture:
- The trackside ESP32 is the transmitter, sending STOP commands.
- Onboard ESP32 modules serve as receivers, applying brakes immediately.

Due to a lightweight packet format, communication works even when power drops or when networks are unstable.

This provides a fast, reliable, and independent safety communication network.

System Workflow Summary

Trackside sensors detect approaching trains.ESP32 uses dual-sensor logic to verify a collision condition. The emergency stop signal is broadcast using ESP-NOW. The on-board ESP32 receives the signal and initiates the braking mechanism. Regenerative braking stores energy in the battery. System resets when the track becomes safe.

III. SOFTWARE FLOW AND COMMUNICATION

Trackside Unit Software Flow

The trackside ESP32 continuously reads the distance values from the two ultrasonic sensors, filters out the noise in the data, and verifies that both sensors detect a train within the danger threshold. If the risk of a collision is confirmed, the ESP32 quickly sends a STOP command packet with the necessary information and broadcasts it through the ESP-NOW protocol. After sending the alert, it resets and resumes its real-time monitoring.

Onboard Unit Software Flow

The onboard ESP32 constantly listens for the STOP packet from the trackside unit. After receiving a valid packet, the controller verifies the message integrity and sends a PWM control to immediately trigger the servo-based braking mechanism. Simultaneously, regenerative braking captures energy by a DC generator that stores the energy in the battery. The system then resets and goes back to listening mode after braking.

ESP-NOW Communication Process

ESP-NOW enables a line-of-sight, peer-to-peer communication between trackside and on-board ESP32 units in a very fast way without the use of Wi-Fi routers or the internet. It boasts extremely low latency-less than 10 ms, enabling immediate transmission of emergency STOP packets. The protocol ensures reliable delivery through MAC-based authentication and checksum verification, ideal for real-time collision prevention

IV. WORKING

There are three circuits, 2 trains, and one control centre. the middle part is the control centre train detection circuit. So the main control circuit consists of 4 ultrasonic sensors.2 ultrasonic sensors are placed on each track, so for 2 tracks, we arrange 4 sensors in the opposite direction. Two trains are equipped with the train circuits, which consist of a motor for the train movement and a servo motor acting as brakes. When the two ultrasonic sensors on the same tracks are detected, the main circuit at the control centre will wirelessly send the signal to both trains, and both trains will automatically stop to avoid a collision. when the servo motor applies brakes, the tyre gets in contact with a gear attached to a motor to generate power, and that circuit is attached to the servo motor.

V. CONCLUSION

The Train Collision Prevention System developed in this project provides an effective and innovative approach to enhancing railway safety. By integrating ultrasonic sensors, ESP32 microcontrollers, servo motors, and wireless communication, the system is capable of detecting trains approaching on the same track and automatically activating the braking mechanism to prevent collisions. The prototype was successfully tested on a miniature track model, demonstrating accurate detection, quick response time, and reliable wireless communication between the on-board and trackside units.

This project establishes a strong foundation for the implementation of intelligent railway monitoring and control systems. With further improvements such as integration with GPS, IoT platforms, and AI-based prediction models, the system can be scaled for real-world applications. Future advancements in communication technologies and automation could transform this prototype into a practical, large-scale solution capable of reducing human error, improving operational reliability, and moving towards a safer and more sustainable railway network.

Results

The results of the proposed Train Collision Prevention System demonstrate effective and reliable performance under various operating conditions. During normal operation, when no obstacle is present on the track, the system maintains safe conditions, indicated by a green LED, and the trains move without interruption. When an obstacle is detected, the system successfully identifies it and activates warning signals through blinking yellow LEDs to alert potential danger. Additionally, when two trains operate on different tracks, the system allows independent movement without generating any false warnings, ensuring smooth functioning. Most importantly, when two trains come onto the same track within the predefined sensing range, the system accurately detects the potential collision and immediately triggers emergency alerts using blinking red LEDs, followed by automatic braking. These observations confirm that the system provides fast detection, accurate decision-making, and effective collision prevention, thereby enhancing railway safety.

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