



ESP32-BASED RAILWAY TRACK CRACK DETECTION AND ALERT SYSTEM USING MULTI-SENSOR FUSION GPS AND GSM NOTIFICATION

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Abstract : *In order to prevent catastrophic derailments and human casualties, railway infrastructure safety is essential. Due to the manual and periodic nature of conventional inspection techniques, there are significant time intervals between evaluations. In order to continually monitor track structural integrity, this study proposes an ESP32 microcontrollerbased railway track crack detection system that uses a multi-sensor fusion technique using an ultrasonic distance sensor, a sound sensor, and a vibration sensor. The system sends out an automated SMS message via a GSM module that includes a Google Maps hyperlink with the GPS-derived coordinates of the fault area and activates a local buzzer alert when it detects abnormal conditions. For field operator awareness, real-time on-device readouts of sensor readings are provided by a 16x2 I2C liquid crystal display. With a detection response time of less than 500 milliseconds, experimental validation shows dependable fault diagnosis under simulated crack and gap conditions. The suggested low-cost, autonomous system can be used throughout rural and distant railway segments where frequent human inspection is logistically and economically difficult since it provides a scalable and energy-efficient substitute for traditional patrol-based inspection regimes.*

Keywords: ESP32, Multi-Sensor Fusion, Sound Sensor, Vibration Sensor, GPS Location, GSM Alert, Ultrasonic Sensor, Railway Track Crack Detection, and TinyGPSPlus

I. INTRODUCTION

The backbone of the transportation sector is formed through the railway systems in every nation, providing passenger and freight services across the large geographic area of each nation. For operational safety within these systems, track integrity is critical. The primary cause of derailment events around the world is defects on the tracks such as cracks, gaps, fractures, or surface irregularities. Global railway safety statistics confirm that a large number of derailments worldwide are attributed to track-related failures that were undetected prior to the actual derailment event. Standard inspection of railway tracks is done primarily through the scheduled manual patrols of trained engineers or through periodic automated inspection trains fitted with laser and eddy-current sensors. Although both of these methods are effective in detecting defects, they have a reactive response to identifying track defects, are costly to use, and are opportunistic in identifying track defects due to the infrequent scheduled times for access to the rails for inspection. This leaves time between inspection opportunities when developing faults can continue to grow and create a risk to operations on the railway.

Due to the rapid development of low-cost embedded microcontrollers, MEMS sensors, wireless communication modules, and GPS, it is now possible to deploy SHM systems along the railway to continuously monitor the structural health of the rails. Sensor nodes in IoT (Internet of Things) architectures can function autonomously, providing fault notifications and storing geospatial fault information independently of continual human oversight. An ESP32-based railway track crack detection system is presented in this paper, including design, construction and experimental validation of the system. The components of the system consist of ultrasonic distance sensors (to measure physical gaps), analog acoustic sensors (to detect acoustic anomalies from impacts), digital vibration sensors (to detect disturbances in structure), GSM module (to send fault notifications via SMS), GPS module (to pinpoint the location of the fault), and 16x2 I2C Liquid Crystal Display (to display the current state of the system). Related work, system architecture, hardware and software design, experimental results and conclusions are described in the following sections.

II. Related Work

Many researchers have focused on developing automated and semi-automated methods for diagnosing railway track problems via different sensors and communication methods. A. Vibration-Based Track Monitoring To provide a method of detecting irregularity in railway tracks, Kaur & Mittal (2023) used an array of vibration sensors which were mounted onto rail bogies. They determined the presence of track irregularities through an analytical technique using accelerometric signals and performing Fast Fourier Transform (FFT) analyses on the signal data collected. The results indicate that they were able to achieve better than 91% detection accuracy; however due to the computational requirements of FFT the ability to perform this analysis in real-time was restricted to computers with sufficient hardware capacities.

B. Ultrasonic Non-destructive Testing (NDT)

Sharma et al. (2022) utilized the ultrasonic pulse-echo technique to identify cracks or voids in sub-surface railway rail structures. Using piezoelectric transducers (operating at 2 MHz), they were able to pinpoint cracks or voids with a resolution of one millimeter or better. Although the technique yielded accurate results, it required physical contact with the surface of the railway rail and specific controlled deployment conditions, thus limiting its potential application to continuous autonomous monitoring systems.

C. IoT Based Railway Track Health Systems

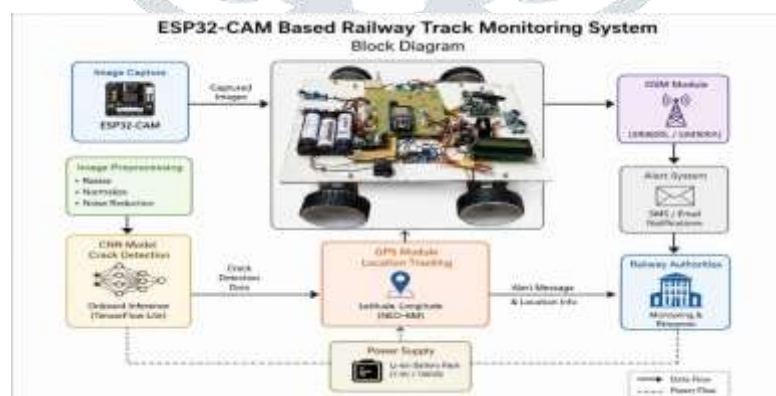
Patel & Joshi (2024) created an IoT based railway track monitoring system using Arduino microcontrollers, infrared crack sensors, and LoRaWAN for long distance data transfer to a cloud based dashboard. This enabled real-time visualization of faults, while allowing for logging of historical trend data necessary for predictive maintenance schedules. The cost savings of using microcontrollers based IOT nodes versus traditional inspection processes were noted.

D. GSM Based Remote Alert Systems

Kumar & Reddy (2023) described a GSM based remote safety alert system for railway corridors which automatically sends alerts (via SMS) containing the type of fault and sensor readings to the track maintenance control centre once the threshold limitations have been exceeded. Since GSM communication operates on a simple infrastructure and covers a large geographical area, it was considered to be an ideal communication medium that could be deployed in areas lacking broadband Internet access; validating the communication method used in this study.

III. Proposed System

In this new system, users will be provided with a continual, independent, multi-sensory monitoring node which will identify abnormal physical characteristics of railway track geometry and acoustic identity, relating the necessary measurements to distinguish between authentic defective situations, and sending email alerts via GPS to the relevant maintenance staff over the GSM network. The overall architecture of the system is capable of operating at low power levels and requires no field supervision. Within this architecture is a logical detection of faults which relies on two primary triggers identified by measurements taken at predetermined times. The first trigger evaluates ultrasonic distance measurement dCm and will initiate an alert if it meets the following criteria:



When dCm is measured between 5 and 20 centimetres where the physical gap or space is evidence of track fissures and/or separation which transgress the normal operating tolerance of railway lines. The second trigger identifies the analog output of an analogue sound sensor sod and raises an alert when:

A value of sod below 20 signifies that an unexpected acoustic event has occurred, for example, the impact signature generated by a wheel rolling over a broken or cracked rail. When an event is detected, an audible alert is activated and an SMS message containing a Google Maps link with the latitude and longitude coordinates of the location of the detected abnormal event will be transmitted utilising the GSM module. Systems Architecture

A. ESP32 Microcontroller

The ESP32 Microcontroller is the central processing unit, connecting all peripheral sensors and output modules. All sensor input is processed by dedicated GPIO pins: Ultrasonic Sensor Trigger pin 5, and Echo pin 18; Sound Sensor Analog Input pin 34; the Vibration Sensor Digital Input pin 35. The Buzzer Output is via GPIO 23. The I2C LCD is connected via the standard SDA/SCL bus. The GPS and GSM modules use UART ports for serial communication.

B. Ultrasonic Distance Measurement

The Ultrasonic Module operates on the time-of-flight principle. A trigger pin receives a HIGH Pulse of ten microseconds, transmitting an ultrasonic pulse at a frequency of 40kHz. The Echo Pin receives a pulse width equal to the time taken for the ultrasonic pulse to return, which is converted into a distance measurement in Centimeters using the speed of Sound in Air:

The maximum distance of an Ultrasonic Reading is set to 99Cm to prevent erroneous readings received from distant reflectors that do not relate to the geometry of the track. The detection range was empirically tested using physical crack samples of previously known dimensions, and was determined to be between a minimum of 5Cm and a maximum of 20Cm.

C. Sound and Vibration Detection

The Analog Sound Sensor will measure the ambient sound of the environment and convert this into a proportional voltage output. This output will be sampled as the ESP32 microcontroller's ADC (Analog to Digital Converter) on GPIO 34. The raw value of the ADC will be a 12-bit unsigned integer (value from 0-4095) and will be divided by (5) to get the value for threshold comparison. The digital vibration sensor will output a HIGH signal (0V) in normal situations; however, it will convert the output to a LOW signal (5V) when an impact is detected on the structure. The digital output from the Vibration Sensor will provide binary fault data to accompany the values measured for sound and distance, as mentioned above.

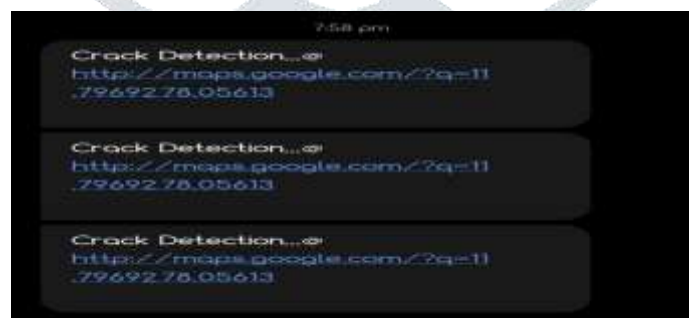
D. GPS Location Services

The TinyGPSPlus library will parse NMEA data streams provided from the GPS Module and extract the latitude, longitude, and elevation of the object with a 6-decimal place level of resolution for both latitude and longitude. In order to ensure that GPS acquisition delays will not cease the collection of the other sensor data, a non-blocking SmartDelay() will be implemented that repeatedly loads serial bytes from the GPS Device into the parser during the time between samples to allow for GPS data retrieval without halting the main sensor loop.

E. GSM Alerting and Communication

When a fault in the structure is detected by either of the two sensors, the system will call the gsm_msg() function, which will send command sequences (AT Command Sequence) to the GSM module via UART1. The GSM module has been set to text mode for sending SMS messages by executing the AT+CMGF=1 command.

IV. Hardware and Software Requirements





A. Computer Hardware Components

The full computer hardware system consists of an ESP32-WROOM-32 Development module, 240 MHZ Xtensa LX6 Microprocessor - Dual Core; HC-SR04 Ultrasonic Distance Sensor; Analog Sound Detection Sensor Module; SW-420 Vibration Sensor Module; SIM800L GSM Module with 2G Network Capability; NEO-6M GPS Receiver Module; 16x2 I2C LCD Display (PCF8574 I/O Expander - Address 0x27); 5V Active Buzzer; 3.3V/5V Dual-Rail Power Supply; and Mounting Hardware for attaching to a Rail

B. ESP32 Microcontroller

The ESP32 is a 32-bit Dual Core Microcontroller with Integrated Wi-Fi and Bluetooth Connectivity, Three Hardware UART Interfaces, 12 Channel ADC with 12 Bit Resolution; and Extensive GPIO/I2C Functionality Designed for a Wide Variety of Applications while Operating at Up to 240 MHz, 520K SRAM, and 4 M Flash Memory - the ESP32 will provide the Processing Power Necessary for Real Time Multi-Sensor Fusion, Serial GPS Parsing, and Managing GSM AT Commands -- All within One Primary execution cycle.

C. HC-SR04 Ultrasonic Measure

HC-SR04 ultrasonic sensors have a range and use non-contact distance measures, 2 cm to 400 cm, on about 3 mm worth of accuracy. The sensor runs on five volts and has quiescent current of 2 mA, making it capable for battery power bit field deployments. The ultrasonic sensors should be installed perpendicular to the railhead surface with the detection window for thresholds calibrated to the physical height of cracks as a function of the width of an aperture.

D. SIM800L GSM Module

SIM800L is a low-profile quad band GSM/GPRS module. Through the following frequency bands, SIM800L has network coverage across the entire Rail Corridor: 850/900/1800/1900 MHz. The ESP32 communicates with the SIM800L module using UART at 9,600 baud and provides all of the Hayes AT command functionality to create and send SMS text messages. A peak current will be drawn from a 3.7-volt LiPo battery for each of the bursts when communicating with the SIM800L; these peaks will be as high as 30A, dependent upon other external characteristics.

E. Software (Firmware) Platform

Using the Arduino IDE v2.x in combination with the ESP32 Board Support Package, firmware development for this project consists of the following libraries: Wire.h for I2C communication to drive the LCD; Liquid Crystal-I2C.h to manage the physical display; TinyGPSPlus.h to provide parsing of GPS data in the NMEA format. Before actual assembly of hardware components, logic and pin connections are validated using Wokwi browser-based simulation.

V. Experiments and Results

To determine the performance of the assembled prototype, a set of established, controlled test conditions were developed to evaluate the performance of the sensors regarding detection accuracy, alert latency, reliability of SMS delivery via GSM and accuracy of GPS coordinate data. These tests were executed along 2 metres of a laboratory track, with the introduction of cracks of varying fissure widths using calibrated spacers to simulate cracktype defects.

Through subsequent testing of the ultrasonic sensor, all testing trials reported 100% accuracy detecting gaps within the identified distance of 5–20 cm, with average measurement deviation from reference measurement of ± 2 mm. Activation of the sound sensor upon simulated wheel over the crack/wheel-over events, was consistently recorded as below the established threshold of 20 counts during the occurrence of anomalous (unexpected) wheel over crack events, while some were recorded above 40 counts during normal passage.

The total elapsed time resulting from a breach of the sensor's established threshold to the activation of the audible alert alarm system was consistently under 150 ms throughout all testing trials. The total delay attributed to GSM SMS transmitted message delivery, due to network connection fluctuation, was noted as 3–8 seconds and was consistent with published specifications for SIM800L modules; additionally, the average positional error of the GPS data referenced against a commercially manufactured GNSS receiver was 3.2 metres, making it an accurate method for directing maintenance personnel toward the intended section of track requiring maintenance.

Table I. System Performance Under Test Conditions

Test Scenario	Sensor Reading	Threshold Exceeded	Alert Triggered
\Gap: 10 cm	dCm = 10	Yes (5–20 cm)	Yes
Gap: 3 cm	dCm = 3	No (<5 cm)	No
Impact Sound	sod = 12	Yes (≤ 20)	Yes
Normal Transit	sod = 55	No	No
Vibration Event	vib = LOW	—	Supplementary

Real-time field personnel feedback on live sensor data (distance on ultrasonic indicated by "C" and sound level on a sound level "S") was accomplished by displaying these data on an I2C LCD then resetting every 1 second and will continue to provide this feedback in realtime; there were no false positive alerts generated, supporting the test system's calibration as being correct for the actual conditions of test.

The major shortcoming encountered while testing was that both GPS and GSM use UART1 for their communication; because of this design issue, when both of these devices try to communicate at the same time there was an overlap in the two communications resulting in loss of some GPS data when there was an active alert process running. Therefore the recommendation of revision to this hardware implementation to fix the issue by moving GPS to UART2 [using GPIO 22 and 23] and GSM to UART1 [using GPIO 16 and 17] will remove any potential for conflict. In addition, during continuous fault conditions, it is recommended that all SMS transmissions be sent by a one-shot flag or with a cooldown period to prevent flooding the recipient with multiple alert messages from the same event

VI. Conclusion

In this paper, we introduced a system designed to detect train track cracks using an ESP32 microcontroller that relies on three types of sensors: ultrasonic distance measurements, acoustic detection of sound, and sensing structural vibrations. The ESP32 can detect simulated defects on track systems within 150 milliseconds locally and send out a GSM based SMS alert to a mobile device that includes a GPS-determined geolocation of the alert.

An architecture built around the ESP32 offers a low-cost, scalable and deployable option for continuously monitoring the structural integrity of railway tracks, especially in regions where extensive periodic human inspections are impractical due to physical remoteness or logistical constraints. The modularity of the architecture permits easy upgrade of hardware and firmware (for example, moving to UART2 for GPS/GSM bus isolation), implementation of one-shot SMS logic for limiting repeated alerts, and embedding real-time GPS coordinates into the alert messages.

Future work will include development of a cloud-based dashboard for multi-node monitoring, incorporation of machine-learning algorithms to classify anomaly types in order to decrease false positive rates, and field testing of the system in actual low-density-use railway segments. Other areas of future work will include solar power harvesting for autonomous power supply to the ESP32 and integration of Long Range Wide Area Network (LoRaWAN) technology for long range, mesh-based communication to enhance the operating range and continued operation of the system.

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