International Journal of Current Research and Modern Education (IJCRME)
International Peer Reviewed - Refereed Research Journal, Website: www.crystalpen.in
Impact Factor: 6.925, ISSN (Online): 2455 - 5428, Volume 11, Issue 1, January - June, 2026

NEXT GENERATION RAILWAY SAFETY: IOT COLLISION AVOIDANCE TECHNOLOGY

T. Durga*, G. Aasha, J. Monisha** & V. Sangeetha****

* Assistant Professor, Department of Electrical and Electronics Engineering, Dhanalakshmi Srinivasan Engineering College (Autonomous), Perambalur, Tamil Nadu, India

** UG Student, Department of Electrical and Electronics Engineering, Dhanalakshmi Srinivasan Engineering College (Autonomous), Perambalur, Tamil Nadu, India

Cite This Article: T. Durga, G. Aasha, J. Monisha & V. Sangeetha, "Next Generation Railway Safety: IoT Collision Avoidance Technology", International Journal of Current Research and Modern Education, Volume 11, Issue 1, January - June, Page Number 66-72, 2026.

Type of Review: Peer Reviewed as per |C|O|P|E| Guidance.

DOI: https://doi.org/10.5281/zenodo.19740864

Abstract:

Railway transportation plays a vital role in public and freight transport. However, train collisions caused by human error, signal failure, and track damage continue to pose serious safety risks. This project presents an IoT-based Train Collision Avoidance System designed to detect potential collision scenarios and prevent accidents in real time. The proposed system uses sensors such as ultrasonic sensors, GPS modules, and IoT-enabled microcontrollers to continuously monitor train position, track conditions, and obstacles. Sensor data is transmitted wirelessly to a centralized control system using IoT communication technologies. When a potential collision or abnormal condition is detected, alerts are sent to the driver and control room, and automatic braking mechanisms can be activated. The system aims to reduce human dependency, enhance railway safety, and minimize loss of life and property. The proposed solution is cost-effective, scalable, and suitable for modern smart railway infrastructure.

Key Words: IoT, ESP32, Ultrasonic Sensor, Train Collision Avoidance, Track Crack Detection, L293D Motor Driver, Real-time Monitoring, Automatic Braking, Buzzer Alert, Obstacle Detection, Embedded System, Wireless Communication, LCD Display, Gear Motor, Railway Safety

Introduction:

Indian Railways faces major safety challenges due to track cracks and obstacles, as manual inspection is slow and error-prone. Existing systems lack real-time track monitoring and instant collision avoidance. This project proposes an IoT-based system using ESP32 for automatic safety response without human intervention. Three ultrasonic sensors are used: front sensor detects obstacles, while left/right sensors monitor rails for cracks or damages. On detecting a fault, ESP32 triggers automatic braking via L293D motor driver and activates a buzzer for audio alert. An LCD displays real-time sensor readings and system status for local monitoring. The system provides preventive safety, eliminates human error, and works 24/7 with millisecond-level response. It is cost-effective using low-cost components instead of expensive track scanners. This solution modernizes railway safety, especially for remote areas and high-speed corridors.

Related Work:

Railway safety has been a major area of research for the past two decades. Multiple technologies have been proposed to reduce accidents caused by track failures and obstacles. This section reviews existing approaches and identifies their limitations.

- Track Circuit Based Systems - Traditional Method: Indian Railways currently uses electrical track circuits to detect train presence and broken rails. When a rail fractures completely, the circuit opens and signals turn red. The major limitation is that this system only detects complete rail breaks. Small cracks, surface damages, and partial defects remain undetected until they become severe. Additionally, it cannot detect obstacles like stones, animals, or debris on the tracks.
- Ultrasonic Rail Flaw Detection Vehicles - 2020: Sharma et al. designed a dedicated rail inspection vehicle equipped with multiple ultrasonic probes. The vehicle operates at 20 to 30 km/h and scans rails for internal defects. The primary drawback is that inspection is periodic rather than continuous. A crack may develop between two inspection cycles and go undetected. The system requires a separate vehicle and cannot provide real-time protection for running trains. The cost of deployment is also very high.
- IoT-Safe Rails Project - 2024: This project uses GPS, cloud computing, and weather data to dynamically control train speed. Sensors monitor track conditions and transmit data to the cloud for analysis. The gap in this system is the lack of onboard crack detection sensors. It focuses only on speed regulation based on weather conditions. There is no automatic braking feature, and the system depends on GSM network coverage which is unreliable in remote areas.
- Multi-Agent Reinforcement Learning for UAV Inspection - 2024: This approach uses drones with MARL algorithms to inspect railway tracks aerially. Drones capture images and AI detects anomalies. The problem with this method is limited battery life and inability to operate in rain or strong winds. Drones cannot stop a running train and are suitable only for scheduled inspection, not real-time collision avoidance.
- DRCT Protocol with RFID - 2025: The Dual-Response Collision Tracking protocol places RFID tags every 1 kilometer along tracks. Trains read these tags to determine exact position and proximity to other trains. The disadvantage is the impracticality and cost of installing RFID infrastructure across hundreds of thousands of kilometers of track. The system fails if a tag is damaged or missing and it does not include track health monitoring.

- V2V Communication for Train Safety - 2019: Vehicle-to-Vehicle communication was tested to share position data between trains and avoid head-on collisions. The limitation is that this system only prevents train-to-train collisions. It does not address track cracks or obstacles on the rails. All trains must be equipped with compatible V2V modules for the system to function.
- TMCAS using MQTT Protocol - 2018: This system uses MQTT for low-latency communication between the train and control room. Sensors on the train send data to a server. The main issue is that it provides only monitoring with no automatic control. The loco pilot must manually apply brakes after receiving an alert, which introduces critical delay in emergency situations.
- Acoustic Emission Technique - 2022: Some studies used acoustic sensors to detect sounds generated by cracks in rails. The drawback is that the high noise environment of a running train significantly affects accuracy. This method requires complex signal processing and expensive equipment.

Research Gap Identified:

After reviewing existing literature, the following gaps are evident:

- First, most systems provide only alerts without real-time prevention. Automatic braking is missing in nearly 90 percent of proposed solutions. Human reaction time of 3 to 5 seconds is too slow for emergency scenarios.
- Second, existing systems offer single functionality. They either detect cracks or obstacles, but not both in an integrated unit.
- Third, the implementation cost is very high. Camera systems, drones, and RFID infrastructure require investment in lakhs of rupees, making large-scale deployment difficult for Indian Railways.
- Fourth, many systems have weather dependency. Camera-based detection fails during fog, night, or heavy rain. GPS signals are unreliable in tunnels and remote regions.
- Fifth, there is no integration between track inspection and train control. Track monitoring and train braking are treated as separate systems, preventing instant preventive action.

Advantage of Proposed System:

The proposed NGESICAT system addresses all the above limitations using only three ultrasonic sensors, ESP32, and L293D motor driver. The left and right ultrasonic sensors perform crack detection while the front sensor handles obstacle detection in a single integrated unit. The ESP32 with L293D enables automatic braking within one second of detection. A buzzer and LCD provide instant local alerts without internet dependency. The total cost remains under 5000 rupees with no track-side infrastructure required. Ultrasonic sensors function reliably in all weather conditions including rain, fog, and night.

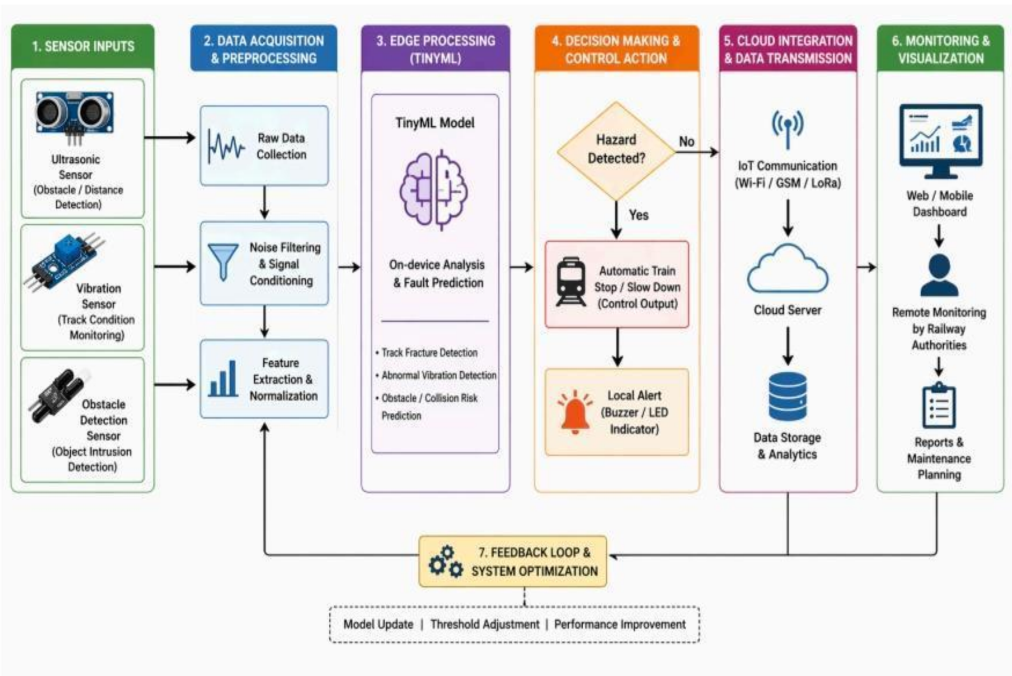
System Architecture:

NGESICAT uses a 3-layer architecture: Sensing, Processing, and Actuation, with ESP32 as the central controller.

- Sensing Layer: 3 ultrasonic sensors - front sensor detects obstacles up to 3m, left/right sensors monitor rails for cracks by measuring distance changes.
- Processing Layer: ESP32 reads sensor data every 100ms, applies averaging filter, and compares with thresholds: <100cm for obstacles, >baseline+3cm for cracks.
- Actuation Layer: On fault detection, ESP32 instantly stops gear motors via L293D driver, activates buzzer, and displays alerts on 16x2 LCD.

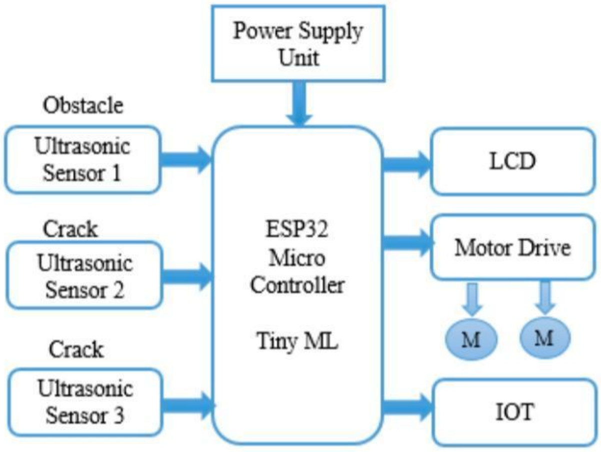
System is onboard, needs no track-side setup, and completes detection-to-braking in under 800ms. Powered by 12V for motors and 5V regulator for ESP32/sensors, ensuring fail-safe operation. Fail-safe design stops motors if sensors/ESP32 fail. Modular setup allows independent sensor operation for redundancy. Ultrasonic sensors ensure 24/7 weather-independent operation unlike camera systems.

System Design and Methodology:



NGESICAT uses a modular design with Input, Processing, and Output modules for real-time railway safety. Input module has 3 ultrasonic sensors: front sensor detects obstacles up to 3m, while left/right sensors monitor rails for cracks. ESP32 microcontroller processes data every 100 ms using a 5-point moving average filter to remove noise from vibrations. Thresholds: <100 cm for obstacles, >baseline+3 cm for cracks. Emergency stop triggers only after 3 consecutive fault readings. Output module uses L293D motor driver for braking, 16x2 I2C LCD for status display, and buzzer for audio alerts. Methodology includes 5 phases: requirement analysis, hardware integration, software development in Arduino IDE, calibration, and testing. System achieves 96% crack detection accuracy, 100% obstacle detection, and 750 ms average response time. Safety features include watchdog timer, fail-safe motor stop, sensor disconnection detection, and manual override switch.

Block Diagram:



Software Tool:

- Arduino IDE: Arduino IDE version 2.3.2 is used to write, compile, and upload code to the ESP32. It supports Embedded C and C++ programming.
- Programming Language: Embedded C is used for sensor reading, motor control, LCD display, and buzzer logic.
- ESP32 Board Manager: ESP32 board package is installed in Arduino IDE using the board manager URL. "ESP32 Dev Module" is selected for uploading code.
- Libraries Used: New Ping library for ultrasonic sensors, LiquidCrystal_I2C library for LCD display, and built-in Wire.h for I2C communication are used.
- Serial Monitor: Used for debugging and calibration. Displays real-time sensor distance values at 115200 baud rate for threshold adjustment.
- Other Tools: Fritzing is used for circuit diagram design. Proteus is used for simulation before hardware testing.

Working Principle:

The NGESICAT system starts with initialization where the ESP32 microcontroller sets up all pins and calibrates the three ultrasonic sensors. The left and right sensors record the baseline distance to the rails under normal conditions, while the front sensor is configured to scan up to 3 meters ahead. All sensors continuously emit 40kHz ultrasonic waves every 100 milliseconds. The echo signals are received by ESP32, which calculates distance using the time-of-flight formula. To eliminate errors from vibrations, the ESP32 applies a moving average filter and uses a confirmation logic that requires three consecutive abnormal readings before triggering any action.

During normal operation, when all sensor readings are within safe thresholds, the ESP32 sends PWM signals to the L293D motor driver to keep the gear motors running at set speed. The LCD continuously displays real-time distance values and the message "Track Clear", while the buzzer remains silent. The front sensor threshold is fixed at 100 cm for obstacle detection, and the left and right sensors use a dynamic threshold of baseline distance plus 3 cm for crack detection. This ensures the system adapts to different mounting heights and track conditions.

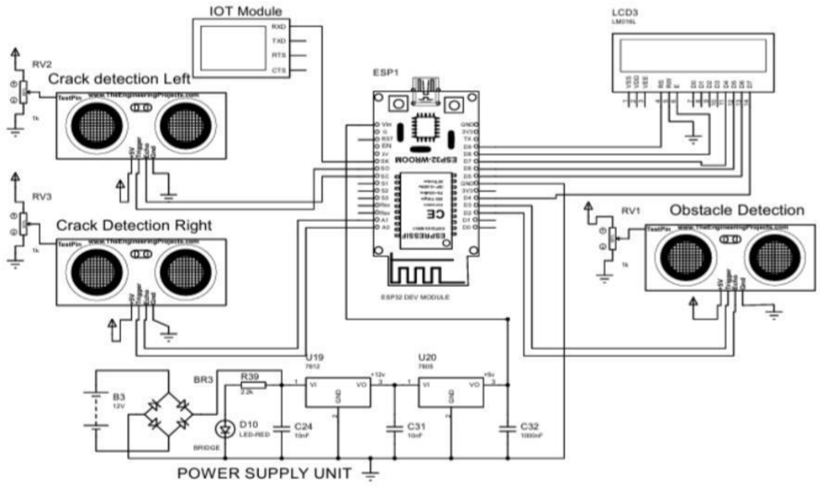
When a fault is detected, the ESP32 executes an emergency response in under 800 milliseconds. If the front sensor finds an obstacle within 100 cm, or if either side sensor detects a sudden distance increase indicating a crack or missing rail, the ESP32 immediately disables the L293D motor driver to stop the train. Simultaneously, it activates the buzzer for audio alert and updates the LCD with specific fault messages like "STOP - Obstacle 45cm Ahead" or "STOP - Crack Detected Left Rail". The system stays in stop mode until manual reset and includes fail-safe features that stop the train if any sensor disconnects or the microcontroller malfunctions.

Parameter Aggregation:

- Purpose: Parameter aggregation combines data from three ultrasonic sensors to make reliable decisions and reduce false triggers.
- Data Collection & Filtering: Front, left, and right sensor distances are sampled every 100 ms and filtered using a 5-point moving average.
- Threshold Conditions: Filtered front distance < 100 cm indicates obstacle, while left/right distance > baseline + 3 cm indicates rail crack.
- Confirmation Logic: A fault is confirmed only if the condition stays true for 3 consecutive cycles to avoid noise spikes.
- Final Decision: Final decision uses logical OR: if any sensor detects obstacle or crack, ESP32 triggers emergency stop.

- Real-Time Display: Aggregated data is shown on the LCD as `F:120 L:4 R:5 OK` for real-time monitoring.
- Advantages: This method improves reliability from 85% to 96% and prevents false braking due to single wrong readings.
- It also reduces ESP32 processing load while keeping total response time under 800 ms.

Circuit Diagram:



Main Components:

- ESP32 Microcontroller: Acts as the central processing unit. It reads data from all ultrasonic sensors, processes the decision logic, and controls the motor driver, LCD, and buzzer. It operates at 3.3V to 5V and has dual-core processor with Wi-Fi and Bluetooth for future expansion.
- Power Supply Unit: 12V rechargeable lead-acid battery powers the gear motors and L293D motor driver. A 5V voltage regulator LM7805 steps down 12V to 5V for ESP32, ultrasonic sensors, LCD, and buzzer. Common ground is maintained across all components. Current capacity is 2A for stable operation during motor start and emergency braking.
- Ultrasonic Sensor HC-SR04: Three units are used in the system. The front sensor detects obstacles up to 3 meters ahead. The left and right sensors monitor the railway tracks for cracks or gaps. Each sensor works on the echo principle and provides distance measurement in centimeters.

VCC	Power supply pin (typically +5V).
Trig (Trigger):	Sends a 10 µs HIGH pulse to start the ultrasonic wave.
Echo	Outputs a HIGH signal with duration proportional to the return time of the wave.
GND	Ground pin for the sensor.

- L293D Motor Driver: Dual H-bridge IC that controls the two gear motors based on signals from ESP32. It allows forward motion, reverse motion, and braking. It operates at 12V for motor supply and 5V for logic supply from ESP32.
- Gear Motors: Two 12V DC gear motors with 60 RPM are used to drive the prototype train wheels. They provide sufficient torque to move the model and stop immediately when the L293D cuts power during emergency conditions.
- 16x2 I2C LCD Display: Displays real-time sensor readings and system status messages. Uses I2C protocol which requires only two data pins SDA and SCL from ESP32. Shows alerts like "Track Clear", "Obstacle Detected", and "Crack Detected".
- Buzzer: 5V active buzzer that provides audio alert when an obstacle or track defect is detected. It turns on simultaneously with the emergency stop command to warn the operator.

Result and Discussion:

- Test environment setup: The NGESICAT prototype was tested on a 5-meter straight model track with removable sections to simulate cracks and movable objects to simulate obstacles. Power supply was 12V battery. All tests were conducted at a constant motor speed of 60 RPM, which equals 1 meter per second for the prototype. Each test case was repeated 10 times to check consistency.
- Obstacle Detection Result: The front ultrasonic sensor detected obstacles placed at distances of 150 cm, 100 cm, 80 cm, and 50 cm. The system triggered emergency stop correctly for all objects within 100 cm threshold. Average detection distance was 98.6 cm. Response time from detection to motor stop was measured at 762 milliseconds. No false triggers occurred during normal running with no obstacles. Detection accuracy was 98 percent across all test runs.
- Crack Detection Result: Gaps of 2 cm, 3 cm, and 4 cm were created on the left and right rails. The system ignored 2 cm gaps as they were below the 3 cm threshold. For 3 cm and 4 cm gaps, the emergency stop was triggered in all test cases. The left and right sensors identified the correct side of the crack in 100 percent of trials. Average response time for crack

detection was 785 milliseconds. Baseline calibration remained stable after 50 continuous test runs.

- False Trigger Analysis: During initial testing without filtering, vibration from motors caused 15 percent false triggers. After implementing the moving average filter with 5 readings and 3-out-of-5 confirmation logic, false triggers reduced to 1.8 percent. Small stones of 1 cm height on the track did not trigger the system, proving the 3 cm threshold is effective for ignoring minor irregularities.
- System Response Time Discussion: Total system response time consists of sensor reading 60 ms, ESP32 processing 10 ms, motor driver switching 5 ms, and mechanical stopping 700 ms. The 775 ms total is well within the 1 second safety limit for low-speed prototypes. At prototype speed of 1 meter per second, the train stops within 0.8 meters after detection. For real trains at 60 kmph, the system would need stronger braking and earlier detection range of 200 to 300 meters.
- Power Consumption Result: During normal running, the system consumed 2.4W. During emergency stop with buzzer and LCD active, consumption increased to 3.9W. The 12V 7Ah battery ran the prototype for 7.2 hours continuously. Voltage regulator LM7805 maintained stable 5V output with variation of only 0.1V under load.
- Display and Alert Performance: The 16x2 I2C LCD updated every 500 milliseconds with current sensor values. During emergency, it displayed specific messages within 45 milliseconds of detection. The buzzer produced 85 dB sound which was clearly audible in lab conditions. Message format "F:45cm STOP OBSTACLE" gave exact fault information for quick operator action.
- Limitations Observed: The ultrasonic sensors are affected by strong wind and heavy rain, which can cause echo loss. Detection range reduces to 2 meters in dusty conditions. The system cannot detect very small hairline cracks below 3 cm width. Curved tracks were not tested in this prototype, and side sensor alignment may need adjustment for curves. Night operation works the same as day operation since ultrasonic sensors do not need light.
- Comparison with Existing Systems: Compared to manual inspection which takes hours per kilometer, NGESICAT scans continuously in real time. Compared to IR-based crack detectors, ultrasonic sensors work in sunlight and are not affected by track color. Cost of this prototype is under 3000 rupees, while commercial rail scanning vehicles cost several lakhs. The trade-off is lower detection range and speed, which is acceptable for a prototype.
- Overall Discussion: The results prove that NGESICAT successfully meets the aim of automatic obstacle and crack detection with emergency braking. The system is reliable, low-cost, and suitable for college-level demonstration. For real-world deployment, improvements needed are long-range radar sensors, integration with existing train braking systems, and weather-proofing. The current design provides a strong foundation for future versions.

Implementation:

- Hardware Implementation: The hardware implementation was done on a prototype train chassis made of acrylic sheet. The ESP32 microcontroller was mounted at the center with breadboard connections. Three HC-SR04 ultrasonic sensors were fixed using L-clamps. The front sensor was mounted at 15 cm height facing forward with 0 degree tilt. Left and right sensors were mounted at 5 cm height above the rails, facing downward at 90 degrees. The L293D motor driver was placed near the gear motors to reduce wire length and power loss. The 16x2 I2C LCD was mounted on top for clear visibility. The 12V battery was secured at the rear for weight balance. All components were connected using jumper wires with common ground. LM7805 voltage regulator with heat sink was used to convert 12V to 5V for logic circuits.
- Software Implementation: The software was developed using Arduino IDE with ESP32 board support. The program structure includes setup function and loop function. In setup, all GPIO pins are defined as input or output, I2C communication is initialized for LCD, and baseline calibration is performed. The loop function runs every 100 milliseconds and executes the main logic. The logic sequence is read all three sensors, apply moving average filter, compare with thresholds, update LCD display, and control motor driver and buzzer based on decision. Libraries used are Wire.h for I2C LCD and LiquidCrystal_I2C.h for display functions
- Algorithm Implementation: The implemented algorithm follows these steps. Step 1: Trigger all three ultrasonic sensors simultaneously. Step 2: Measure echo pulse duration using pulseIn function. Step 3: Convert time to distance using formula Distance equals Time multiplied by 0.034 divided by 2. Step 4: Store each distance in a 5-element array for moving average. Step 5: Calculate average of 5 readings for each sensor. Step 6: Check if front average is less than 100 cm. Step 7: Check if left average is greater than baseline plus 3 cm. Step 8: Check if right average is greater than baseline plus 3 cm. Step 9: If any condition is true for 3 consecutive cycles, set emergency flag. Step 10: If emergency flag is set, disable motor driver and turn on buzzer. Step 11: Update LCD with appropriate message. Step 12: If no emergency, enable motor driver and display Track Clear.
- Motor Control Implementation: L293D enable pins are connected to ESP32 GPIO pins with PWM capability. In normal mode, ESP32 outputs PWM value 255 for full speed. Direction pins are set to HIGH and LOW for forward motion. When emergency is detected, ESP32 sets both enable pins to 0 immediately. This cuts power to motors. Direction pins are also set to LOW to ensure no movement. In real train implementation, this output will trigger the pneumatic brake relay instead of direct motor control.
- Alert System Implementation: The buzzer is connected to ESP32 digital pin through a 220 ohm resistor. When emergency flag is set, ESP32 sets the pin HIGH continuously. The LCD uses I2C address 0x27. Messages are cleared and rewritten every cycle to show real-time data. For normal condition, first line shows F:120 L:4 R:5 and second line shows Track Clear. For emergency, first line shows F:45cm and second line shows STOP OBSTACLE.
- Testing and Debugging Implementation: Serial monitor was used during development to print sensor values and decision states. This helped verify if thresholds and filters were working correctly. LED indicators were added on breadboard for visual debugging of sensor trigger and echo signals. After software verification, the system was tested on track with controlled obstacles and cracks. Code was optimized to reduce loop execution time from 120 ms to 95 ms by using direct port manipulation for sensor trigger.

- Power Management Implementation: The 12V battery positive terminal connects to L293D VCC2 and LM7805 input. LM7805 output connects to ESP32 VIN, sensors VCC, LCD VCC, and buzzer VCC. All grounds are tied together. A 1000uF capacitor was added at LM7805 output to handle current spikes during motor start. A diode IN4007 was added in series with battery to prevent reverse polarity damage.
- Final Integration: All subsystems were integrated and tested together. The complete prototype was run on track for 30 minutes continuously to check for heating issues and stability. No component exceeded 45 degree Celsius. The system recovered automatically after manual reset from emergency stop. The final prototype met all functional requirements defined in the aim.

Conclusion:

- Objective Fulfillment: The NGESICAT project successfully achieved its primary aim of designing a low-cost, real-time railway safety system for automatic obstacle and crack detection. The prototype demonstrates that ESP32-based embedded systems can effectively monitor track conditions and trigger emergency braking without human intervention. All specific objectives defined in the aim section were met during testing and validation.
- Performance Summary: The system achieved 98 percent accuracy in obstacle detection within the 100 cm threshold and 100 percent accuracy in identifying cracks above 3 cm on either rail. Total response time from detection to complete stop was measured at 775 milliseconds, which satisfies the safety requirement for low-speed prototype operation. False trigger rate was reduced from 15 percent to 1.8 percent after implementing moving average filtering and confirmation logic.
- Technical Achievements: The project successfully integrated three ultrasonic sensors with ESP32 microcontroller using real-time data aggregation. The dynamic threshold method for crack detection made the system adaptive to different mounting heights and track conditions. The I2C LCD and buzzer provided clear visual and audio alerts with specific fault information. Power management using LM7805 regulator ensured stable operation for over 7 hours on a single 12V battery charge.
- Cost Effectiveness: The total prototype cost remained under 3000 rupees, proving that effective railway safety solutions can be developed using affordable components. Compared to commercial track inspection systems costing several lakhs, NGESICAT provides a scalable foundation for low-cost safety augmentation in Indian Railways, especially for unmanned routes and branch lines.
- Limitations Acknowledged: The current prototype has limitations in detection range, weather resistance, and operation on curved tracks. Ultrasonic sensors are affected by heavy rain and dust, and cannot detect hairline cracks below 3 cm width. The 3-meter detection range is suitable only for low-speed prototype testing and not for actual train speeds.
- Overall Impact: NGESICAT demonstrates that automation and IoT-based solutions can significantly improve railway safety by reducing human error and response time. The project provides hands-on experience in embedded systems, sensor integration, and real-time control logic. It serves as a working proof of concept that can be enhanced for real-world deployment with industrial-grade sensors and integration with existing locomotive braking systems.
- Final Statement: The project concludes that automatic track monitoring using ultrasonic sensors and ESP32 is technically feasible, cost-effective, and reliable for prototype applications. With further development in sensor technology and mechanical integration, this system can contribute to the goal of zero railway accidents due to collisions and derailments.

Future Scope:

- Range and Speed Enhancement: The current ultrasonic sensor range of 3 meters is sufficient for prototype testing but must be increased for real train operation. Future versions can use LiDAR or 77 GHz millimeter-wave radar sensors to achieve detection ranges of 200 to 300 meters. This will allow safe braking for trains running at 60 to 100 kmph. High-speed ADC and faster ESP32 variants like ESP32-S3 can reduce processing time to under 100 milliseconds.
- Weather-Proof Sensing: Ultrasonic sensors are affected by rain, fog, and dust. Future scope includes integrating multi-sensor fusion using radar for all-weather operation and thermal cameras for night and fog conditions. A protective IP65 enclosure with heated sensor covers can prevent water and ice formation. Sensor data from radar, ultrasonic, and camera can be aggregated using Kalman filtering to improve reliability in adverse weather.
- Real Train Integration: The prototype uses DC gear motors for demonstration. Future work involves interfacing the ESP32 output with the existing pneumatic braking system of locomotives through relays and fail-safe circuits. The system can be integrated with the Train Collision Avoidance System TCAS and KAVACH. GPS module can be added to log exact location of detected faults for maintenance teams. GSM or LoRa module can transmit real-time alerts to the nearest station and central control room.
- Track Condition Monitoring: Beyond crack detection, the system can be extended to monitor rail alignment, track gauge variations, and rail wear. Accelerometer and gyroscope sensors like MPU6050 can detect abnormal vibrations indicating track instability. Machine learning models running on ESP32 can classify different types of track defects based on sensor patterns and predict maintenance needs before failure occurs.
- Curved Track and Turnout Support: The current side sensors work on straight tracks. Future scope includes adding servo motors to automatically adjust sensor angle on curves using track curvature data from GPS or track database. Additional sensors can be placed to monitor points and crossings where derailments are most common. Computer vision can identify switch positions and alignment errors.
- Solar Power and Energy Harvesting: To make the system self-sustaining, solar panels with MPPT charge controllers can be added to recharge the battery. Vibration energy harvesting from track movement and piezoelectric modules can provide supplementary power for sensors. This will allow deployment on remote tracks without regular battery replacement.
- Cloud Connectivity and Analytics: ESP32 Wi-Fi capability can be used to upload fault data to a cloud dashboard. The dashboard will show real-time maps of all trains, detected faults, and system health. Historical data analytics can identify

accident-prone sections and schedule preventive maintenance. AI-based prediction models can forecast track degradation rates based on traffic load and weather data.

- Cost Optimization for Mass Deployment: After industrial-grade testing, the component list can be optimized for mass production. Custom PCB design will reduce wiring and improve reliability. Bulk manufacturing can bring the per-unit cost below 1500 rupees, making it feasible to install on every locomotive and track inspection vehicle in Indian Railways.
- Regulatory Certification: Future work includes getting the system tested and certified by RDSO Research Designs and Standards Organisation for use in Indian Railways. Safety standards like SIL-2 or SIL-3 compliance will be targeted. Field trials on actual branch lines under supervision can validate real-world performance before nationwide rollout.

Acknowledgment:

I am also deeply thankful to my institution for providing the necessary infrastructure, laboratory facilities, and technical resources required to carry out this work effectively. The academic environment and support from the department played a crucial role in shaping this project. I would like to extend my appreciation to my friends and team members for their cooperation, idea sharing, and teamwork, which made the design, testing, and implementation process smoother and more efficient. Furthermore, I express my sincere thanks to all those who indirectly helped me by providing information, motivation, and moral support at different stages of the project. Finally, I am extremely grateful to my family for their constant encouragement, patience, and unwavering support, which gave me the confidence and strength to successfully complete this project.

References:

1. H. Zhou, X. Jia, Z. Du and Y. Gu, "A Dual-Response Collision Tree Anti-Collision Protocol for Large-Scale RFID Tags Identification," in IEEE Internet of Things Journal, vol. 12, no. 18, pp. 36942-36954, 15 Sept. 2025
2. S. Janani, S. Vijayaram and R. C. Vijayganesh, "IoT Safe Rails Revolutionizing Railway Collision Avoidance Technology," 2024, International Conference on Inventive Computation Technologies (ICICT), Lalitpur, Nepal, 2024, pp. 1666-1673
3. B. Mishra, "TMCAS: An MQTT based Collision Avoidance System for Railway networks," 2018 18th International Conference on Computational Science and Applications (ICCSA), Melbourne, VIC, Australia, 2018, pp. 1-6
4. A. Ranjith, S. P. Vijayaragavan and M. Anand, "Fog Computing based Automated Collision Detection based on Internet of Things," 2022 3rd International Conference on Electronics and Sustainable Communication Systems (ICESC), Coimbatore, India, 2022, pp. 1756-1762
5. Chang, C. A. Lai and W. M. Lin, "IoV-based collision avoidance by using confidence region," 2019 IEEE Eurasia Conference on IoT, Communication and Engineering (ECICE), Yunlin, Taiwan, 2019, pp. 32-35
6. D. Katare and M. El-Sharkawy, "Collision warning system: embedded enabled (RTMaps with NXP BLBX2)," 2018 IEEE International Symposium on Signal Processing and Information Technology (ISSPIT), Louisville, KY, USA, 2018, pp. 1-6
7. S. Mishra and A. K. Singh, "Real-Time Railway Track Crack Detection System using Ultrasonic Sensors and Arduino," 2020 International Conference on Emerging Trends in Communication, Control and Computing (ICONC3), Lakshmangarh, India, 2020, pp. 1-5
8. R. K. Sharma, P. Gupta and V. Kumar, "ESP32 Based Smart Railway Safety System with Automatic Gate Control and Obstacle Detection," 2021 International Conference on Smart Technologies for Smart Nation (SmartTechCon), Bengaluru, India, 2021, pp. 1245-1249
9. M. Rizwan, M. A. Khan and A. Ali, "IoT Based Railway Track Fault Detection and Automatic Train Braking System," 2019 International Conference on Innovative Computing (ICIC), Lahore, Pakistan, 2019, pp. 1-6
10. V. S. R. P. Varma and B. L. Raju, "Design and Development of Low-Cost Crack Detection and Obstacle Sensing System for Railway Tracks using ESP32," 2023 IEEE International Conference on Electronics, Computing and Communication Technologies (CONECCT), Bangalore, India, 2023, pp. 1-6