An Intelligent Railway Level Crossing System with Multi-Zone Train Monitoring and Predictive Safety

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***Abstract*—This research work proposes a multi-zone sensor-based intelligent railway level crossing to be automated by an intelligent system proposed for the intelligent railway level crossing. The four IR-sensors R1, R2, R3 and R4, an Arduino Uno, a Servo Motor, an LCD display, an LED and a buzzer were used to develop the multi-zone sensor-based intelligent railway level crossing. The four IR-sensors R1, R2, R3 and R4 were installed in different zones. Zone 1 contains the two sensors R1 and R2. The two sensors R1 and R2 are used to detect an incoming train and to calculate the speed of the train. The system proposed for the intelligent railway level crossing uses the speed of the train to calculate the estimated time of arrival (ETA) of the train at the level crossing. Zone 2 contains the two sensors R3 and R4. The two sensors R3 and R4 are installed in Zone 2 to monitor the crossing area and to confirm the departure of the train from the level crossing. Zone 3 contains the LCD display, the LED and the buzzer. The system proposed for the status of the train and the gates at the level crossing by displaying the status on the LCD display and by giving audible and visual warnings by means of the buzzer and the LED. Zone 4 contains the ESP32-based IoT module. The IoT module proposed for the intelligent railway level crossing sends warning messages to the operator in case of errors with the sensors, in case of abnormal sequences of sensor activation and in case of emergencies. Therefore, the multi-zone sensor-based intelligent railway level crossing proposed is a low-cost, reliable and rapidly responsive system to improve safety at railway level crossings.**

***Index Terms*—Railway Level Crossing, IR Sensor, Train Detection, Speed Estimation, ETA, Sensor Validation, Adaptive Gate Control, Fail-Safe System, IoT.**

I. Introduction

Railway level crossings are key spots where rail tracks meet roads, and they need solid safety measures to stop accidents. In many rural areas, crossings still rely on manual gate handling and simple warning systems. Problems can follow. Human error, late operation, weak warning and limited monitoring still happen, which creates a need for an automated and reliable railway crossing system that can raise safety. Several automatic railway gate systems already use IR sensors, ultrasonic sensors, Arduino and IoT technologies. Many of the current systems, though, focus mainly on train detection and gate control. They leave out a few important functions, including sensor sequence validation, train speed estimation, ETA calculation and fail-safe operation. This paper presents a multi-zone intelligent railway level crossing system built around four IR sensors. The sensors sit in different zones to detect an approaching train, estimate its speed, watch the crossing area and confirm when the train has left. Speed is calculated from the time gap between IR1 and IR2. That value is then used to estimate the train's Estimated Time of Arrival (ETA), which allows earlier warning and gate control that adjusts to the situation. The system also checks the sensor trigger order, IR1 to IR2 to IR3 to IR4, to spot abnormal activation and possible sensor faults. That matters. This ensures that both IR3 and IR4 confirm that the crossing is clear before the gate opens. The LCD is used to show the status of the train and LEDs and buzzer are used for warning. In case of any sensor faults or emergency conditions, an alert notification is sent by an ESP32 based IoT module.

The technical novelty of the proposed system is the integration of multiple safety-oriented functions into a single multi-zone framework. The proposed system, unlike systems primarily designed for automatic gate control or train detection, integrates sensor self-testing, estimation of train speed and ETA, sensor sequence validation, adaptive gate control and dual-condition safe exit verification using IR3 and IR4. The integrated approach allows continuous tracking of sensor behavior and train movement, reduces unnecessary gate waiting and improves reliability of level-crossing operation.

The remainder of this paper is organized as follows. The literature review is provided in Section II and Section III describes the proposed methodology. Section IV describes the hardware components and Section V presents the experimental results and discussion. Finally, Section VI concludes the paper and explains the future scope of the proposed system.

II. Literature Review

Pradheep et al. proposed an automatic railway based on the IoT gate control system for real time monitoring of train

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movement operate the crossing gate without human time and intervention . The system employed two ultrasonic sensors to detect the arrival and departure of trains. The decision making and communication process was done by a microcontroller and the physical movement of the gate was controlled by a servo motor. An audio warning buzzer was also integrated to provide a warning during gate operation [1]. Another real-time train tracking and automatic gate control system was developed using a combination of IR and ultrasonic sensors. The sensing units were connected to an Arduino Uno which served as the main controller. The researchers also added a backup redundant sensor to allow the system to continue to work if one of the primary sensors failed [2].

Naveenkumar et al. demonstrated a VLSI- based automatic gate control system. In this design, two IR sensors detected the arrival and departure of the train. The overall operation was controlled by a Finite State Machine (FSM) with states Idle, Detect, Close Gate, Train Passing and Open Gate. Thus the gate changed its state according to the information from the sensors [3]. An Arduino-based solution was proposed where the main components included an Arduino microcontroller, a motor controller and a motor to operate the railway gate [4].

Automation of railway crossing has also been considered with AI techniques. Sivasankari et al. combined video analytics, sensor data, automated control and IoT communications. A Pi camera was used for train detection and the combination of the IoT modules allowed the system to monitor the crossing in real-time. The aim of this approach was to enhance safety by fusing vision data and sensor-based monitoring [5].

In another study, Chowdhury et al. developed a sensor-based system to automatically control the railway gate as well as track the trains in real-time. Another obstacle-detecting system was added to make sure the crossing area was clear before The gate was powered up. This feature was intended to reduce the risk of closing the gate while an obstacle remained in the crossing area [6].

IoT connectivity was another important feature explored in an automatic railway gate control system. Naik et al. used sensors to detect arrival and departure of every train, while the hardware was programmed using software developed in the Arduino IDE. Through the IoT functionality, the system could send notifications using the Blynk application and Gmail. This provided an additional way to monitor the railway crossing remotely and could support faster responses to abnormal situations [7].

Karuppusamy et al. aimed to automate the railway crossing system with AI and IoT. The system is based on a NodeMCU microcontroller, Firebase cloud platform and monitoring camera. It was a human safety device for the detection of the train and the automatic control of the [8].

Rajesh et al. used Arduino technology in the system to control the automatic railroad gates. The heat sensor was used to improve security by detecting any living objects near the railroad crossing fence [9].

Gangwar et al. developed a prototype system for automatic con- trol of railroad crossing barriers. The system comprises sensor circuits which sense the train and sends signal to the Zigbee module. In the system,an LCD is used to display the status of train arrival [10].

Maran et al. employed an ATmega328P microcon- troller and two Passive Infrared (PIR) motion sensors to identify the presence and motion of the incoming or outgoing train. The gate movement was controlled by a servo [11].

Bolla et al. used the proximity sensors to de- termine the position of the train. Two sensors were used to improve the system reliability. The microcontroller processed the sensor signals and controlled the LED, buzzer and smart platform according to the train's position [12].

Mostafa et al. used ultrasonic sensors to detect trains. The microcontroller interpreted the sensor signals and con- trolled the gate depending on the train position. The crossing status was displayed on an LCD and communication between the control room, train driver and sensors was carried out via a GSM module [13].

Janakiram used IR and PIR sensors to enhance the safety at the railroad level crossings.When a train was detected, the gates automatically descended and warning signals kicked in. Whenever an obstacle was identified, the system would generate an alert. The system gave ongoing surveillance to reduce accidents and improve railroad crossing safety [14].

Jothibasu et al. developed an IoT based railroad gate control system using GPS and LoRa technology for train location detection and automatic control of the railroad gate. The train unit used an ESP32, a GPS module, and a LoRa transceiver to continuously send the train's location data.The system's status was also indicated by an LCD and a buzzer for warnings [15].

There are existing studies that have developed automatic railroad gate control systems using various sensors, IoT, AI and communication technologies; however, the majority of the systems mainly concentrate on train detection and automatic gate operations. Sensor self-test, train speed estimation, ETA calculation, sequential sensor validation and fail-safe exit verification are not normally implemented in one system.

To overcome these limitations, the proposed system performs a sensor self-test before the normal operation to check if all sensors are working properly. It employs four IR sensors to achieve multi-zone train detection and monitoring, train speed and ETA calculation using IR1 and IR2, and expected sensor sequence validation. In addition, the system uses dual-condition verification with IR3 and IR4 for safe gate opening. In addition, IoT-based alerts are provided for sensor faults and abnormal sensor conditions.

III. Proposed Framework

This system proposes a multi-zone sensor-based intelligent railway level crossing system. The system consists of four IR sensors, an Arduino Uno microcontroller, a servo motor, an LCD, red and green LEDs. The overall architecture and connections of the proposed system are shown in Fig. 2. a buzzer and an ESP32 IoT module.

The purpose of this system is to make the existing railway crossing system more advanced, safer, and more efficient,

especially in rural areas. Upon system start-up, the system goes through a sensor self-test to ensure that all the necessary sensors are functioning properly. If any sensor fails to respond within a set time frame, the system detects this as a sensor fault. Upon detection of a sensor fault, an alert message is sent to the operator in charge. The specific functions of those four IR sensors are shown in Table I. Table I shows the role

TABLE I
FUNCTION OF SENSORS

Sensor	Function
IR1	Detect approaching train
IR2	Speed estimation
IR3	Gate control and monitoring
IR4	Train exit verification

of each IR sensor in the proposed system. After detecting the train using IR1 and IR2, the system calculates the train's speed by measuring the time difference between the detection points of the two sensors. The speed is calculated using the following equation:

$$Speed = \frac{Distance_{IR1-IR2}}{\Delta t} \tag{1}$$

where $Distance_{IR1-IR2}$ is the known distance between IR1 and IR2, and Δt is the time difference between the activation of the two sensors.

Using the calculated speed and the known distance between the detection point and the crossing area, the system calculates the *Estimated Time of Arrival (ETA)*. The ETA is used to provide an early warning to road users and to support adaptive gate control by determining the appropriate gate closing time.

$$ETA = \frac{Distance_{IR2-Crossing}}{Speed} \tag{2}$$

The ETA is a time-to-arrival estimate that is calculated from the measured speed of the train and the known distance from the detection point to the crossing. This is not a prediction based on machine learning. So, the ETA estimation is the expected arrival time given the assumption that the measured train speed is roughly constant.

The overall operation of the proposed system is shown in Fig. 1. The step-by-step algorithm of the proposed system is presented in Algorithm 1. The system continuously monitors the sensor activation sequence. The distance between the detection point and the crossing area is known. Using this information and the calculated speed of the train, the system can estimate the time that it will take for the train to arrive at the crossing (ETA). In order to control the gate in a safe manner, the gate is closed on the basis of the train's speed and the estimated time of arrival (ETA) at the crossing. Should the train be traveling at a high speed, the gate will close as quickly as possible. Conversely, when the train is traveling at slow speeds, there will be an appropriate amount of time prior to the arrival of the road vehicles, in order to allow them to pass through safely.

Algorithm 1 Proposed Railway Level Crossing Operation

1: Start.
2: Initialize Arduino, IR Sensors, LEDs, LCD, Buzzer, Servo Motor, and IoT Module.
3: Perform sensor self-test.
4: If any sensor fails, display "Sensor Fault", send an alert, and keep the system in a safe state.
5: If a train is detected by IR1, turn on the warning LED and buzzer and display "Train Detected".
6: Calculate the train speed from the time difference between IR1 and IR2 when IR2 detects the train.
7: Calculate ETA from the known distance between the detection point and the crossing.
8: Track the sensor activation order:
IR1 $\rightarrow$ IR2 $\rightarrow$ IR3 $\rightarrow$ IR4.
9: Send an alert if a timeout occurs or an abnormal sequence is detected.
10: When the train reaches IR3, close the railway gate using the servo motor.
11: Monitor IR3 and IR4 while the train is crossing.
12: Open the gate only when both IR3 and IR4 become clear.
13: Stop the buzzer and display the system status on the LCD.
14: If needed, send an IoT notification.
15: Restart the system and return to the monitoring mode.
16: End.

After the train passes the IR3 sensor, the gate closes and will stay closed for the rest of the train's passage through the crossing. The system continues to monitor the train's progress until it has passed the IR4 sensor. The LCD shows the system status at each stage of operation as shown in Table II.

TABLE II
LCD STATUS TABLE

System State	LCD Display
System starts	System initializing
Self-test	Checking Sensors
All sensors OK	All sensors OK
IR1 triggered	Train detected
IR2 triggered	Speed: XX km/h
ETA Calculated	ETA: XX s
IR3 triggered	Gate close
IR4 Detected	Train exiting
IR3 & IR4 Clear	Gate opening
Wrong Sequence	Sensor fault

These messages show the current status of the system in real time. Here, in order to provide fail-safe operation, the gate is only re-opened when both IR3 and IR4 have confirmed that the crossing area is now clear.

When a train is detected, the buzzer and red LED activate to warn people. The gate opens again only after the train has completely passed the crossing. After the train completely exits, the green LED lights are activated and the system returns to its initial state.

In addition, if any sensor error or other emergency situation is detected, the ESP32 IoT module immediately sends a warning message to the railway operator.

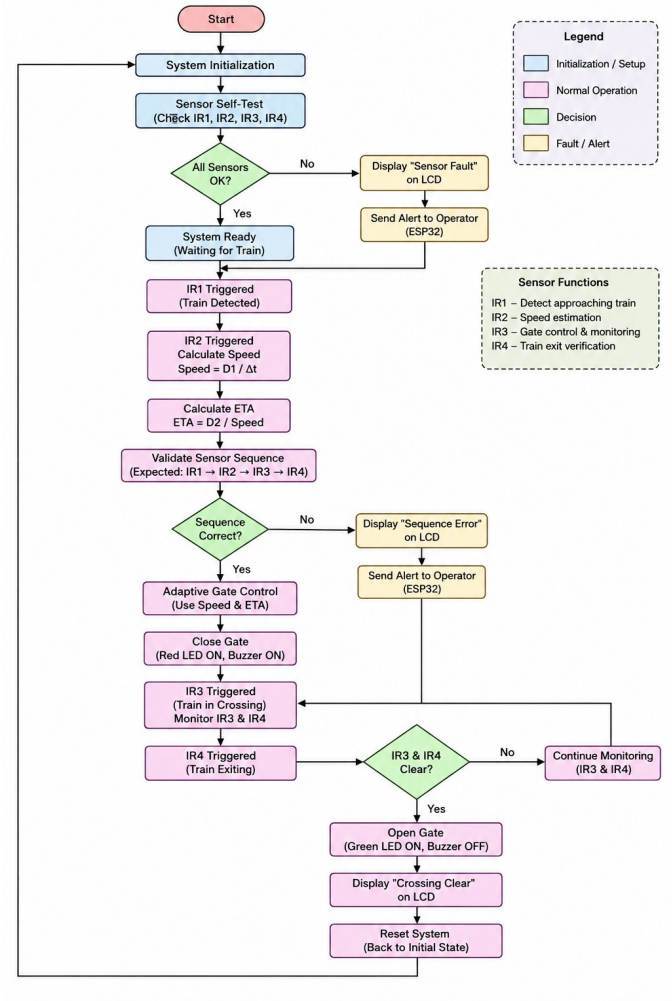


Fig. 1. Flowchart of the proposed railway level crossing system.

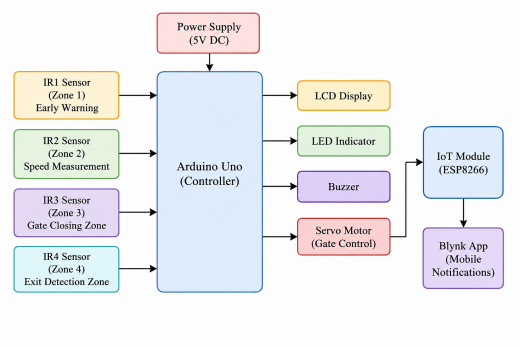


Fig. 2. Block diagram of the proposed multi-zone intelligent railway level crossing system.

IV. Hardware Components

The main hardware components of the proposed system are Arduino UNO, four IR sensors, a servo motor, LCD display, red and green LEDs, a buzzer and an ESP32 IoT module. The Arduino Uno is the brain of the whole system. The IR sensors are used to detect the train, estimate the speed of the train, monitor the railway crossing and verify whether the train has come out from the crossing. The servo motor is used to control the railway gate and LCD is used to show the status of the system, the speed of the train and the estimated time of arrival (ETA) at the crossing. The LEDs and buzzer are used to give visual and audible warnings respectively. The ESP32 is used to send alerts to a remote location in case of any sensor fault or emergency condition.

V. Results and Discussion

A. self-test and train detection

At the beginning of every test, the system performed a self-test of all four IR sensors. The sensors were tested to verify whether they were responding sequentially or not. When all sensors were functioning properly, the LCD showed "All Sensors OK" and the system started its operation.It shows in figure 3. If a sensor fails to respond, the system identified

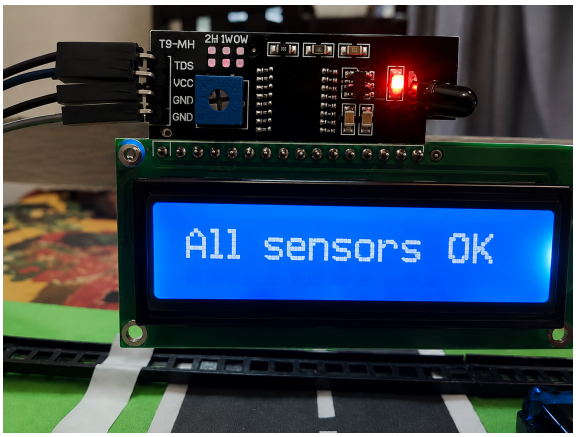


Fig. 3. System Block Diagram

which sensor is not responding and find out the fault and generated an alert message. The four IR sensors were used for different implementation in four different zones . IR1 detected the approaching train, IR2 was used for speed estimation, IR3 detected the train entering the crossing area and IR4 verified the train's exit.

B. Sensor sequence validation

Both normal and abnormal sensor sequences were used to test sensor sequence validation process. During normal train movement, the expected sequence was IR1 → IR2 → IR3 → IR4. If the sensors were activated in this order, the system would continue normal operation. Abnormal sequences were also tested by skipping sensors in an unexpected order. When an unexpected sensor was activated, the system identified the event as a sensor fault and displayed "Sensor Fault" on the LCD. An alert message was also sent via the ESP32 IoT module to the operator.

C. Train speed and ETA Measurement

The train speed was calculated by measuring the time difference between the activation of IR1 and IR2. The calculated speed was used to predict the train's ETA (Estimated Time of Arrival) to the railway crossing. The calculated speed and ETA were displayed on the LCD. The train speed and ETA for eleven test runs were calculated and shown in Table III.

TABLE III
TRAIN SPEED AND ETA RESULTS

Test	IR1 Time (s)	IR2 Time (s)	Calculated Speed (m/s)	Actual Speed (m/s)	ETA (s)
1	0	0.49	0.26	0.26	2.25
2	0	0.52	0.24	0.23	2.39
3	0	0.51	0.25	0.23	2.37
4	0	0.61	0.21	0.19	2.82
5	0	0.66	0.19	0.19	3.05
6	0	0.67	0.19	0.18	3.06
7	0	0.61	0.21	0.18	2.80
8	0	0.67	0.19	0.16	3.09
9	0	0.59	0.21	0.19	2.73
10	0	0.78	0.16	0.15	3.61
11	0	0.56	0.23	0.21	2.57

The calculated ETA values were compared with the actual arrival times for evaluating the estimation error which is shown in Table IV.

TABLE IV
ETA AND ERROR ANALYSIS

Test	Calculated ETA (s)	Actual Arrival Time (s)	Absolute Error (s)	Percentage Error (%)
1	2.25	2.28	0.03	1.32
2	2.39	2.53	0.14	5.53
3	2.37	2.53	0.16	6.32
4	2.82	3.04	0.22	7.24
5	3.05	3.04	0.01	0.33
6	3.06	3.29	0.23	6.99
7	2.80	3.29	0.49	14.89
8	3.09	3.54	0.45	12.71
9	2.73	3.04	0.31	10.20
10	3.61	3.80	0.19	5.00
11	2.57	2.79	0.22	7.89

The ETA estimation achieved an MAE of 0.223 s, RMSE of 0.265 s, maximum error of 0.49 s and mean percentage error of 7.13%.

D. Automatic and Adaptive Gate Control

IR3 detects a train on the tracks. The railway gate is closed by the servo motor. As long as a train is passing the gate is closed,as shown in figure 4. IR3 and IR4 are monitored in the meantime. For a high-speed approaching train, the system will close the gate earlier according to the calculated ETA. For a lower-speed train, the system will delay the closure of the gate for an appropriate time to reduce waiting time.

E. Train Passing and Exit Verification

In the train passing stage, the LCD shows "Train Passing" while the gate is closed. Then, when the train leaves the crossing, IR4 will be triggered. Instead of opening the gate right away after IR4 has been triggered, the system first checks the status of IR3 and IR4. When both IR3 and IR4 are clear, it will then display "Crossing Clear" on the LCD and open the gate. The verification of both IR3 and IR4 helps prevent the gate from opening prematurely.

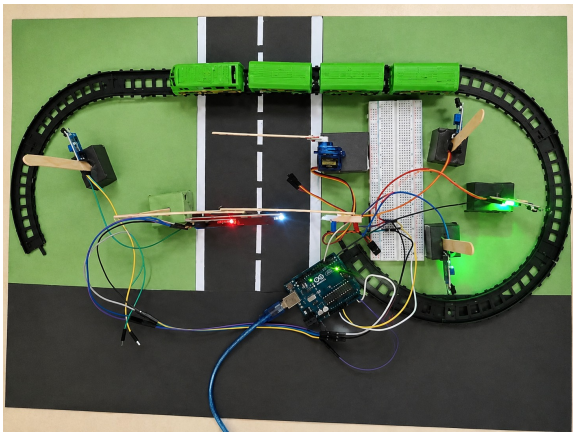


Fig. 4. Closed Gate

F. LCD, LED, and Buzzer Response

The LCD properly indicates the status of the system in all phases of the operation such as System Initializing, Checking Sensors, All Sensors OK, Train Detected, Measuring Speed, Estimating Time of Arrival, Gate Closed, Train Passing through the Crossing, Train exiting the crossing, and Crossing is Clear. The red LED and buzzer are on when train is approaching and the gate is operating, and off when train has completely left the crossing and crossing area is verified to be clear.

G. IoT Notification

For emergency and abnormal situations, the ESP32-based IoT module was tested. It generates an alert message for the operator if a sensor fault has occurred or if the wrong sensor activation sequence has been selected. Thus, in addition to the local display on the LCD as well as the indication via the red LED and buzzer, remote monitoring is also possible via the alert messages.

H. Safety Margin

The ETA is used for early warning and adaptive gate-control support, while direct sensor detection is retained as the primary local safety mechanism. A safety margin is maintained before the expected arrival of the train and the gate is not opened based only on ETA. The required sensor states verify the condition of train exit and the gate remains closed. In case of speed change, missed detection, abnormal sequence of sensors, timeout and communication failure, the system goes to a safe state and generates an alert.

I. Strengths of the Proposed System

The proposed system has many strengths. Firstly, it is based on low cost and simple hardware architecture using IR sensors and Arduino Uno. Second, the multi-zone sensor arrangement allows the train to be detected, its speed estimated, the gate controlled and the exit verified at different locations. Third, the sensor self-test and the sequence validation can help detect abnormal sensor conditions. Fourth, the system estimates

speed and ETA for early warning. Finally, dual-condition exit verification with IR3 and IR4 avoids early gate opening and IoT-based alerts inform the operator of abnormal conditions remotely.

J. Final Discussion

The proposed system successfully executed sensor self-testing before operation, multi-zone train detection, speed and ETA estimation, and sensor sequence validation. The railroad gate was also operated automatically by the system. The safe opening of the gate was verified by IR3 and IR4.

TABLE V
COMPARISON OF PREVIOUS WORK AND OUR PROPOSED SYSTEM

Work	Self-Test	Speed & ETA	Sequence Validation	Safe Exit	IoT/Remote Alert	Main Limitation / Research Gap
Pradheep et al.[1]	No	No	No	Yes	Yes	Only concerned with automatic gate control and IoT notification.
Priyadharshini et al. [2]	No	No	No	Yes	Yes	Includes redundant sensors but does not include speed estimation, ETA calculation, or sensor sequence validation.
Naveenkumar et al.[3]	No	No	No	Yes	No	Focuses on FSM-based gate control but lacks sensor self-testing and speed estimation.
Chowdhury et al.[6]	No	No	No	Yes	No	Mainly focuses on automated gate operation without sensor self-testing or speed estimation.
Naik et al.[7]	No	No	No	Yes	Yes	Contains obstacle detection and real-time tracking, but does not include sensor self-testing and sensor sequence validation.
Mostafa et al.[13]	No	No	No	Yes	Yes (GSM)	Provides GSM communication and gate-status monitoring but lacks speed estimation and sensor validation.
Jothibasu et al.[15]	No	Location detection	No	Yes	Yes	Uses GPS and LoRa for train tracking, requiring additional communication hardware, with no sensor sequence validation.
Our Proposed System	**Yes**	**Yes**	**Yes**	**Yes (IR3 + IR4)**	**Yes**	**Combines sensor self-testing, speed and ETA estimation, sequence validation, and dual-condition safe exit verification into one system.**

In addition, IoT-based alerts were used to inform the operators about sensor faults and abnormal conditions. The results show that the proposed system succeeded in achieving its main objectives and can provide a reliable and effective solution to enhance railroad crossing safety, especially in rural areas.In table V, we represent final comparative analysis of our proposed system and the previous works.

VI. CONCLUSION

The current prototype has been tested in a controlled environment and thus does not fully replicate the real railroad operating conditions. IR sensors are sensitive to sunlight, rain, dust, fog, obstruction, sensor alignment and other environmental factors. The experimental results thus demonstrate the functional feasibility of the system, but not the guaranteed railroad reliability at the field level. Practical railroad deployment will require extensive outdoor and long-term testing.

In the future, the system can be enhanced by adding the feature of computer vision for obstacle detection. A more advanced IoT-based remote monitoring system can also be added. Machine learning can also be used to predict train arrival time and improve automatic gate control. Furthermore, a dedicated mobile application can be developed to provide real-time information about train movement, estimated arrival time and gate status to mobile users in the areas along the train's route.

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