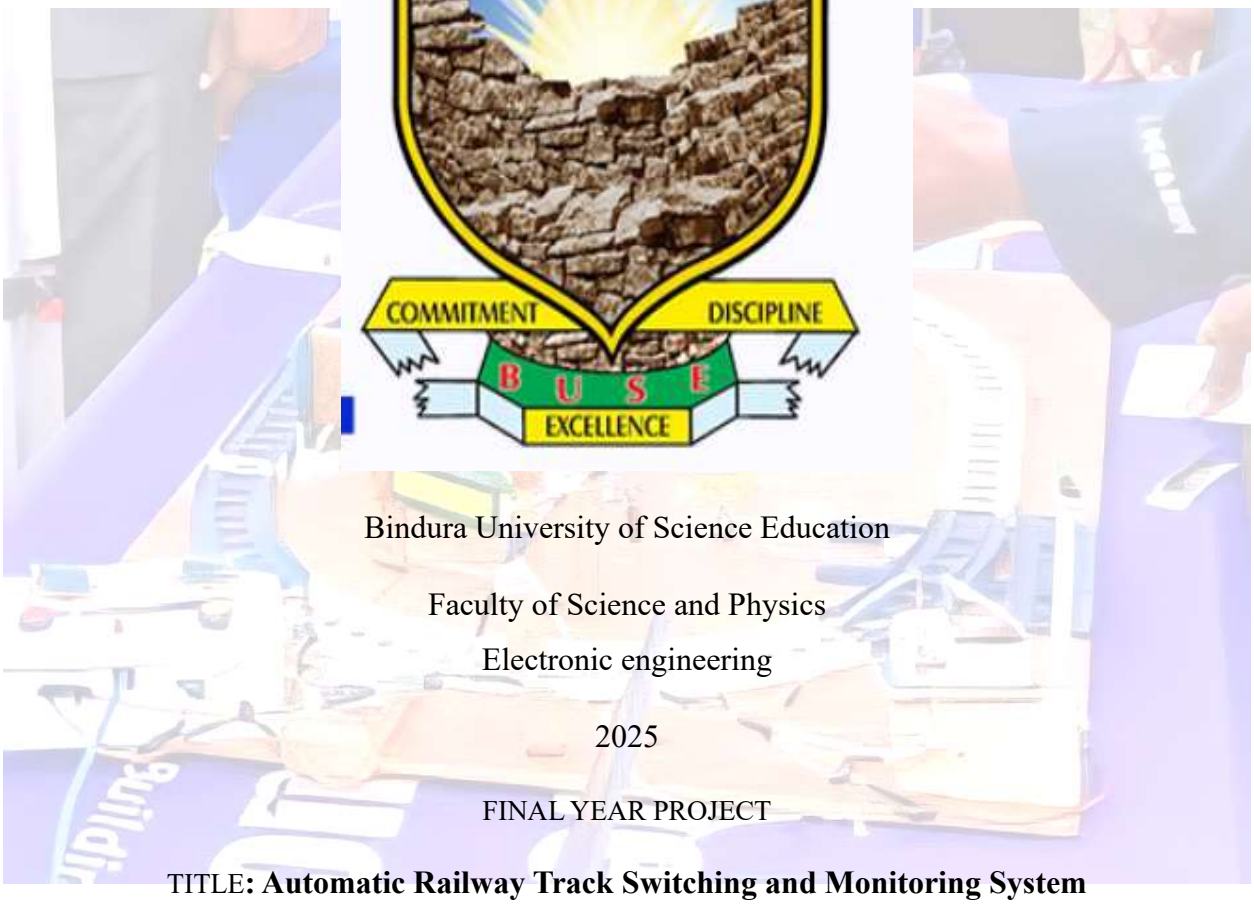

Bindura University of Science Education

Faculty of Science and Physics

Electronic engineering

2025

FINAL YEAR PROJECT

TITLE**: Automatic Railway Track Switching and Monitoring System**

BY: NGONIDZASHE MUHLANGA

REGISTRATION NUMBER: B221627B

COURSE CODE: EEE5000

PROJECT SUPERVISOR: ENGINEER M TAKAWIRA

A project work submitted in fulfillment of the Bachelor of Science (BSc) in Electronic Engineering as a requirement of the final year project.

Declarations

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Declarations

I hereby certify that the work which is being presented in the project **Automatic Railway Track Switching and Monitoring System** in the partial fulfillment of the requirements for the award of the degree of BACHELOR OF SCIENCE and submitted in the DEPARTMENT OF ELECTRONIC ENGINEERING, BINDURA UNIVERSITY OF SCIENCE EDUCATION, is an authentic record of my own work carried out during the time period from **2022 of joining the EE program to 2026 of project submission** under the supervision of **Engineer M Takawira, Electronic engineering department.**

The matter presented in this project has not been submitted by me for the award of any other degree of this or any other institute.

STUDENT NAME: **NGONIDZASHE MUHLANGA**

DATE OF SUBMISSION 24 JUNE 2026 SIGNATURE Muhlanga

This is to certify that the above statement made by the candidate is correct to the best of my/our knowledge.

SUPERVISOR NAME: **ENGINEER M TAKAWIRA**

DATE OF SUBMISSION 29 JUNE 2026 SIGNATURE

Dedication

I dedicate this project to my beloved family for their unwavering love, support and encouragement throughout my academic journey. To my parents, whose sacrifices have made my education possible and to my friends for their constant motivation.

This work is also dedicated to the hardworking men and women of the National Railways of Zimbabwe (NRZ), who continue to serve the nation despite numerous challenges. May this project contribute in a small way toward improving railway safety and efficiency in Zimbabwe.



Acknowledgement

I would like to express my sincere gratitude to the Almighty God for granting me good health, strength and wisdom throughout the completion of this project.

I am deeply grateful to my supervisor, **Engineer M. Takawira**, for his invaluable guidance, constructive criticism, technical insight and continuous support from the beginning to the end of this project. His expertise and patience have greatly shaped the quality of this work.

Special thanks go to the entire staff of the Department of Electronic Engineering at Bindura University of Science Education, particularly the lecturers and technicians who provided me with the necessary resources and assistance during the development and testing of the prototype.

I would also like to thank my family for their endless love, prayers and encouragement. Their belief in me has been a constant source of strength.

Finally, I extend my appreciation to my fellow final-year students and friends for their moral support, ideas and willingness to assist whenever needed.

Thank you all.

Ngonidzashe Muhlanga

June 2026

Abstract

A compact, low-cost prototype for automated railway turnout control and condition monitoring is presented. The system uses two ESP32 controllers: a trackside unit that performs RFID identification, servo-driven point actuation, vibration-based tamper detection, and event-triggered image capture and a control-room unit that provides operator displays, manual override, GSM/SMS event reporting, and logging. Secure UART messaging with checksum validation links the nodes and a usage-based estimator tracks actuator life. Laboratory tests under controlled conditions showed reliable RFID detection, average servo actuation below one second, effective vibration alerting, and robust soft-switching between automatic and manual modes. The prototype targets affordable, scalable upgrades for resource-constrained rail networks.

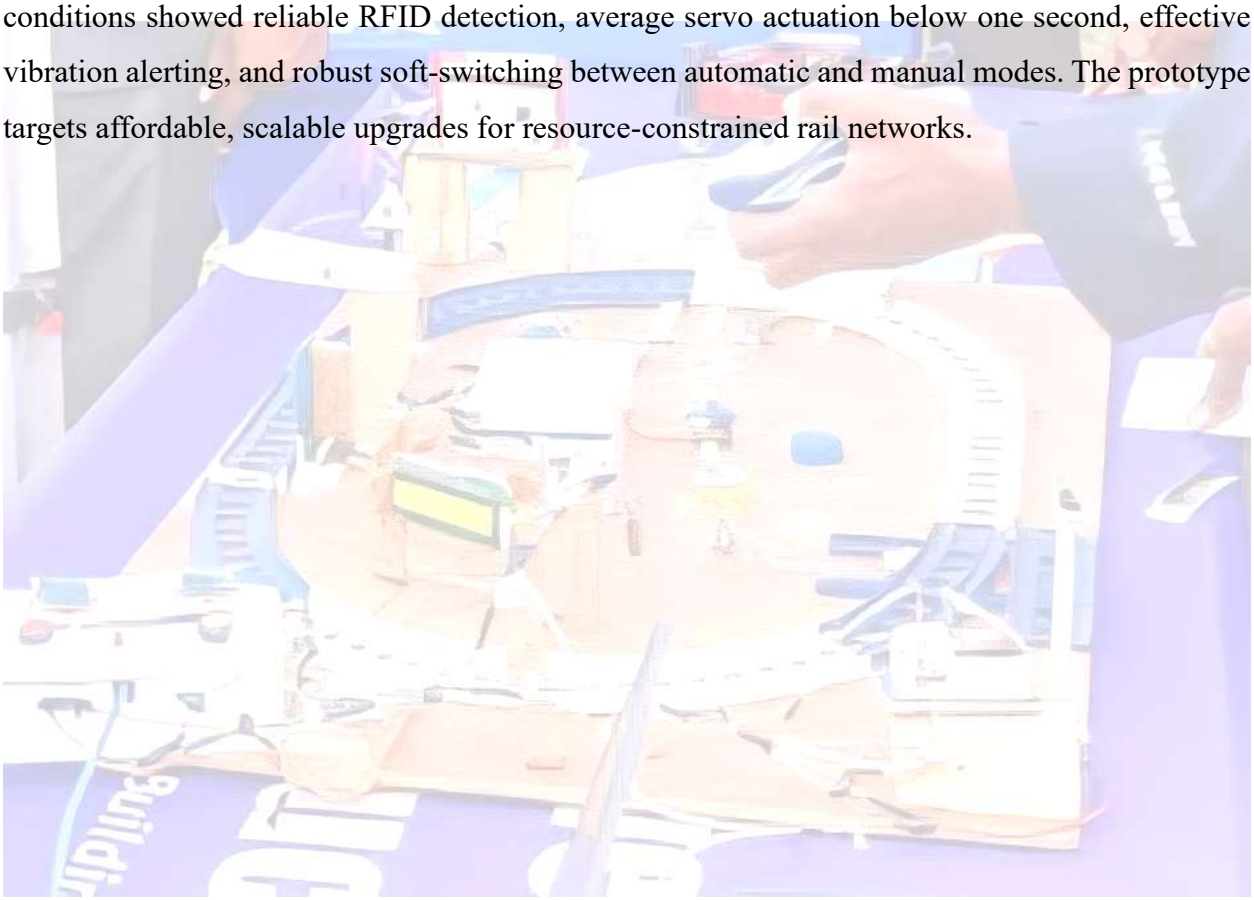

Table of abbreviations

Table 1.1: Table of abbreviations

ABBREVIATIONS	EXPANDED FORM
ESP32	Espressif Systems 32-bit MCU
RFID	Radio Frequency Identification
UART	Universal Asynchronous Receiver-Transmitter
OLED	Organic Light-Emitting Diode
IoT	Internet of Things
SMTP	Simple Mail Transfer Protocol
Wi-Fi	Wireless Fidelity
GPIO	General Purpose Input/Output
PWM	Pulse Width Modulation
HMI	Human-Machine Interface
OTA	Over-The-Air Updates
GSM	Global System for Mobile Communication
SMS	Short Message Service
MCU	Microcontroller Unit
ADC	Analog-to-Digital Converter
SPI	Serial Peripheral Interface
I²C	Inter-Integrated Circuit
DOF	Degrees of Freedom
AES	Advanced Encryption Standard

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1. Chapter 1: Introduction

1.1 Background

Railway transportation remains a cornerstone of national infrastructure, enabling the large-scale movement of freight and passengers from one point to the other. In Zimbabwe, the railway network is particularly vital for sustaining macroeconomic activity, playing a bigger role in the distribution of mining output, agricultural produce and industrial goods. Despite this reliance, the National Railways of Zimbabwe (NRZ) continues to operate with ageing infrastructure and legacy manual systems, especially in track switching, turnout mechanics and route allocation.

Traditional turnout mechanisms depend on personnel to manually reposition track points, a process that can be slow, labor-intensive and misaligned with the efficiency demands of modern, high-capacity rail networks. Manual systems are prone to serious human error, often aggravated by operator fatigue, poor visibility and maybe communication failures. As highlighted by Olaby et al. (2022), reliance on human-dependent switching introduces operational inconsistencies that can compromise both safety and reliability.

Recent advances in embedded systems, Internet of Things (IoT) architectures and solid-state sensors provide more friendly pathways for rail modernisation. Low-power microcontrollers such as the ESP32 can be integrated with RFID-based train identification, servo-driven mechanical actuation, piezoelectric vibration sensors for tamper detection, and real-time telemetry dashboards. Deploying such intelligent, automated switching frameworks enhances local safety margins, reduces transit delays and eliminates manual points-handling which produces a robust and cost-effective automation solution tailored to resource-constrained environments like Zimbabwe.

1.2 Problem Statement

Railway point control systems that rely exclusively on human intervention are highly susceptible to operational faults, including incorrect routing, incomplete locking of switch rails and delayed responses during emergencies. Such errors often lead to derailments, collisions and significant service disruptions. While human oversight remains important, research shows that manual

intervention frequently introduces delays and inconsistencies when not effectively integrated with automated systems (Zhang, Bai, Song & Dong, 2024).

The seriousness of these challenges is evident in accident statistics. Eliopoulou and Papanikolaou (2007) highlight the persistent risks associated with outdated practices and recent data from ZimNow (2024) reports 54 rail traffic accidents in Zimbabwe during the second quarter of 2024, comprising 47 shunting incidents and 7 mainline accidents. These figures underscore ongoing safety concerns linked to ageing infrastructure and limited automation.

The absence of automated decision-making, real-time monitoring, and intelligent condition assessment further compounds these risks. Current systems lack capabilities for automatic route allocation, predictive maintenance, and tamper detection, leaving critical infrastructure exposed to theft, vandalism, and undetected mechanical deterioration. As a result, railway operations face higher maintenance costs, reduced reliability, and compromised safety standards.

These limitations highlight the urgent need for an integrated, intelligent and cost-effective railway switching framework that reduces dependence on manual point switching while enhancing safety, responsiveness, and operational efficiency. This vision aligns with the soft-switching model proposed by Zhang, Bai, Song and Dong (2024), which advocates seamless coordination between automated control and human oversight.



The wreckage at the scene of the accident near Gwanda in Zimbabwe. (Twitter: SA National Traffic Updates)

Figure 1.1: Derailment Incident

Figure (1.1) shows a Derailment incident caused by a manual switching error (SA National Traffic Updates, 2025).

1.3 Aim

To design and prototype an automatic railway track switching and monitoring system that integrates RFID-based train identification, servo-driven actuation, tamper detection and real-time monitoring for improved safety and efficiency.

1.4 Objectives

1. Implement a servo-based mechanism to actuate turnout points automatically.
2. Create an RFID-driven identification and route assignment for trains.
3. Provide a local control-room interface and a remote dashboard for real-time status and alerts.
4. Integrate tamper detection with a usage-based predictive maintenance routine to monitor actuator performance and reliability.

1.5 Scope

This project focuses on the development of a functional prototype of an automatic railway management system. The system integrates two ESP32 micro-controllers, MFRC522 RFID modules for train detection, SG90 servo motors for track switching, piezoelectric vibration sensors for tamper detection, and an ESP32-CAM module for visual surveillance. A local control-room interface is implemented using dual OLED displays, push-button controls, text commands controls and buzzer alerts, while a remote web dashboard provides real-time monitoring.

The prototype is developed and tested under laboratory conditions to evaluate performance, response time, and reliability. The predictive maintenance model is limited to usage-based cycle counting for servo actuators.

1.6 Significance of the Study

This project advances railway safety and operational efficiency by minimising reliance on manual switching procedures. The proposed framework delivers a low-cost, scalable, and

context-appropriate solution tailored to the National Railways of Zimbabwe (NRZ) and comparable networks in other developing regions. By integrating RFID, IoT, and embedded systems, the design addresses real-world engineering challenges while aligning with Zimbabwe's Education 5.0 philosophy of innovation and industrialisation. Furthermore, the incorporation of a soft-switching framework (Zhang, Bai, Song & Dong, 2024) ensures that human operators retain the ability to safely override automated processes when necessary, thereby balancing technological autonomy with essential human oversight.

1.6.1 Novel Contributions of the Study

This project introduces a unified automation framework that integrates:

- ✓ RFID-based train identification
- ✓ Servo-driven switching
- ✓ Vibration-based tamper detection
- ✓ IoT-enabled remote monitoring
- ✓ A usage-based predictive maintenance model
- ✓ A soft-switching manual override mechanism

Unlike conventional systems that concentrate solely on automatic switching, this design integrates real-time monitoring, security safeguards, and predictive maintenance within a single embedded platform, specifically tailored for resource-constrained environments such as the NRZ.

1.7 Chapter Summary

The motivation behind developing an automated railway track switching and monitoring system has been summarized in this chapter. It pointed out that manual switching in the NRZ was not suitable, that there were increasing accidents on the railways and the low-cost intelligent automation was needed. The chapter also stated the purpose, objectives, scope and significance of the study which will act as the basis of the following chapters.

2 Chapter 2: Literature Review

2.1 Introduction

The empirical works and theoretical background of the design for automatic railway track switching and condition monitoring system are summarized in this chapter. The section summarises several different strategies of switch actuation, sensor technologies and their pros and cons and predictive maintenance paradigms, actuation and simulation for S&C, secure communication techniques and representative implementations of sensor integrated railway systems. The review is comprised of peer reviewed research and technical reports using recent case studies to cover the well-known principles, limitations in practice and improvement areas that may need to be covered by current project.

2.2 Theoretical Background

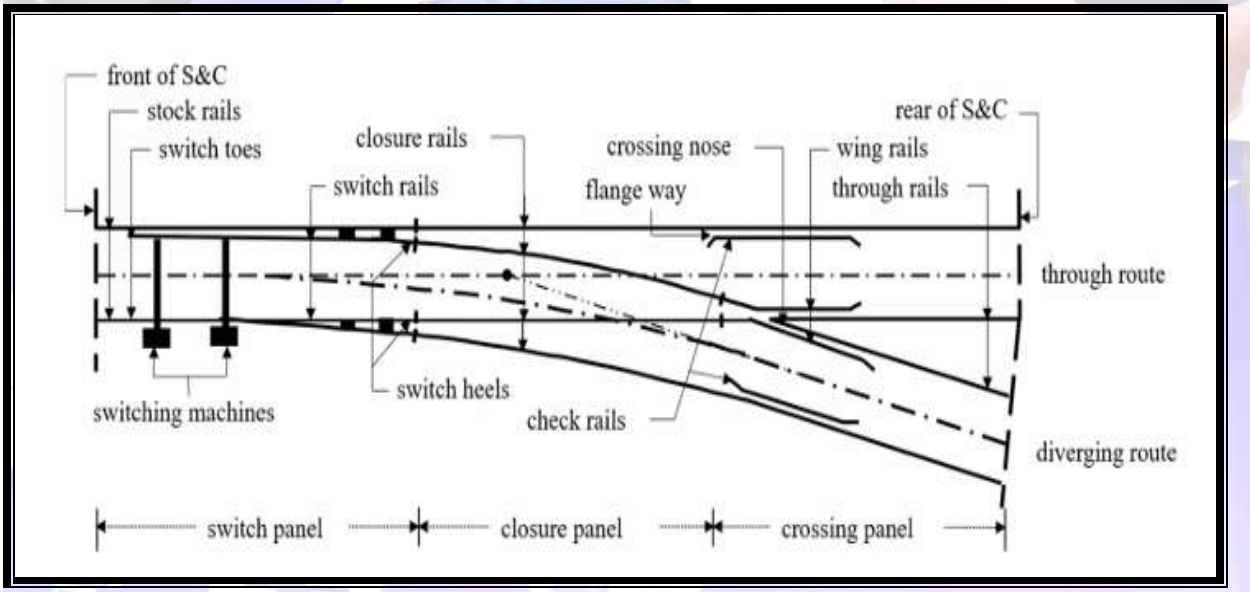


Figure 2.1: Standard Railway Turnout

Figure (2.1) depicts Layout and components and nomenclature for a standard railway turnout. (Source: Bezin and Pålsson 2023) Control systems theory, sensor technology, embedded systems and communication protocols are the fundamentals of railway automation. This section reviews the principles and compares the primary sensor and component technologies described in the literature.

2.1.1 Control of track switching

Track switching control integrates accurate actuation with efficient decision analysis. Commonly applied actuators are servo motors and linear actuators, with their drive usually based on PWM signals. The relationship between servo angular position and PWM duty cycle can be modelled using a linear approximation on a servo's range:

$$\boldsymbol{\theta = k\,D}$$

Equation 2.1: Servo Angular Position

From equation (2.1), $\boldsymbol{\theta}$ denotes the servo angular position (degrees), $\boldsymbol{D}$ is the PWM duty cycle (percentage), and $\boldsymbol{k}$ is a proportional constant calculated empirically for the servo. This linear model is a realistic control approximation for hobby class servos like SG90 that would cost less to model (Olaby et al., 2022).

Smooth and consistent motion can be achieved through incremental position changes combined with controlled acceleration and deceleration profiles, which minimise mechanical shocks and overshoot (Olaby et al., 2022). In embedded implementations, reliable actuation is maintained by applying these incremental updates with carefully regulated acceleration and deceleration, thereby reducing mechanical stress and preventing overshoot (Olaby et al., 2022). To manage switching operations, control architectures frequently adopt either a state-machine structure or a cascaded controller arrangement. Building on this, Zhang, Bai, Song and Dong (2024) propose a soft-switching framework that enables seamless transitions between automated and human-assisted modes, effectively combining autonomous decision-making with operator override to enhance safety.

Zhang, Bai, Song & Dong. (2024) are introducing a soft switching framework, where automatic and human assisted modes can switch seamlessly and integrated, so that the automated decision-making with the operator override is implemented safely. Sensor and actuator interfacing still requires basic electrical relationships. For current limiting and sensor conditioning, we apply Ohm's law:

$$V = I \cdot R$$

Equation 2.2: Ohm's Law

From equation (2.2 above) (V) is voltage, (I) current, and (R) resistance. Technical works include those that incorporate series resistors, current-limited circuits and decoupling capacitors to shield microcontrollers and sensors from transient loads.

Sensor fusion combining RFID, vibration sensing and camera data improves decision accuracy and fault tolerance by providing complementary detection and verification modalities (Olaby et al., 2022; Qing et al., 2019).

2.2 Sensor Technologies and Component Comparison in Railway Systems

Data can be found in Table 2.1 for key sensor and component technologies found in the literature and typical railway automation applications.

Table 2.1: Comparison of sensor technologies used in railway automation systems

Sensor / Component	**Common Alternatives**	**Advantages Highlighted in Literature**	**Limitations Noted in Literature**	**Typical Applications**
RFID (HF 13.56 MHz)	IR, Ultrasonic, Magnetic	Unique identification, non-contact, reliable in harsh environments	Limited reading range, affected by metal	Train detection & and identification
Piezoelectric Vibration	Accelerometer, Strain Gauge	Passive, high sensitivity to impacts/tampering, low power	Requires filtering and signal conditioning	Anti-theft and anti-tamper monitoring
Infrared (IR)	Ultrasonic, Laser	Low cost, fast response	Affected by dust, sunlight and weather	Basic train presence detection

Ultrasonic	IR, Microwave	Good for distance measurement	Poor performance in rain, wind or dust	Obstacle and level crossing monitoring
ESP32 Microcontroller	Arduino Uno, Raspberry Pi	Built-in Wi-Fi, dual-core, rich peripherals, low cost	Relatively higher power consumption	IoT-based railway monitoring systems
ESP32-CAM	Raspberry Pi Camera, USB Camera	Integrated wireless, SD card support, and cost-effective	Moderate image quality in low light	Visual surveillance and timed image capture

2.2.1.1 Key observations from the literature:

- RFID operating at HF 13.56 MHz provides unique identification and non-line-of-sight detection, making it an effective solution for train recognition and route allocation. Its application is constrained by limited read range and susceptibility to interference in metallic environments (Olaby et al., 2022).
- The piezoelectric vibration sensors have proven to be satisfactory for tamper detections and monitoring structural health due to high sensitivity and low power consumption, but they need signal conditioning and filtering to separate relevant events from background noise (Qing et al., 2019).
- Infrared and ultrasonic sensors are cheap and fast for presence detection, however they suffer from environmental interference (dust, sunlight, rain).
- Low cost ESP32 microcontrollers paired with integrated Wi Fi, allow good processing capability for embedded IoT applications (Hercog et al., 2023; Annavarapu, 2025), but require proper power management in field deployments.
- Cost effective but weak in low light compared to premium cameras, ESP32 CAM modules provide a great solution for visual verification.

Literature shows a trend of hybridization IoT architectures which is low risk where RFID is used for identification, piezoelectric sensor for security, and camera for visual confirmation (Olaby et al., 2022; Qing et al., 2019; Hercog et al., 2023).

2.2.2 Predictive maintenance approaches

Predictive maintenance approaches for switch actuation vary from physics to data based statistical approach. Papa et al. (2020) state that frequent monitoring and statistical characterisation on actuator current and displacement allows for early identification of anomalous behavior and their MANTIS project stresses the relevance of seasonal models because switch behavior will be affected by temperature. An alternative for embedded systems is to assess actuator wear with cumulative cycle counts, a simpler and more convenient tool for the estimation of component health:

$$\text{Health}(\%) = 100 \times \left(1 - \frac{\text{Count}}{\text{MaxCount}}\right)$$

Equation 2.3: Usage-based predictive maintenance

The Count is the number of switching cycles performed in use and MaxCount is either manufacturer's or empirically determined maximum suitable ones (Papa et al., 2020; Hu et al., 2023) from Equation (2.3). This is a low computational cost model that can be a useful guideline for maintenance thresholds to field technicians. However, the literature suggests that use of solely models should be augmented with environmental and electrical indicators (temperature, humidity, current profiles) to limit false positives and compensate for seasonality in the model (Papa et al., 2020; Peinado Gonzalo et al., 2022).

Although the usage-based cycle counting methodology reported in Equation 2.3 is a computationally economical model that can be quickly implemented in low-cost microcontrollers, the process of electromechanical wear and failure tends to follow a non-linear pattern rather than a simple linear progression. This base layer cycle model would be further supplemented by active current profile signature assessment in an industrial field scenario. The ESP32 can read the peak inrush and running current during turnout travel by introducing a low-side shunt resistor or a non-invasive current transducer on the actuator power rail. Any structural obstruction caused by the

metal, ballast intrusion or mechanical stiffening of switch rail tongue will immediately cause the current draw to increase. This occurs due to greater motor load. Combining cycle lifetime decay with monitoring its current profile in real time provides a dual-metric predictive maintenance framework that greatly reduces false positive readings due to seasonal environmental factors in the system.

2.2.3 Track modelling and simulation

Switches and crossings, S&C, are imperative to meet the requirements of high-fidelity modeling in order to test actuator performance and control algorithms. Li et al., the authors of this paper, (2020), and Dutta et al. (2024), have demonstrated that switch blades are able to be simulated in finite element (FE) methods as well as actuator and control system models constructed in MATLAB/Simulink. The FE rail model employed with six DOF nodes using Timoshenko beam components had an error not exceeding about 4% from the analytical solution. The simulation time was close to real time (1.2s for simulating 1s vs few hours/secs for co-simulation). The REPOINT switch simulation twin also revealed that redundant actuation (three actuators) can complete switching operations with settling times below 4s and motor currents below 20A and phase and gain margins exceeding the requirement in considerable detail. These modelling approaches provide important information for the validation of a servo-based prototype and also enable mechanical design and control system tuning.

2.2.4 Actuation technologies for switches and crossings

Olaby et al. (2020) report a number of novel mechatronic systems developed within the S CODE project:

Table 2.2:Switch and crossing operation technologies

Condition Monitoring Actuators	combine displacement and current sensors to observe problems with switch performance.
Fault Tolerant Control (FTC)	closed loop architectures to accommodate sensor faults while maintaining safe operation.

High-Redundancy Actuators (HRA)	Several small actuators operate together in parallel or series, ensuring the system continues to function even if one unit fails.
Maglev Actuators	The electromagnetic actuation is contactless and eliminates mechanical wear to extend service life.
New Locking Ideas	Magnetorheological fluid dampers provide can secure locking capabilities while allowing adaptive adjustment to changing conditions.

Though these technologies could represent radical innovation, their cost and complexity restrict their application in resource-constrained settings. This project uses SG90 servo motors for cost-effectiveness purposes but does so with fault tolerance (with manual override) and predictive maintenance (cycle counting) applied for the same goals.

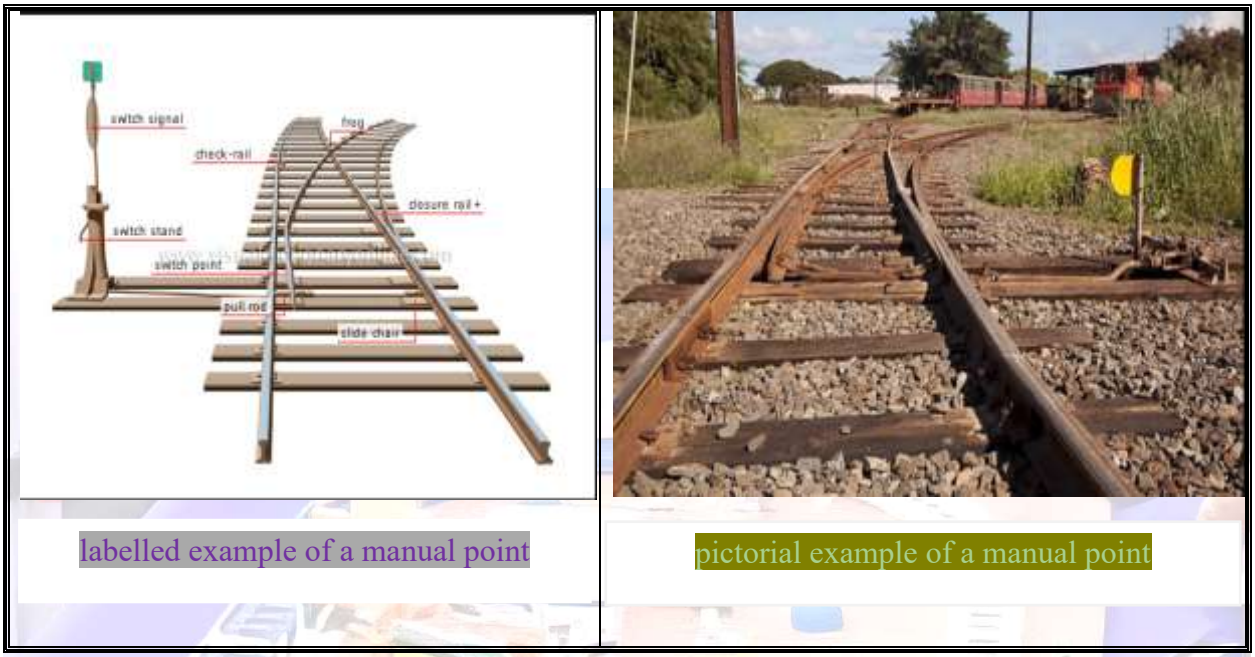
2.2.5 Railway switching through secure communication

Nanda et al. (2020) has proposed a secure GPS/RF based switching system using AES 128 encryption. They used GPS modules to position trains and RF transceivers for communication, with AES keys to prevent cyber-attacks against their data. AES was selected for its better transfer throughput and reduced CPU consumption compared to DES, 3DES, Blowfish and RC4. This, by contrast, implements UART between trackside and control room ESP32 units and validates every token in the data for integrity. Data packets with inconsistent checksums are rejected and retransmitted at the next scheduled cycle. Though full AES encryption is nowhere in sight, those responsible for secure communication and protection from unauthorised access still apply. Potential extensions may incorporate AES or TLS-based protocols on the wireless multi node deployments.

2.3 Review of Related Systems / Technologies

2.3.1 Manual switching and its limitations

2.3.1.1 Manual Railway Point Operation



labelled example of a manual point

pictorial example of a manual point

Figure 2.2: Manual Railway Points

Figure (2.2) shows a typical lever-operated railway point mechanism and associated fittings used in conventional railway switching operations.

Manual railway switching systems depend heavily on human operators to physically reposition turnout points using lever mechanisms or mechanical linkages. Although such systems are relatively simple and inexpensive, they impose significant operational constraints, including slow response times, susceptibility to human error, inconsistent switching accuracy and heightened derailment risk (Matias & Ferreira, 2020). In many developing railway networks, including the NRZ, manual switching remains prevalent due to ageing infrastructure and limited investment in modern automation technologies. These shortcomings underscore the need for automated turnout actuation systems designed to enhance operational safety, improve switching precision and accelerate response efficiency.

2.3.1.2 Manual point maintenance

Routine maintenance of manual railway points is labor-intensive and follows scheduled inspection and corrective maintenance procedures to maintain safe operation.

Routine Activities

- Daily and weekly inspections involve checking switch-rail alignment, locking integrity, fastenings and rail wear.
- Monthly maintenance includes lubrication, tightening fittings, measuring gauge and switch throw and recording wear measurements.
- Corrective maintenance includes ballast repacking, replacement of worn rails or sleepers and repair of damaged fittings.
- Most maintenance tasks are performed manually using hand tools and basic mechanical equipment.

Record Keeping and Quality Control

Maintenance activities depend on inspection logs, wear records, and maintenance registers for tracking component deterioration and scheduling preventive interventions (Papa et al., 2020; Matias & Ferreira, 2020).

Major Challenges

The NRZ maintenance environment is constrained by several systemic challenges:

- Ageing infrastructure and deferred maintenance
- Inadequate funding and persistent resource shortages
- Theft and vandalism of critical railway equipment
- Shortage of skilled personnel
- Restricted maintenance windows caused by operational demands

Collectively, these limitations foster reactive maintenance practices that heighten the risk of turnout failures and derailments (Peinado Gonzalo et al., 2022; Hu et al., 2023).

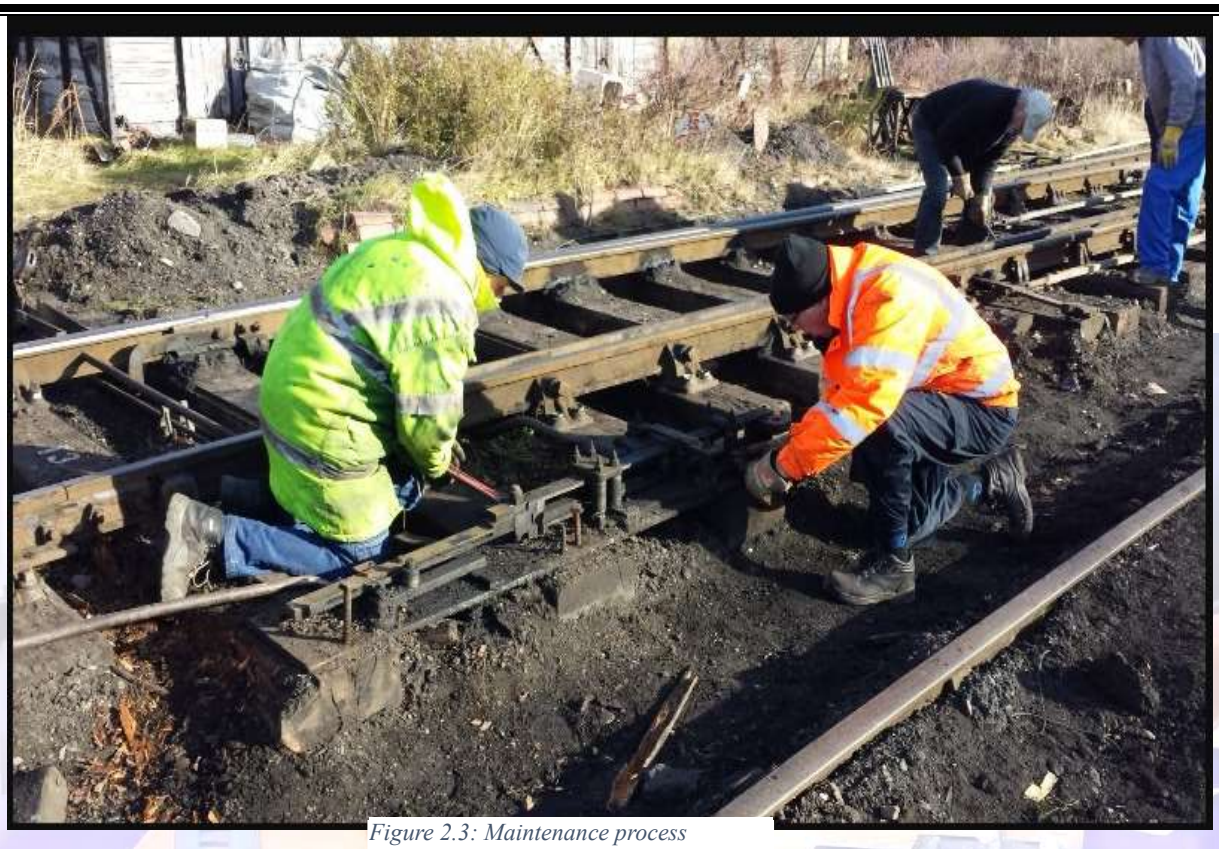


Figure 2.3: Maintenance process

Figure (2.3) shows a photograph illustration of common maintenance tasks: greasing slide chairs, measuring gauge and tightening fastenings

In summary, manual railway switching systems are labor-dependent, inefficient and difficult to maintain consistently, creating the need for automated railway switching and monitoring technologies.

2.3.2 Servo-Based Railway Point Actuation Systems

(Objective 1: Automatic turnout actuation)

Servo-based actuation systems are increasingly used in railway automation because they provide accurate angular positioning, low power consumption and simplified control using Pulse Width Modulation (PWM) signals. Compared with traditional DC motor systems, servo motors offer

improved positional control without requiring complex feedback mechanisms (Olaby et al., 2022). Research by Zhang, Bai, Song & Dong. (2024) demonstrated that soft-switching frameworks combining automatic and manual control improve railway safety by allowing seamless transitions between autonomous operation and operator intervention. Similarly, Li et al. (2020) and Dutta et al. (2024) showed through simulation studies that accurate turnout alignment and controlled actuator motion are essential for reliable railway switching operations. Modern railway actuation technologies include:

- servo-based actuation
- fault-tolerant actuator systems
- redundant actuator architectures
- maglev-based switching mechanisms
- intelligent locking systems

Although advanced actuation technologies provide improved reliability, their cost and implementation complexity limit adoption in resource-constrained railway environments. Consequently, low-cost servo-based actuation systems remain suitable for embedded railway automation prototypes.

The present project adopts SG90 servo motors because they provide:

- precise angular positioning
- low-cost implementation
- simplified PWM control
- compact embedded integration

2.3.3 RFID-Based Train Identification and Routing Systems

(Objective 2: RFID-based identification and routing)

Sensor-based railway automation systems commonly employ infrared, ultrasonic and magnetic sensors for train detection. While these devices are effective for identifying object presence, they lack the ability to uniquely distinguish individual rolling stock. RFID technology addresses this limitation by assigning unique identifiers to locomotives and wagons, thereby enabling automatic route allocation and intelligent switching decisions (Olaby et al., 2022; Li et al., 2020).

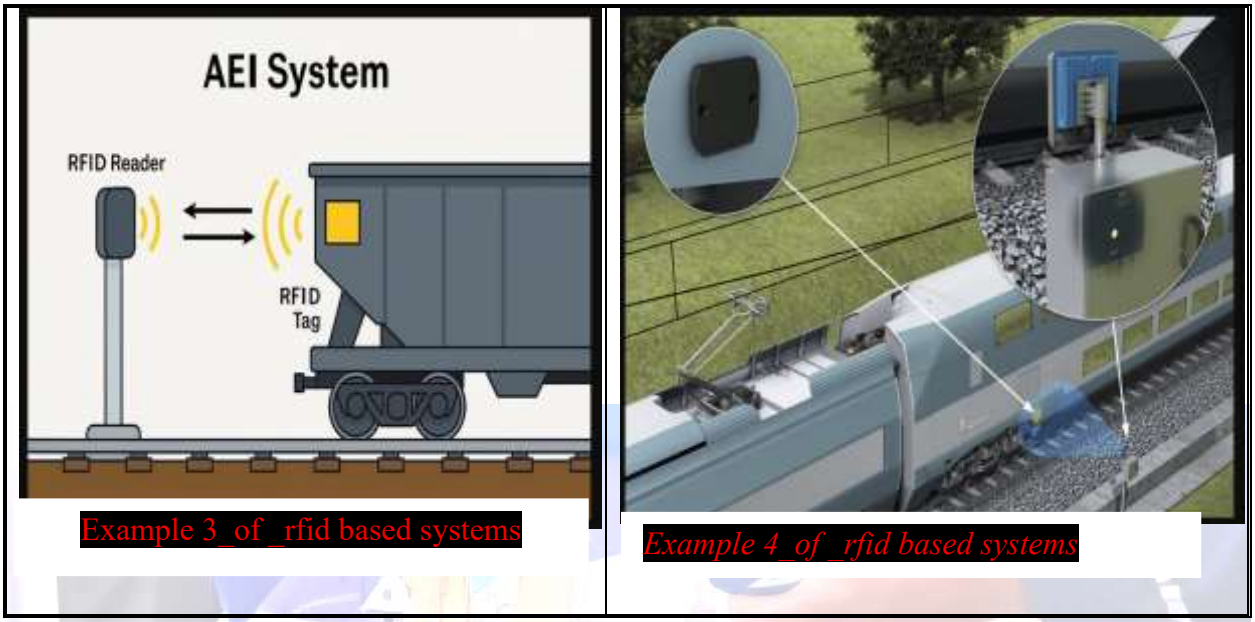


Figure 2.4: RFID-based systems

Figure 2.5 illustrates representative examples of RFID-based railway automation systems employed for train identification, tracking, and route management. In these systems, RFID tags affixed to locomotives or railway assets communicate wirelessly with readers strategically positioned along the track. As a train approaches a reader, the unique identification data stored within the tag is transmitted to the control unit, where it is processed to support automated routing and monitoring functions.

RFID technology enables wireless transmission of identification information between tags attached to rolling stock and fixed trackside readers. When a train passes near the reader, the tag's unique identifier is processed by the control system to determine the required switching route.

Compared with conventional sensing methods, RFID systems provide:

- unique train identification,
- non-contact operation,
- improved routing reliability,
- reduced human intervention,
- integration with embedded and IoT systems.

2.3.3.1 *CASE STUDY:*

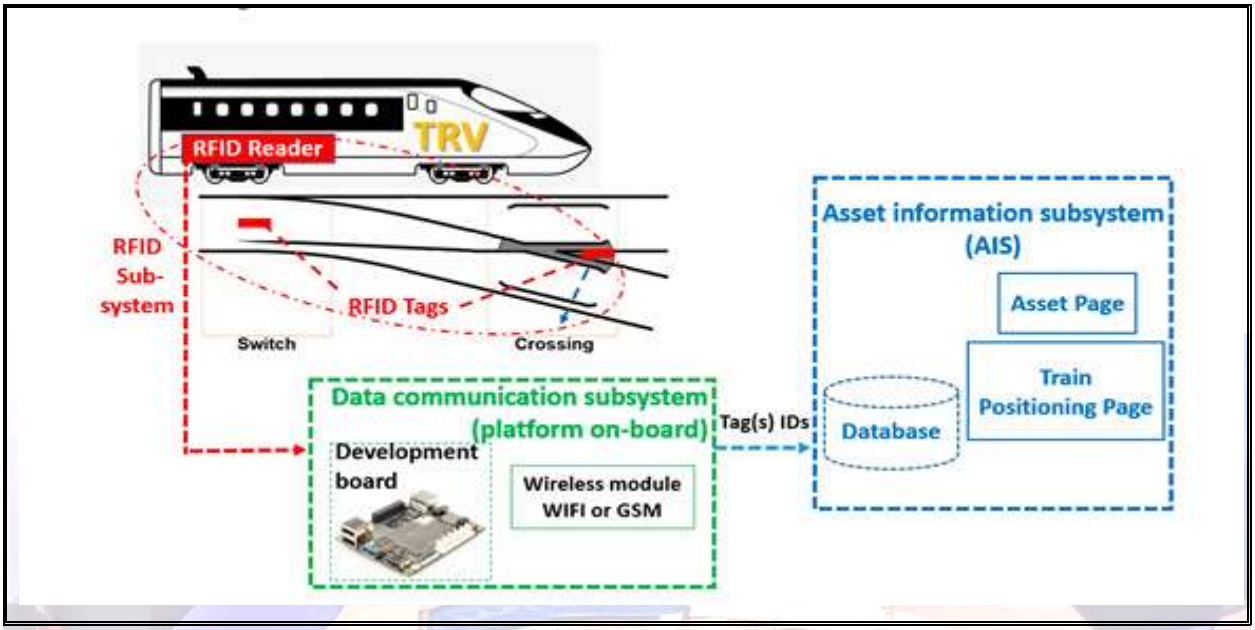


Figure 2.5: Case study of an RFID-based system

Source: Adapted from (Olaby et al., 2022)

Figure (2.5) illustrates an RFID-based railway monitoring and identification system adapted from Olaby et al. The figure demonstrates how RFID tags and readers are integrated within railway infrastructure to enable automatic train identification, position tracking and route management are achieved through wireless communication between the train and the central control system.

2.3.4 IoT-Integrated Monitoring and Control Systems

(Objective 3: Real-time monitoring and remote dashboard systems)

IoT-based railway systems integrate sensing technologies, wireless communication, embedded processing and cloud connectivity to enable real-time monitoring and remote control of operations (Padhi et al., 2022).

ESP32-based IoT architectures are particularly suitable for railway automation because they provide:

- integrated Wi-Fi connectivity
- low-cost implementation
- real-time embedded processing

- support for web dashboards and alerts
- compatibility with multiple communication protocols

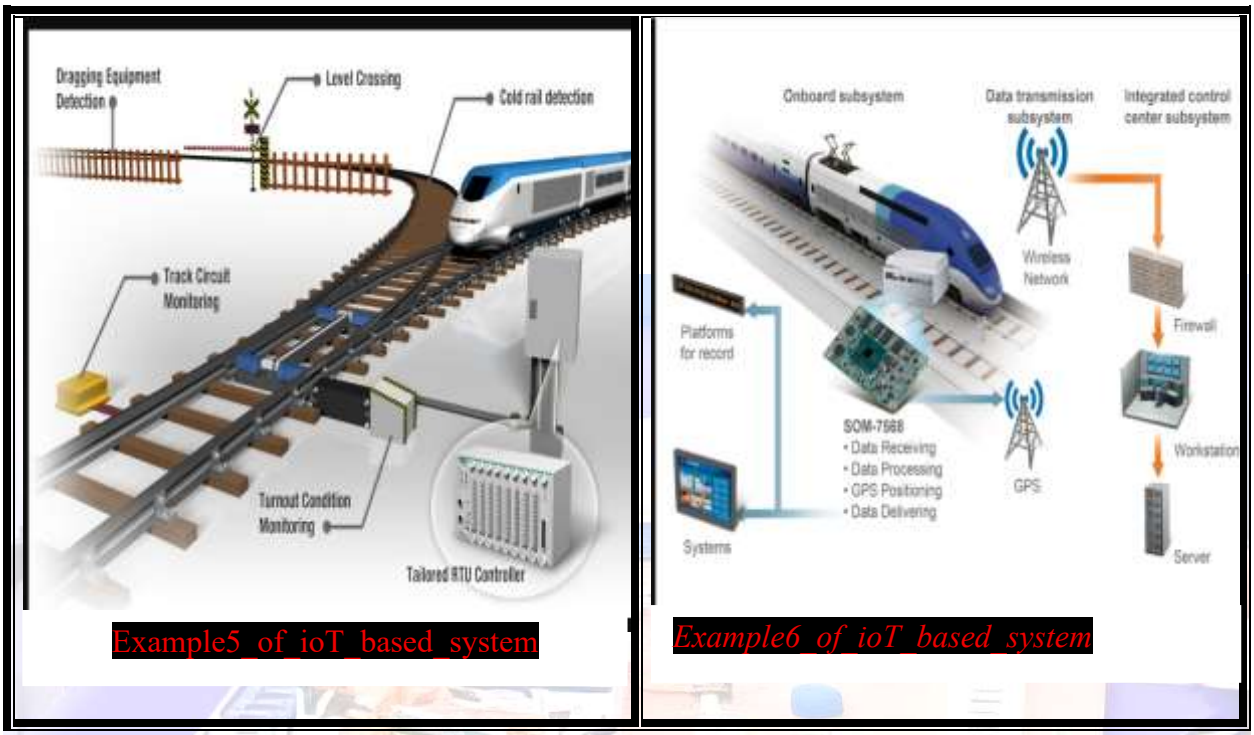


Figure 2.6:IoT-based railway monitoring systems

Figure (2.6) illustrates distributed IoT railway architectures supporting remote monitoring, condition tracking and centralized control.

IoT-enabled railway systems allow operators to:

- monitor turnout conditions remotely
- receive alerts in real time
- Visualisation of operational status through interactive dashboards
- Support for predictive maintenance functions
- Improved operational coordination across distributed assets

However, the literature also highlights persistent challenges in field deployments, particularly concerning cybersecurity, power stability, communication reliability and OTA firmware management (Hercog et al., 2023; Annavarapu, 2025).

The present project applies IoT principles through ESP32-based wireless monitoring, OLED visualization, web dashboard updates and email alert systems.

2.3.5 Tamper Detection, Computer Vision, and Predictive Maintenance Systems

(Objective 4: Tamper detection and predictive maintenance)

Modern railway monitoring systems increasingly integrate condition monitoring, tamper detection and predictive maintenance techniques to enhance operational safety and reduce infrastructure failures. Computer vision technologies provide automated inspection capabilities for identifying defects in railway infrastructure. Mcineka et al. (2024) introduced a vision-based monitoring framework that employed the Histogram of Oriented Gradients (HOG), the Circular Hough Transform (CHT) and Linear Support Vector Machine (LSVM) classification, achieving a detection accuracy of 94%.

Krč et al. (2020) further demonstrated that accelerometer-based monitoring combined with neural network models can identify railway conditions with high classification accuracy.

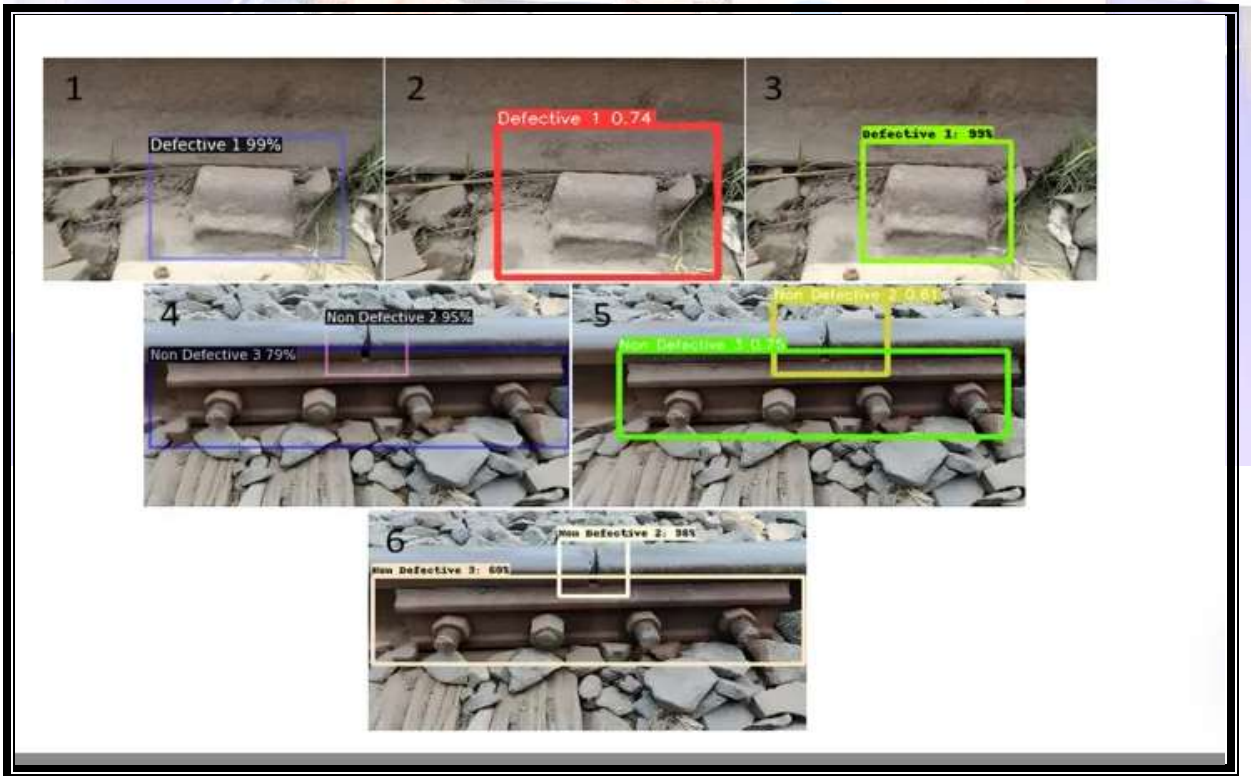


Figure 2.7: Computer vision-based railway defect detection

Figure (2.7) shows railway components classified as defective and non-defective using machine-learning-based image analysis techniques.

In addition to visual monitoring, vibration-based sensing technologies provide effective tamper detection and structural monitoring capabilities. Piezoelectric vibration sensors are widely used because they offer high sensitivity to mechanical disturbances, require minimal power and provide reliable performance in harsh environments.

Predictive maintenance approaches reviewed in the literature include:

- actuator current monitoring,
- displacement analysis,
- vibration analysis,
- statistical degradation modelling,
- usage-based cycle counting.

Papa et al. (2020) proposed usage-based maintenance estimation methods that calculate actuator health based on cumulative switching cycles. These approaches are computationally efficient and well-suited for implementation in low-cost embedded platforms. The present project implements:

- vibration-based tamper detection,
- ESP32-CAM event image capture,
- usage-based actuator maintenance estimation,
- real-time alert generation.

This combination supports proactive maintenance and improved railway infrastructure security.

2.4 Secure GPS/RF-Based Switching Systems

Nanda et al. (2020) proposed a system using GPS to gather train positional data, which is processed to determine the next station code, then transmitted via encrypted RF communication to wayside cabins to actuate track switching. The transmitter on the train includes a GPS module (Adafruit

Ultimate GPS Breakout, -165 dBm sensitivity, 10 Hz updates), RF transmitter, microcontroller (Arduino Nano) and power supply. The receiver near the track includes an RF receiver module and microcontroller, with data decrypted using AES-128 before actuating relays.

The system was tested in a simulated environment with a DC motor representing the switching mechanism, demonstrating successful track change for two case scenarios (Train 1 from "ABC" to "LMN", Train 2 from "ABC" to "XYZ"). The authors note that AES with 128-bit key is optimal for small data packets, being "fast enough, power consumption is very less and from the security perspective the data is very well protected and unbreakable."

This approach provides an alternative to RFID-based train detection. While this project uses RFID for positive identification, the GPS/RF approach offers longer range (up to 1 km) and eliminates the need for trackside RFID readers. However GPS signals may be unavailable in tunnels or urban canyons, whereas passive RFID remains functional. A hybrid approach combining both technologies could provide redundancy.

2.4.1 Dynamic Modelling and Simulation of Switches

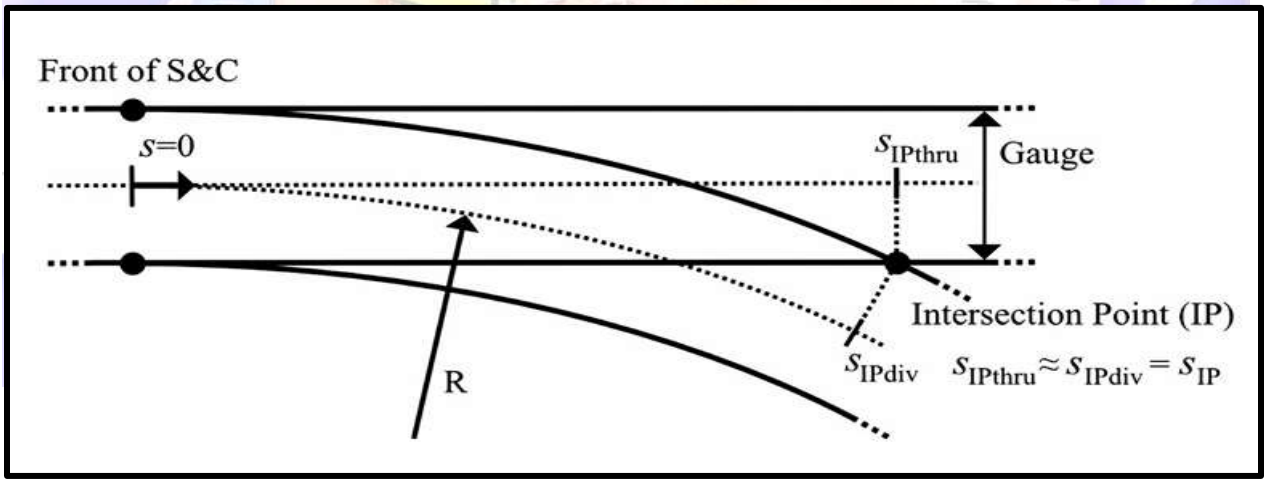


Figure 2.8:Turnout Modelling

Figure 2.9 (adapted from Bezin & Pålsson, 2023) illustrates the geometric complexity of Switches and Crossings (S&C) through the layout and nomenclature of a standard right-hand turnout. The diagram highlights critical structural components—including the stock rails, switch rails,

crossing/frog, and check rails—which govern the wheel-rail interface and facilitate the directional transition of rolling stock.

The figure identifies key components including the stock rails, switch rails, crossing (frog) and check rails. As noted by Bezin & Pålsson (2023), the primary challenges in S&C simulation include:

1. large and sudden changes in rail profile geometry along the track,
2. simultaneous contact of wheels with multiple rail bodies for example stock rail and switch rail simultaneously,
3. varying track properties throughout the turnout.

These challenges informed the mechanical design of the servo-actuated switching mechanism developed in this project, where precise alignment of the switch rail against the stock rail is essential for safe operation. Li et al. (2020) and Dutta et al. (2024) established comprehensive frameworks for simulating railway track switch dynamics, demonstrating that finite element (FE) modelling of switch blades can be effectively integrated with actuator and control system models within a unified software environment such as MATLAB/Simulink. Their findings highlight that:

- the FE-rail model treats each switch blade as a cantilever beam with variable cross-section, employing Timoshenko beam elements with six degrees of freedom per node.
- Validation against analytical solutions shows maximum errors below 4%, and simulation runs approximately real-time (1.2 s to simulate 1 s) compared to co-simulation approaches requiring several hours per second.
- The REPOINT switch simulation twin demonstrated that redundant actuation (three actuators) can tolerate single actuator failures, completing switching operations with settling times under 4 seconds and motor currents below 20 A.
- Control system design using cascaded PI controllers achieved stability margins well above requirements (phase margin 88.6°, gain margin 38.8 dB).

These modelling approaches are valuable for validating this project's servo actuation system before hardware implementation. The principles of beam bending and actuator-rail interaction inform the

mechanical design of the track switching mechanism, while the control system design principles guide the development of smooth servo positioning algorithms.

2.4.2 Sensor-based automation and RFID systems

Sensor-based automation employing infrared, ultrasonic, and magnetic sensors provides basic presence detection but lacks the capability to uniquely identify rolling stock. RFID systems overcome this limitation by assigning unique identifiers to trains or wagons, thereby enabling automatic route allocation and integration with optimisation frameworks (Olaby et al., 2022; Li et al., 2020). A case study by Olaby et al. (2022), which positioned tags at fixed reference points and utilised a vehicle-mounted reader, exemplifies a robust positioning and identification strategy for switch inspection and routing.

2.5 Gap Analysis

The literature identifies several persistent gaps that motivate the present work (Hu et al., 2023; Annavarapu, 2025; Peinado Gonzalo et al., 2022; Matias & Ferreira, 2020; Olaby et al., 2020):

1. **Limited system integration** — most studies focus on isolated subsystems rather than unified, low-cost platforms.
2. **Inadequate predictive maintenance** — many models neglect practical, usage-based Remaining Useful Life (RUL) estimation suitable for embedded devices.
3. **High cost of advanced actuation** — state-of-the-art actuators remain unaffordable for resource-constrained networks.
4. **Transferability of ML models —** location-specific training requirements reduce generalisability (Krč et al., 2020).
5. **Environmental sensitivity** — vision and some sensor modalities degrade under adverse conditions (Mcineka et al., 2024; Matias & Ferreira, 2020).
6. **Scalability and cost constraints** — commercial CBTC and PLC solutions are expensive; low-cost alternatives often lack field-ready robustness.
7. **Insufficient real-world validation** — few studies document laboratory-tested, low-cost prototypes tailored to developing-country conditions.

8. **Communication security vulnerabilities** — many prototypes lack encryption and robust authentication (Nanda et al., 2020).
9. **Seasonal model requirements** — predictive models must account for temperature and humidity effects (Papa et al., 2020).

The proposed dual-ESP32 prototype addresses these gaps by integrating RFID identification, servo actuation, vibration-based tamper detection, timed image capture with email alerts, usage-based predictive maintenance, checksum-validated UART communication, a dual-OLED local interface and a responsive web dashboard designed for affordability and field resilience.

2.6 Conceptual framework

In total, the conceptual framework incorporates four interdependent layers: sensing (RFID, piezoelectric and camera); local control (ESP32 trackside and control-room units) communication (UART for local links; Wi-Fi for remote dashboards); and application (predictive maintenance, manual override and operator interfaces). It incorporates the framework by Zhang, Bai, Song & Dong. (2024) soft-switching paradigm for the management of transitions between automated and manual control and routing optimisation philosophies from Li et al. (2020) to allow dynamic route selection according to the identity of the train and other operational contextual information. The review by Peinado Gonzalo et al. informs both condition-monitoring KPIs (section 4.2) and RUL estimation (section 3). Notably, the theoretical framework proposed by Van de Walle et al. (2022), together with the empirical findings reported by Papa et al. (2020), provides a strong foundation for this study.

2.7 Summary

This chapter has reviewed the theoretical and applied literature underpinning automatic track switching and condition monitoring. Key contributions from Matias & Ferreira (2020), Bezin & Pålsson (2023), Olaby et al. (2022), Krč et al. (2020), Mcineka et al. (2024), Papa et al. (2020) and others establish the technical foundations and highlight practical constraints. The review identifies a clear need for an integrated, low-cost, field-validated prototype. The prototype combines RFID identification, robust actuation control, tamper detection, visual verification and pragmatic predictive maintenance objectives that the present project addresses.

3 Chapter 3: RESEARCH METHODOLOGY

3.1 Introduction

This chapter gives and outlines the methodological framework adopted for the design and implementation of the automatic railway track switching and monitoring system. It details the research design, system requirements, system architecture, control logic and implementation processes

3.2 Research Design

3.2.1 Project Approach

The project followed a design-science methodology, combining theoretical modelling with practical prototyping. The process comprised four stages:

1. **Problem analysis** — identifying inefficiencies in manual switching systems and reviewing literature on automation technologies.
2. **System design** — specifying hardware and software requirements based on identified gaps.
3. **Prototype development** — assembling subsystems using ESP32 microcontrollers, RFID readers, servo actuators, vibration sensors, and camera modules.
4. **Evaluation** — laboratory testing to measure detection accuracy, actuation response time, predictive maintenance functionality, and communication reliability.

This iterative approach ensured that theoretical insights from Chapter 2 were translated into a practical, low-cost prototype in a laboratory environment simulating railway operations. It is more appropriate than pure waterfall or simulation-only methods for an embedded system requiring physical hardware integration and immediate feedback on servo positioning, vibration thresholds, dual-display rendering, and camera operations. The approach aligns with the Education 5.0 principles by emphasizing innovation through a functional prototype that addresses real-world railway maintenance and security challenges in the Zimbabwean context.

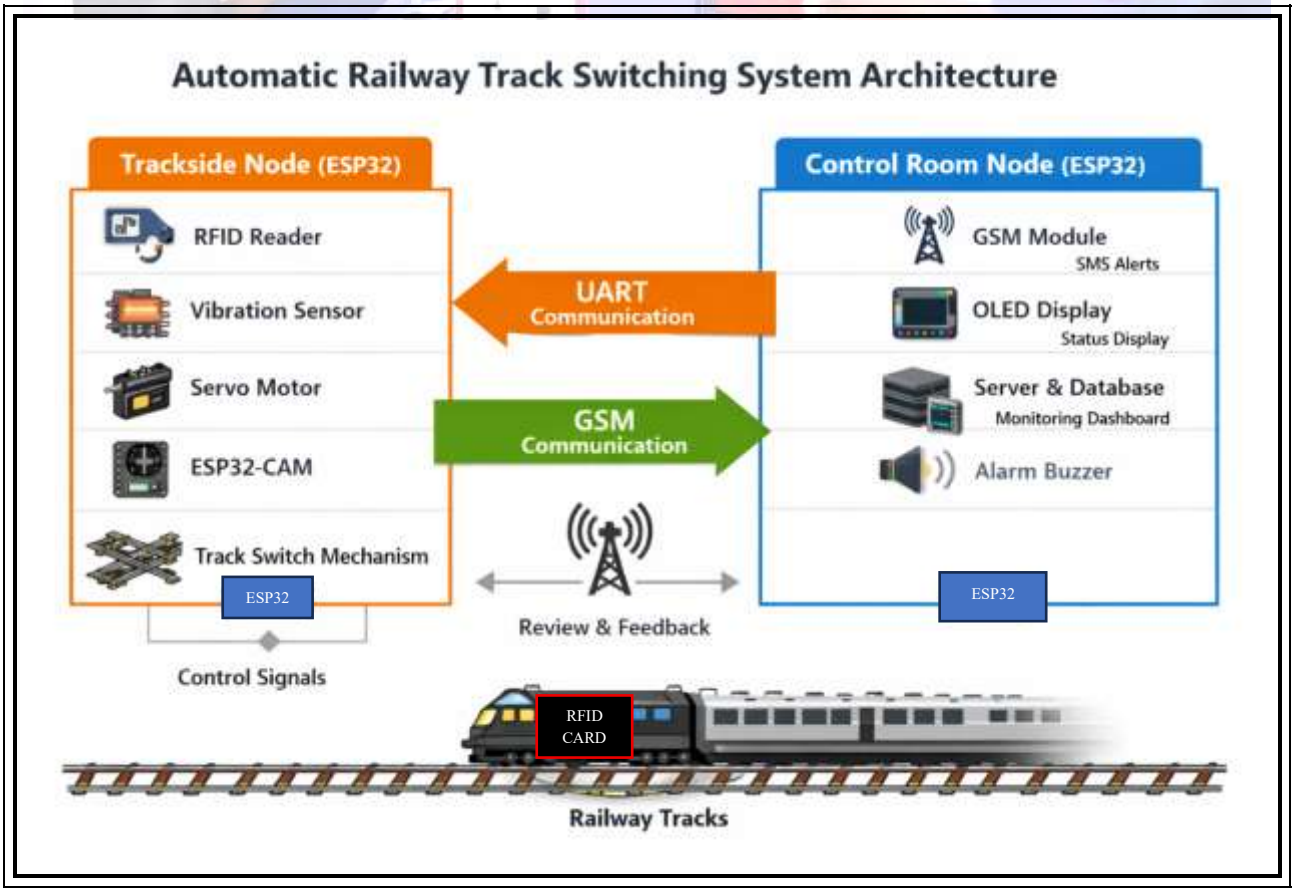


Figure 3.1:Research Design Framework

Figure (3.1) shows a schematic diagram illustrating the four-stage design-science process used in the project.

This approach ensured that theoretical insights from the literature were translated into a functional prototype suitable for resource-constrained railway environments.

3.3 System Requirements Specification

3.3.1 Hardware Requirements

The hardware subsystem was designed to be affordable, robust and suitable for embedded railway automation. Each component is described below.

The system consists of two ESP32-based units:

- Track-side Controller
- Control Room Unit

Track-Side Components

- ESP32-WROOM-32 DevKit
- MFRC522 RFID Reader
- 2 × SG90 Servo Motors
- Piezoelectric Vibration Sensor
- ESP32-CAM Module (image capture only)
- Voltage regulator (3.3V)
- LEDs with resistors

Control Room Components

- ESP32-WROOM-32
- 2 × OLED Displays (SSD1306)
- Push buttons
- Buzzer
- Status LEDs

ESP32-WROOM-32 DevKit V1

Primary processing unit equipped with integrated Wi-Fi and a dual-core processor.



Figure 3.2: ESP32-WROOM-32 DevKit V1

- The ESP32-WROOM-32 was selected for this project due to its dual-core architecture, integrated Wi-Fi and multiple communication interfaces (SPI, I²C, UART, PWM). These features make it particularly well-suited for real-time embedded applications requiring multitasking and network connectivity. In comparison with the Arduino Uno, the ESP32 offers substantially higher processing capability and built-in wireless support, thereby enabling more efficient system integration (Espressif Systems, 2023; Hercog et al., 2023).

Figure (3.2) shows a picture of the ESP32 development board used as the primary controller for both the trackside subsystem and control room sub system.

MFRC522 RFID Reader

RFID detection module for train identification.

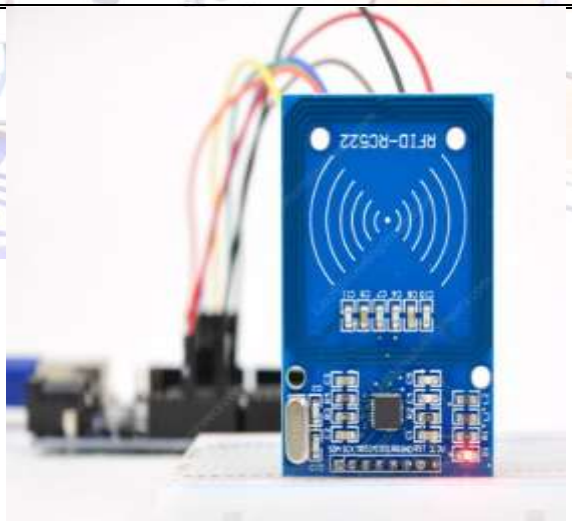


Figure 3.3: MFRC522 RFID Reader

- The MFRC522 module operates at 13.56 MHz and provides reliable short-range identification. Unlike IR or ultrasonic sensors, which only detect presence, RFID provides **unique identification**, enabling automatic route allocation and improved operational safety (Olaby et al., 2022; NXP, 2020).

Figure (3.3) shows an image of the MFRC522 module used for short-range RFID detection.

SG90 Servo Motor

Track switching actuator



Figure 3.4: SG90 Servo Motor

- The sensor generates voltage in response to mechanical disturbances, making it ideal for detecting tampering, impacts, or structural anomalies. Its passive operation and low power consumption make it suitable for continuous monitoring (Qing et al., 2019)

Figure (3.4) shows a photograph of the SG90 servo used for point actuation.

Piezoelectric Vibration Sensor

Tamper-detection module.



Figure 3.5: Piezoelectric Vibration Sensor

- The sensor generates voltage in response to mechanical disturbances, making it ideal for detecting tampering, impacts, or structural anomalies. Its passive operation and low power consumption make it suitable for continuous monitoring (Qing et al., 2019)

Figure (3.5) shows an image of the piezoelectric sensor used for vibration-based tamper detection.

ESP32-CAM Module

Image-capture and surveillance unit.



- The ESP32-CAM integrates a camera with Wi-Fi capability, enabling low-cost image-based monitoring. It supports event-triggered capture and SMTP email transmission, making it suitable for security and verification tasks (Espressif Systems, 2022).

Figure 3.6:ESP32-CAM Module

Figure (3.6) shows an ESP32-CAM which is used for event-triggered picture capture and also web based live streams.

OLED Display

User interface display



- OLED displays offer high contrast, low power consumption and excellent visibility, making them suitable for control-room interfaces where operators require clear real-time feedback (Adafruit, 2021).

Figure 3.7: OLED Display

Figure (3.7) shows an OLED display which is used for real-time system status and event and display.

Push Button

Manual override control



Figure 3.8: Push Button

Push buttons provide a reliable manual override mechanism, supporting the soft-switching framework in which human intervention can safely interrupt automated control (Zhang, Bai, Song & Dong, 2024).

Figure (3.8) shows a picture of the push button used for manual interrupt for point switching on the design project.

Buzzer

Audio alert device.



Figure 3.9: Buzzer

- The buzzer provides immediate audible feedback for faults, tamper events, or switching errors, improving operator response time and enhancing system safety (Horowitz & Hill, 2015).

Figure (3.9) shows an image of the buzzer used for audible fault and alert notifications.

Software Requirements

Table 3.1:Development Tools

ARDUINO IDE	firmware development

CIRKIT MAKER	circuit diagram drawing
PROTEUS	circuit simulation
WOKWI	virtual prototyping and debugging
AUTOCAD	sketching prototype
ANDROID STUDIO (flutter framework)	mobile app development
VS CODE	web interface
CANVA	Sketch enhancement and polishing

Table 3.2:Programming Languages

C++ embedded firmware	microcontroller programming
Java (dart interface)	mobile app development
HTML.CSS. JavaScript	web dashboard

Table 3.3:Libraries

<MFRC522>	RFID communication
<ESP32Servo>	PWM-based servo control
<WiFi & AsyncWebServer.h>	dashboard hosting
<LiquidCrystal_I2C>	trackside welcoming display
<ESP_Mail_Client>	captured pictures send to email
<Adafruit_GFX.h>	Control- room OLED displays
<Adafruit_SSD1306>	OLED displays quality
<TinyGsmClient.h>	GSM interface

Table 3.4:Communication Protocols

UART (115200 BAUD)	trackside ↔ control-room communication. control-room unit↔ GSM Module communication
SPI	trackside unit ↔ RFID communication
WI-FI	dashboard updates and email alerts

INTERRUPT	trackside unit ↔ESP32 CAM communication. Trackside unit ↔Signaling trigger

Communication Security

Checksum validation is used to ensure data integrity over the UART. Each packet includes a computed checksum; mismatched packets are discarded. Future versions may incorporate AES-128 encryption following the secure architecture demonstrated by Nanda et al. (2020).

Simulation Tools

Proteus and Wokwi were used for circuit-level simulation. Dynamic modelling principles from Li et al. (2020) and Dutta et al. (2024) provide a foundation for future integration of finite-element rail models with actuator control simulations.

3.4 System Requirements Analysis

3.4.1 Functional Requirements

The system was required to:

- automatically detect trains using RFID technology
- switch railway tracks automatically
- support manual override operation
- monitor vibration disturbances
- capture and transmit images
- provide remote monitoring
- estimate actuator health using predictive maintenance logic

3.4.2 Non-Functional Requirements

The system was designed to satisfy the following non-functional requirements:

- low power consumption
- low implementation cost
- modular architecture

- ❖ real-time operation
- ❖ fault tolerance
- ❖ communication reliability

3.4.3 System Constraints

The project was limited by:

- ❖ laboratory-only testing conditions
- ❖ short-range HF RFID detection
- ❖ limited budget
- ❖ absence of real railway infrastructure for field testing

3.5 System Architecture

The developed system follows a distributed embedded architecture consisting of two interconnected ESP32-based subsystems:

- ➢ Trackside ESP32 Controller
- ➢ Control Room ESP32 Controller

The architecture was designed to improve modularity, communication reliability, fault isolation, and operational safety.

The trackside subsystem performs:

- ▪ RFID-based train identification
- ▪ servo-based track switching
- ▪ vibration monitoring
- ▪ image capture
- ▪ local decision processing

The control-room subsystem manages:

- ▪ system visualization
- ▪ manual override control
- ▪ alarm handling

- operator interaction

Communication between the two controllers is achieved using UART serial communication with checksum validation to ensure reliable data transmission.

Wi-Fi communication is additionally used for:

- web dashboard updates,
- remote monitoring,
- email notifications,
- OTA firmware updates.

The system architecture supports real-time operation by implementing non-blocking task execution which enables simultaneous sensing, communication and actuation processes. The distributed design adopted in this project enhances scalability, modularity and fault isolation by separating the trackside subsystem from the control-room subsystem. This separation reduces computational overload on individual controllers while improving communication efficiency and overall system reliability. The architecture accommodates future expansion through integration of cloud monitoring services, advanced predictive analytics, GPS-based train localization and centralized railway traffic management systems.

3.5.1 Operation Overview

The operational sequence of the system begins with continuous RFID scanning for approaching train tags. When a valid tag is detected, the ESP32 processes the unique identifier and determines the required track direction based on predefined routing logic. The corresponding servo motor is actuated to reposition the railway point mechanism. Following successful switching, the updated system status is transmitted to the control-room ESP32 via UART communication. Simultaneously, the ESP32-CAM captures an image of the switching event and transmits it through the wireless monitoring system. OLED displays in the control room update the current system state, while the predictive maintenance algorithm increments the actuator usage counter.

- **RFID reader** — continuously detects approaching train tags and transmits identification data to the trackside ESP32 controller, which processes the information to determine the switching route.

- **Servo motors** — reposition the track points under ESP32 control, while the vibration sensor monitors disturbances and reports abnormal activity for tamper detection.
- **ESP32-CAM module** — captures event-triggered images during train detection or alert conditions and transmits them through the wireless communication network.
- **UART communication** — links the trackside subsystem with the control-room subsystem, enabling real-time synchronization and status updates.
- **Control-room interface** — OLED displays present operational information, while manual override, audible alarms and mobile dashboard integration enhance operator control and monitoring.

The distributed architecture improves modularity, fault isolation, scalability, and communication reliability, ensuring robust performance within the railway automation system.

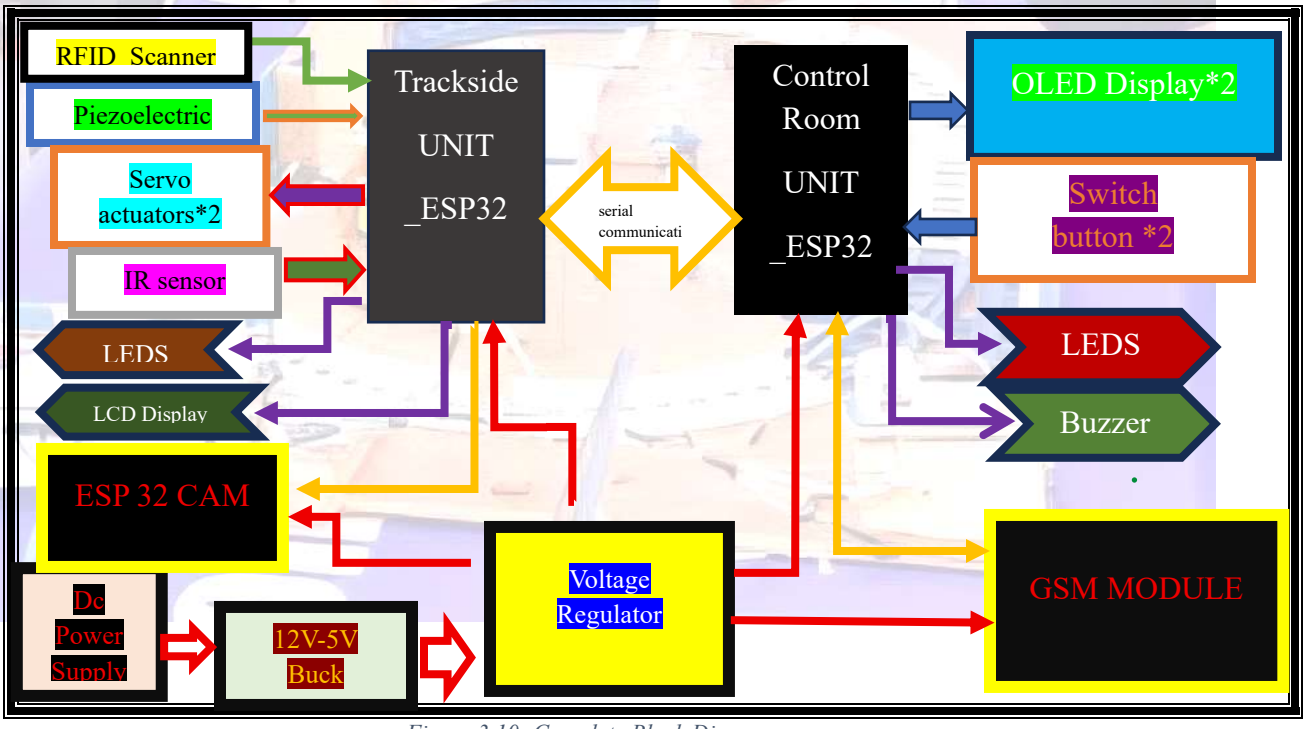


Figure 3.10: Complete Block Diagram

Figure (3.10) illustrates the complete architecture of the Automatic Railway Track Switching and Monitoring System. The diagram shows the interaction between sensing, processing, communication, monitoring actuation subsystems and powering systems.

3.5.2 Subsystems

Track-Side Subsystem:

- RFID-based train detection
- Servo-based switching
- Vibration-based intrusion detection
- Image capture and email alerts
- Ir or interrupt for triggering incoming train

Control Room Subsystem:

- Displays system status through OLED displays
- Allows manual override through buttons
- Provides alerts via buzzer and LEDs

Communication Subsystem:

- UART for local communication
- Wi-Fi for remote monitoring

3.6 Signal Flow

The signal flow within the system follows a closed-loop embedded control process consisting of sensing, processing, communication, and actuation stages.

Input signals are obtained from:

- the RFID reader
- vibration sensor
- manual override push buttons
- Ir or interrupt pin

The ESP32 processes these signals using embedded decision-making algorithms and generates output responses including:

- servo actuation

- OLED updates
- buzzer alerts
- LED alerts
- UART transmission
- web dashboard updates
- email notifications
- Sms notificatios or missed call

The signal-flow architecture ensures real-time coordination between the trackside and control-room subsystems, while maintaining communication reliability and operational safety.

3.6.1 Sensor and Actuator Integration

The system operates as a real-time embedded control loop that integrates sensing, processing, and actuation.

- RFID detection — the MFRC522 reader functions as the primary train detection module, communicating with the ESP32 via the SPI protocol. Upon detecting a valid RFID tag, the unique identifier (UID) is processed to determine the required switching action.
- Tamper detection- the piezoelectric vibration sensor is interfaced through an analog input and continuously monitors mechanical disturbances. A threshold-based algorithm detects tampering when the sensed voltage exceeds a predefined level, triggering alerts such as buzzer activation, UART transmission, and email notification.
- Servo actuation -servo motors are controlled using PWM signals generated by the ESP32. The duty cycle determines angular position, enabling precise track switching. Each operation increments a cycle counter used in predictive maintenance calculations.
- Visual verification -the ESP32-CAM module captures images during key events such as train detection or intrusion, transmitting them via SMTP email to administrators for remote monitoring.
- Control room interface - OLED displays provide real-time visualization of track position, system status, and alerts. Push buttons allow manual override, with all inputs debounced in software to ensure reliability.

The system is implemented using a non-blocking programming approach, ensuring concurrent execution of sensing, communication, and control tasks. This design maintains real-time responsiveness and fault tolerance, which are critical for safe railway operations.

3.7 System Flowchart

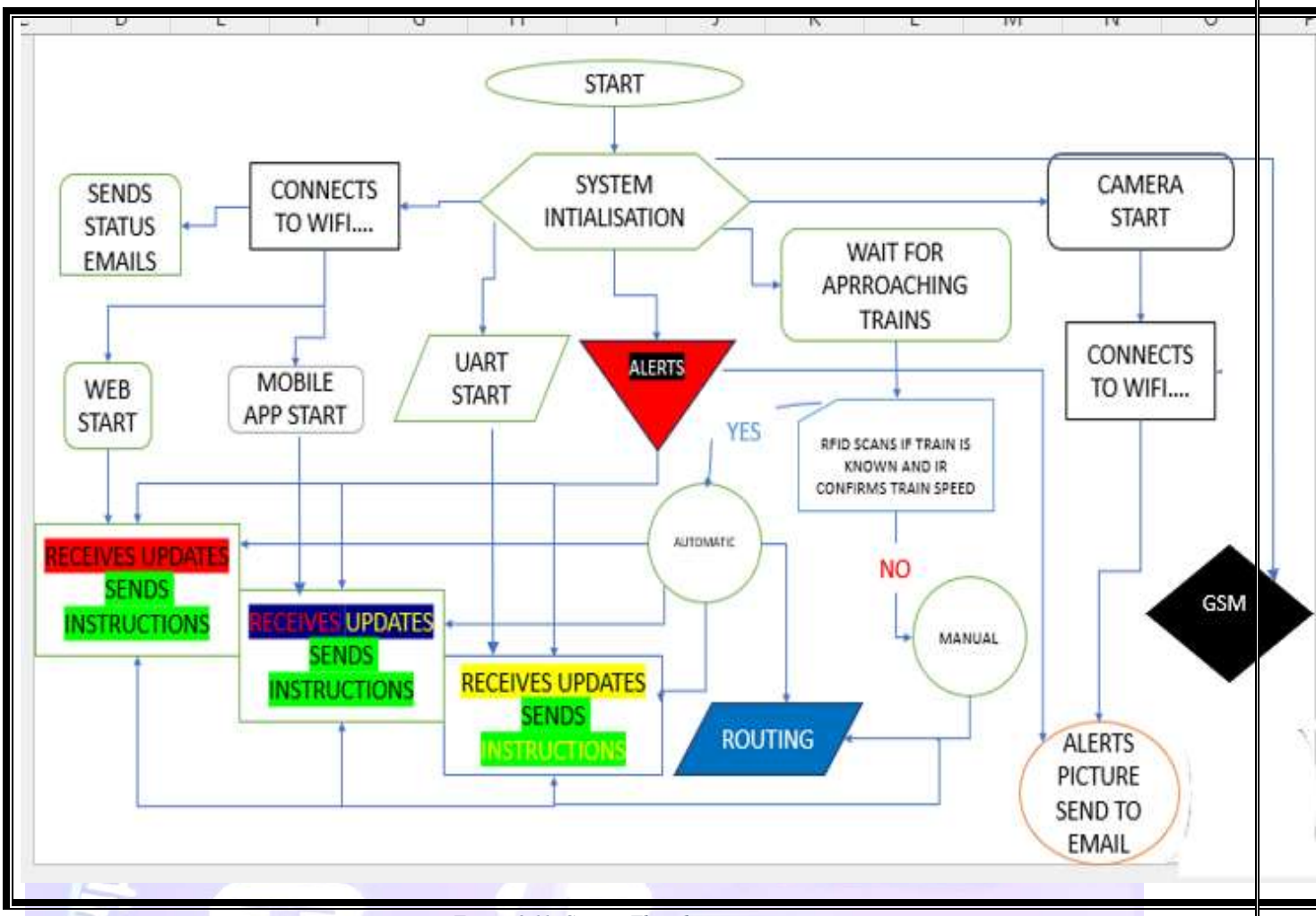


Figure 3.11: System Flowchart

Figure (3.11) illustrates the operational flowchart of the complete railway switching system. The flowchart describes the initialization process, continuous RFID scanning, train detection, switching decision logic, servo actuation, image capture, alert generation and system status updating procedures. The flowchart further demonstrates how manual override and communication validation are integrated into the operational sequence to improve reliability and fault tolerance. The system works mainly with an internet (WIFI) connection and if there is no

internet the main functions will be a local control room for monitoring and control, a GSM based SMS interface and a local mobile app which just require esp32 local Ip address to connect.

3.8 System Design and Implementation

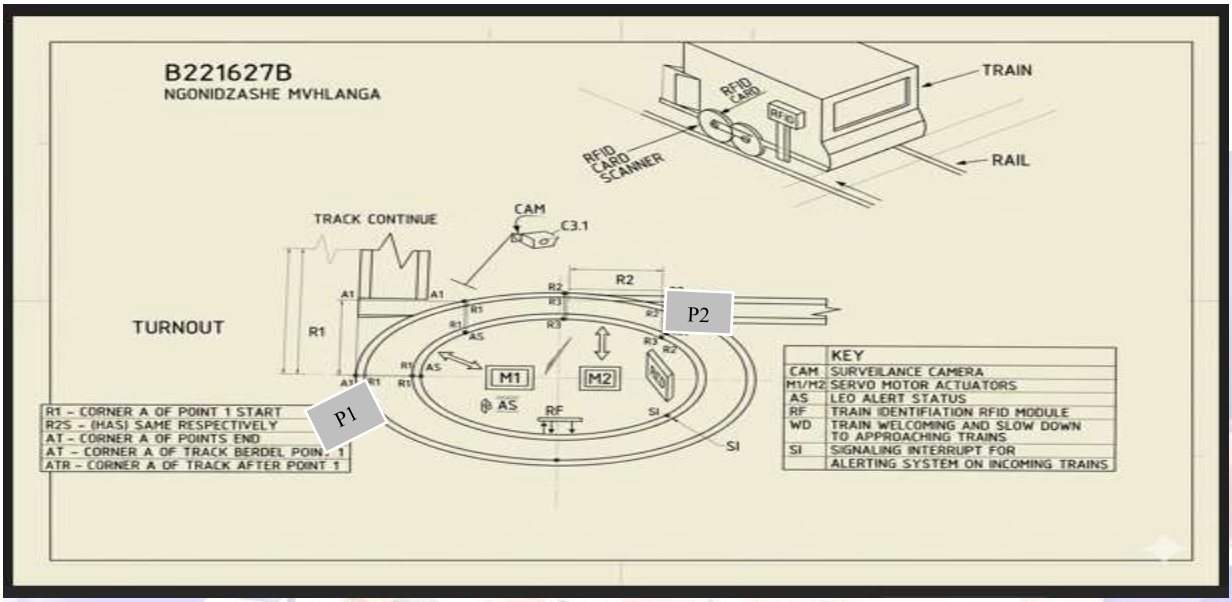


Figure 3.12:Integrated turnout design with RFID scanner, surveillance cameras, and servo actuators.

Figure 3.14 shows an isometric and track top view drawing board sketch (edited by Canva) of the proposed system prototype a complete circular track and 2 turnout positions, interrupt and RFID reader positions

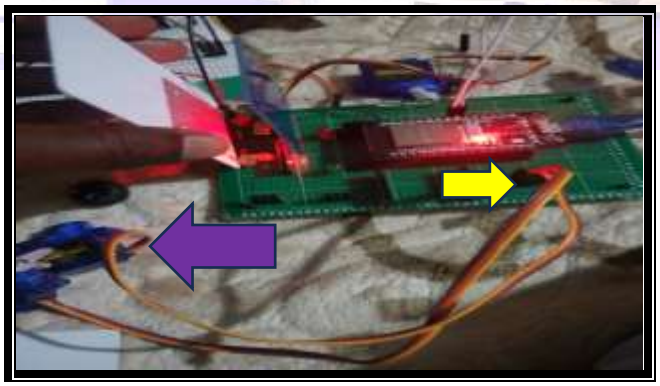


Figure 3.13:servo actuators calibration

Figure 3.13 shows a Veroboard result of two servo motor actuators connected to an esp32 microcontroller pin 12 and pin 13 and powered from an external 5 volts with a common ground with the system esp32

3.8.1 RFID-Based Train Detection System

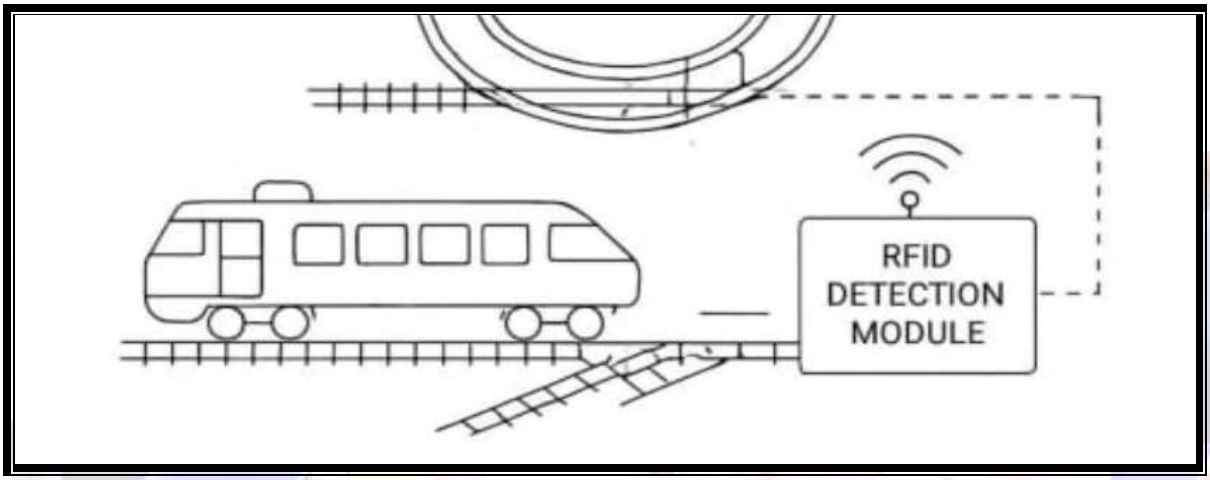


Figure 3.14: RFID detection module schematic showing train identification process.

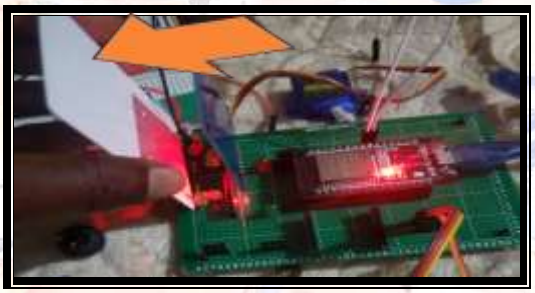


Figure 3.15:RFID Card Testing

Figure 3.15 shows RFID card training and configuration. This is a Veroboard result of an RFID module connected using SPI and 3.3volts from the ESP32

Response period:

$$T_r = T_d + T_s$$

Equation 3.1:Response Time

Equation (3.1) defines Response time (T_r){ system responsiveness} as the sum of the Detection delay (T_d), {time taken for the RFID reader to detect a tag}and the Servo switching delay (T_s), {time taken for the servo to move from one position to another}.

- This model expresses the total system response time as the sum
- This equation is used to evaluate whether the system meets real-time operational requirements.

3.8.2 Servo-Based Track Switching Mechanism

SG90 servo motors were used for railway point actuation because they:

- provide accurate angular positioning
- simplify position control
- require minimal external circuitry
- operate efficiently using PWM control signals

The servo angular position is determined using the proportional PWM relationship:

$$\theta = kD$$

Equation 3.2:Servo Angular Position Model

*Equation (3.2) defines the linear relationship between the PWM duty cycle **D**and the resulting servo angle **θ**. Where: θ represents servo angular position, **D** represents PWM duty cycle, **k** represents the proportional constant.*

- Smooth switching was implemented using incremental PWM transitions to reduce mechanical stress and overshoot.
- Increasing the duty cycle increases the angular displacement.
- The constant ***k*** depends on the servo's internal gearing and electrical characteristics.
- This model is used to compute the precise switching angle required for point movement.

3.8.3 Vibration Monitoring System

A piezoelectric vibration sensor was integrated for tamper detection and railway security monitoring. The sensor converts mechanical disturbances into electrical signals. Threshold-based signal processing was implemented to differentiate valid vibration events from background environmental noise

3.8.4 Power Management Design



Figure 3.16:Buck Converter Calibration

The buck converter was calibrated to provide a regulated output voltage suitable for powering the GSM module. As shown in Figure 3.14, the digital multimeter reading confirmed an output of 4.39 V. This value is within the acceptable tolerance range for GSM operation, ensuring stable supply under load conditions.

Power regulation was implemented using:

- buck converters
- voltage regulators
- decoupling capacitors

The total power consumption was estimated using:

$$P=V\cdot I$$

Equation 3.3:Power Consumption

Equation (3.3) calculates the electrical power consumed by each subsystem where [V]represents the supply voltage, and [I]represents the current drawn by the component

- This is essential for ensuring that the power supply can support peak loads, especially during servo actuation and camera transmission.

Separate power rails were used for:

- servo motors
- logic circuitry
- communication modules

3.8.5 Control Logic

The control algorithm was implemented using a finite-state machine structure consisting of:

- Idle State
- Detection State
- Switching State
- Alert State
- Manual Override State

This approach improves:

- system stability
- event synchronization
- fault isolation

System States Table

Table 3.5:System Operational States

System State	*Description*
Initialization State	The ESP32 controllers initialize all peripherals including RFID readers, servo motors, OLED displays, UART interfaces, vibration sensors, and Wi-Fi modules.
Idle State	The system continuously waits for RFID tag detection while monitoring communication and vibration sensor status.
Detection State	A valid RFID tag is detected and processed to determine the required railway route configuration.
Switching State	PWM control signals are generated to actuate the servo motors responsible for railway point switching.
Authorized Switch	Triggered when an authorized RFID tag is read; perform soft switch, increment cycle counter, and log event.
Monitoring State	The system updates OLED displays, UART communication logs, web dashboard information, and predictive maintenance counters.
Unauthorized Alert	Triggered on unknown RFID; trigger camera capture, sound alarm, and queue GSM/SMS alert.
Manual Override	Entered when control-room command or local pushbutton toggles; suspend automatic switching until cleared. Transitions between states are guarded by **minimum inter-switch interval** and checksum-verified communications.

3.8.6 Manual Override Logic

Manual override functionality was implemented to support soft-switching operation.

When an operator presses a push button:

- automatic control is temporarily suspended
- manual commands are prioritized
- safe state transitions are enforced

This prevents command conflicts between human and automated control systems.

3.8.7 Communication Security

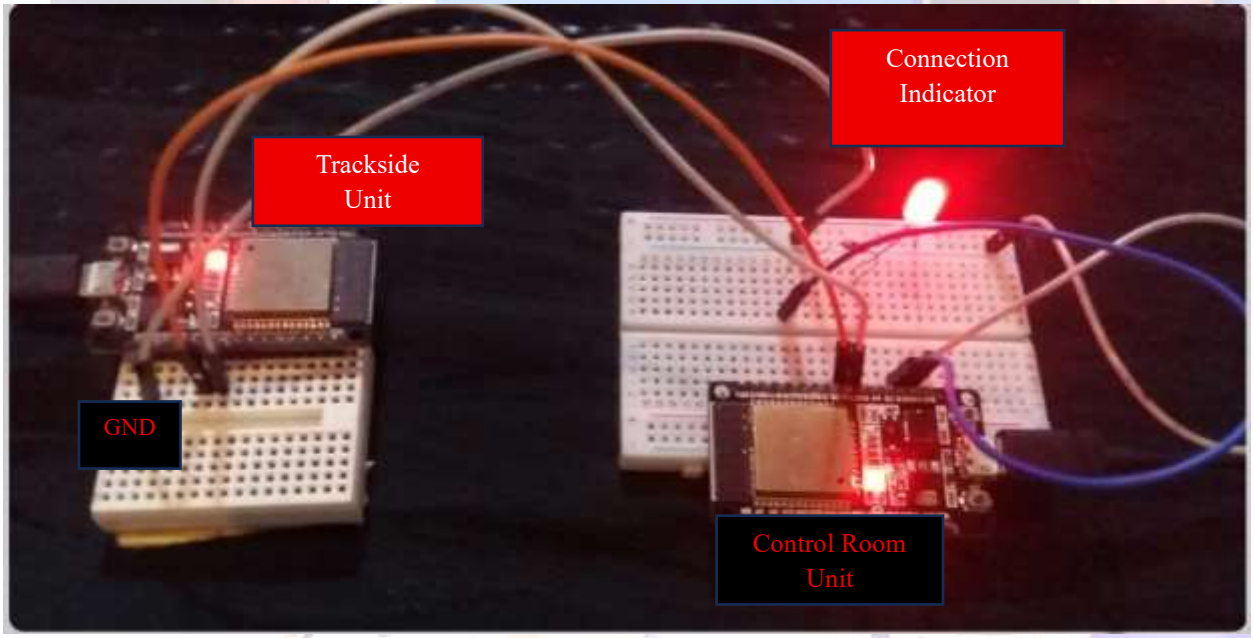


Figure 3.17;Serial Communication breadboard Testing

Figure 3.17 shows two ESP32s connected with three wires which are for transmission, reception and a ground to ensure the system has a common ground

The UART communication between trackside and control room ESP32 units includes checksum validation to ensure data integrity, on checksum mismatch, the packet is discarded and the requesting unit waits for the next scheduled transmission.
Each transmitted packet includes:

- Start byte (0xAA)
- Data payload (system status, track position, alert flags)
- Checksum byte (XOR of all data bytes)

- End byte (0xFF)

The receiver calculates the checksum of the received data and compares it with the transmitted checksum. If they match, the packet is accepted; if not, it is discarded and a retransmission is requested. This approach, while simpler than the AES encryption used by Nanda et al. (2020), provides protection against transmission errors and basic tampering detection.

The structure is shown below:

Field	Description
0xAA	Start Byte
Data	System Information
XOR	Checksum
0xFF	End Byte

3.8.8 Predictive Maintenance Algorithm

The system implements a usage-based predictive maintenance model that estimates actuator health according to switching cycles.

$$\boldsymbol{Health}(\%) = \left(\mathbf{1} - \frac{\boldsymbol{N_{cycles}}}{\boldsymbol{N_{max}}}\right) \times \mathbf{100}$$

Equation 3.4:Predictive Maintenance Algorithm

Equation (3.4) Where:$\boldsymbol{N_{cycles}}$is the current number of switching cycles, $\boldsymbol{N_{max}}$is the maximum allowable switching cycles.

- Maintenance alerts are triggered when actuator health falls below predefined thresholds.

3.8.9 Sensor Specification

Table 3.6: Sensor Specifications

COMPONENT	*OPERATING PRINCIPLE*	*ELECTRICAL SPECS*	*INTERFACE*
MFRC522 RFID	Electromagnetic coupling (13.56 MHz)	3.3V, ~13–26 mA	SPI
Piezo Sensor	Piezoelectric effect	Analog output (0–3.3V)	ADC
ESP32-CAM	Image sensing + WiFi	5V, up to 300mA	WiFi/UART
SG90 Servo	PWM-controlled position	5V, ~500mA peak	PWM
OLED SSD1306	Electroluminescence	3.3V, ~20mA	I2C

Table 3.7:Trackside Pin Mapping

ESP 32 Pin	Component	Function
GPIO 5	MFRC522 SDA (SS)	SPI chip select for RFID
GPIO 18	MFRC522 SCK	SPI clock
GPIO 23	MFRC522 MOSI	SPI MOSI
GPIO 19	MFRC522 MISO	SPI MISO
GPIO 21	MFRC522 RST	RFID reset

ESP 32 Pin	Component	Function
GPIO 15	SG90 Servo 1 PWM	Point actuator A control
GPIO 2	SG90 Servo 2 PWM	Point actuator B control
ADC1_0 (GPIO 36)	Piezo Vibration sensor	Analog tamper/vibration input
GPIO 25	Wire	System signaling for incoming train
GPIO 27	ESP32-CAM trigger	Camera capture trigger (active high)
5V VIN	Servo power rail	External 5V supply for servos
3.3V	ESP32 VCC	MCU power rail
GND	Common ground	System ground reference

Table 3.8: Control Room Pin Mapping

ESP32 PIN	*COMPONENT*	*FUNCTION*
GPIO 4	GSM TX	Sends GSM network status to main control room unit
GPIO 5	GSM RX	Receives instructions from main control room unit
GPIO 16	UART RX	Receive data from the Trackside unit
GPIO 17	UART TX	Send data to the Trackside unit
GPIO 14	Push Button 1	Manual Toggle Point 1
GPIO 15	Push Button 2	Manual Toggle Point 2
GPIO 23	Red/Green LED - Point 1	Health Status Indicator (P1)

GPIO 25	Red/Green LED - Point 2	Health Status Indicator (P2)
GPIO 18	Active Buzzer	Audio Alert
GPIO 21	OLED 1 SDA	I2C Data (First OLED)
GPIO 22	OLED 1 SCL	I2C Clock (First OLED)
GPIO 26	OLED 2 SDA	I2C Data (Second OLED)
GPIO 27	OLED 2 SCL	I2C Clock (Second OLED)
3.3V / 5V	Power	Power supply for OLEDs & Buzzer

3.8.10 GSM-Enabled Control Room

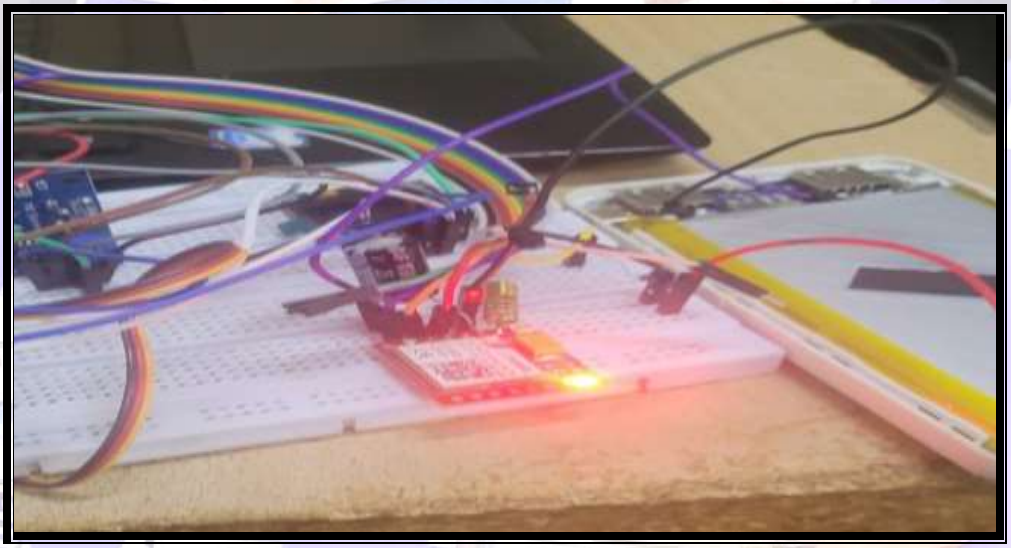


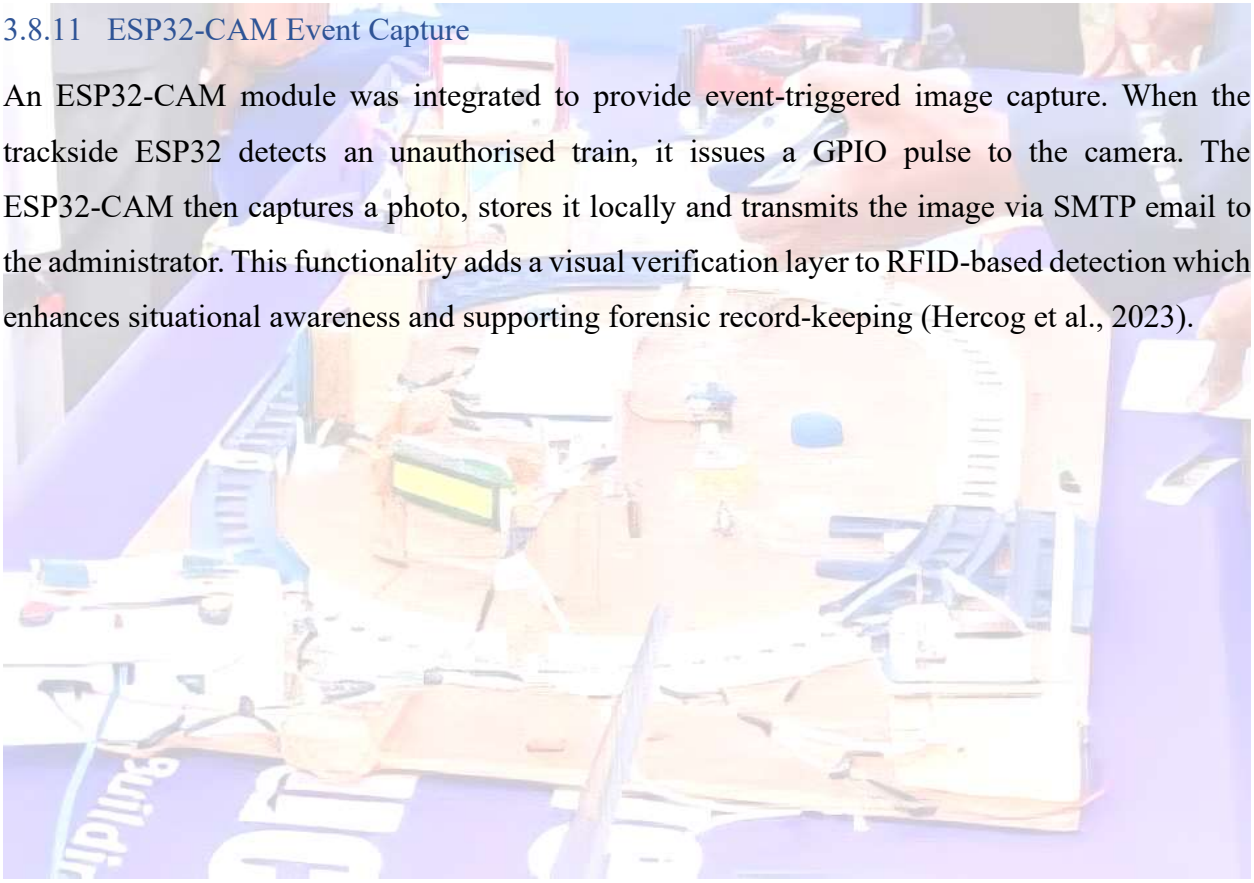
Figure 3.18:GSM Breadboard Testing

A breadboard prototype was assembled to validate GSM communication. The setup incorporated the microcontroller, sensor interface and GSM module, powered via USB and a Li-Po battery pack (Figure 3.18). During testing, the red LED indicator confirmed successful module initialisation, while AT command responses verified network registration. SMS transmission trials were completed without error, demonstrating reliable communication capability.

The control room subsystem was extended with a SIM800 GSM modem connected via UART1. This addition enables event-based SMS alerts and remote administrative control. Operators receive notifications such as unauthorised train detection or point toggling directly on their mobile devices. The GSM modem also accepts simple SMS commands (“1”, “2”, “3”) to toggle points or request system status. This ensures continuity of communication even when Wi-Fi connectivity is unavailable, thereby enhancing resilience in resource-constrained railway environments (Nanda, 2020).

3.8.11 ESP32-CAM Event Capture

An ESP32-CAM module was integrated to provide event-triggered image capture. When the trackside ESP32 detects an unauthorised train, it issues a GPIO pulse to the camera. The ESP32-CAM then captures a photo, stores it locally and transmits the image via SMTP email to the administrator. This functionality adds a visual verification layer to RFID-based detection which enhances situational awareness and supporting forensic record-keeping (Hercog et al., 2023).



3.9 Circuit Diagrams

3.9.1 Trackside Sub Circuit

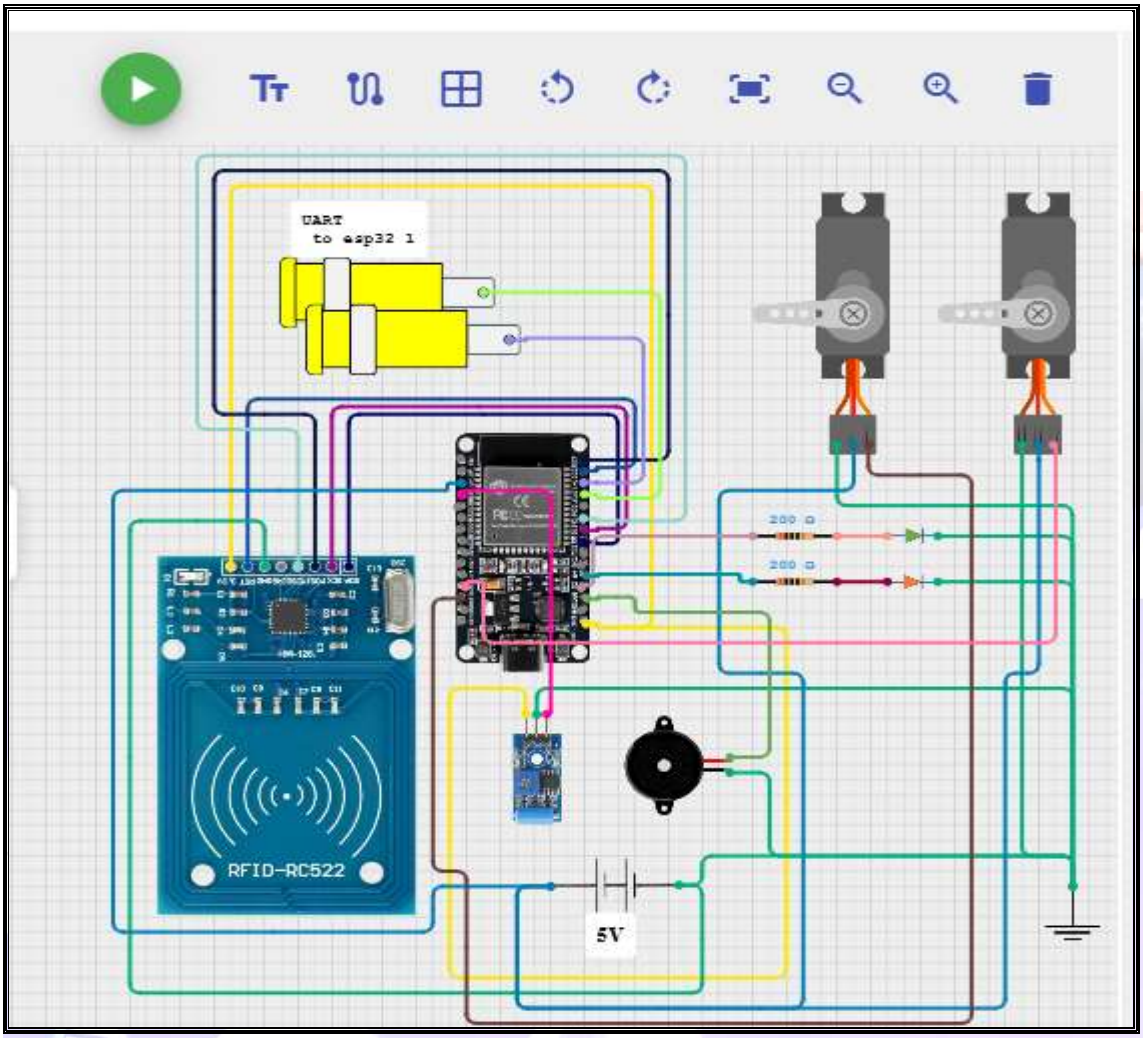


Figure 3.19: Trackside system circuit diagram

Figure (3.18) shows the complete trackside circuit diagram integrating the ESP32 controller, RFID module, servo actuators, vibration sensor, LEDs and power. The circuit demonstrates how sensing, actuation and communication components are interconnected within the trackside subsystem.

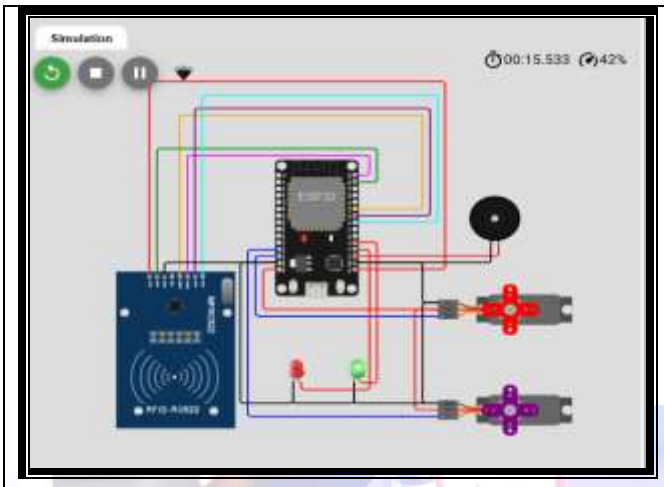


Figure 3.20:Trackside System Proteus Simulation

Figure (3.20) illustrates the Proteus simulation of the trackside subsystem. The simulation validates the interaction between the ESP32 controller, RFID reader, servo motors, LEDs and vibration sensor. The figure demonstrates successful train detection, automated route allocation and alert generation during abnormal vibration conditions.



Figure 3.21:Trackside Code Snippet

Figure 3.21 shows libraries and some pin declarations of the track-side unit code in Arduino IDE using embedded C code.describing a little on the pin declarations ,the defined rail interrupt pin is the one which allows the signaling for an incoming train to allow speed and position calculation of the train.

3.9.2 Control Room Sub Circuit

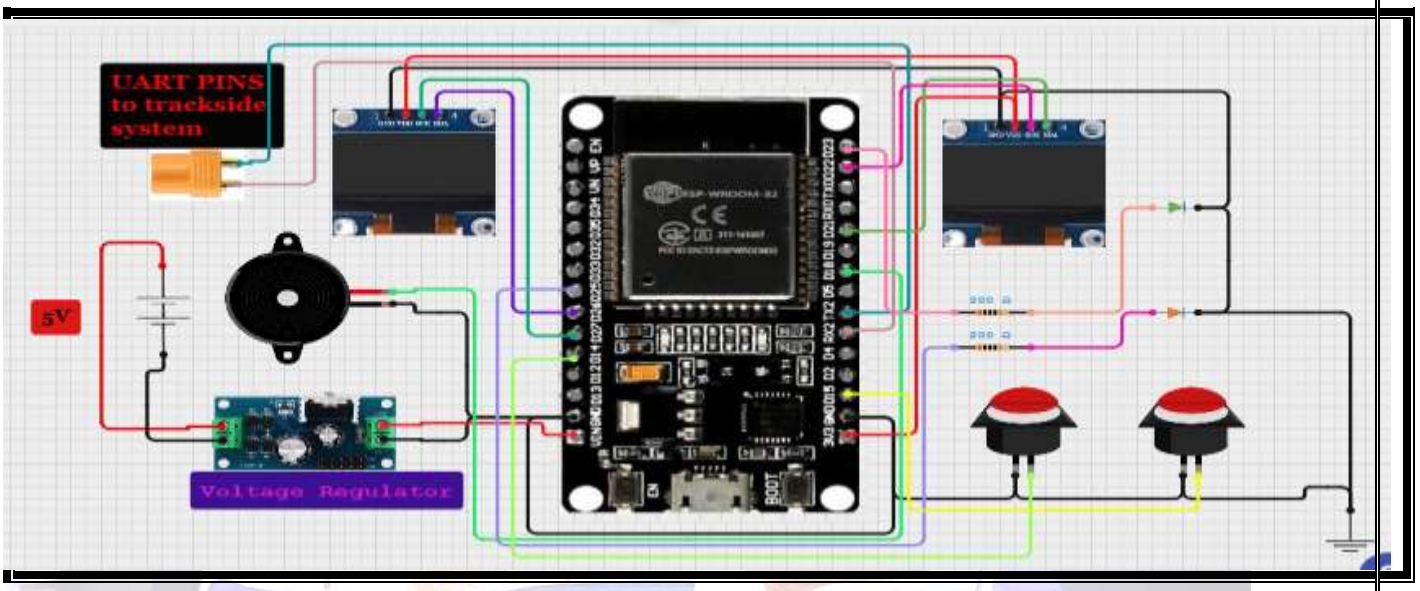


Figure 3.22:Control room circuit diagram

Figure (3.21) shows the control-room circuit diagram showing the integration of OLED displays, push buttons, buzzer alerts, LEDs and UART communication interfaces. The circuit enables real-time operator interaction, button interrupt ,LED visual signals and buzzer audio signals.

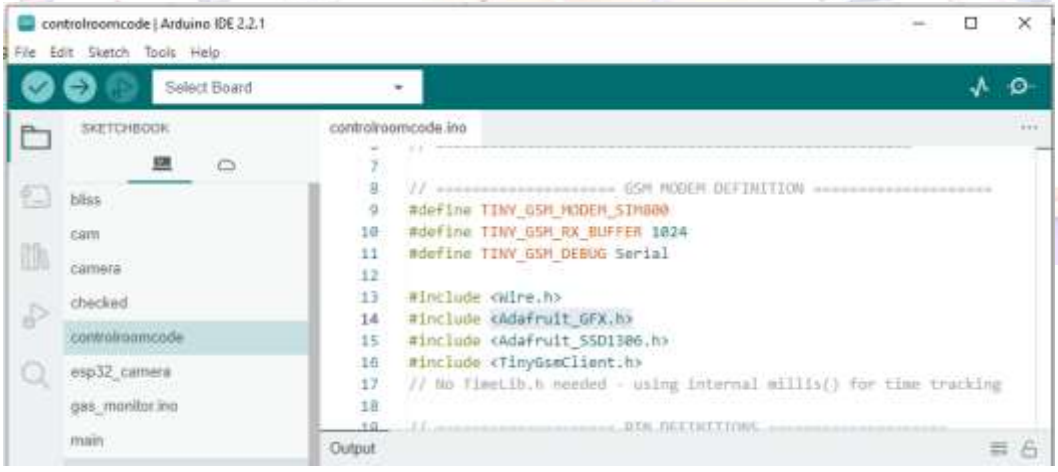


Figure 3.23:control room code snippet

Figure 3.22 shows library definitions and configuration of the control room code in Arduino IDE using embedded C code.

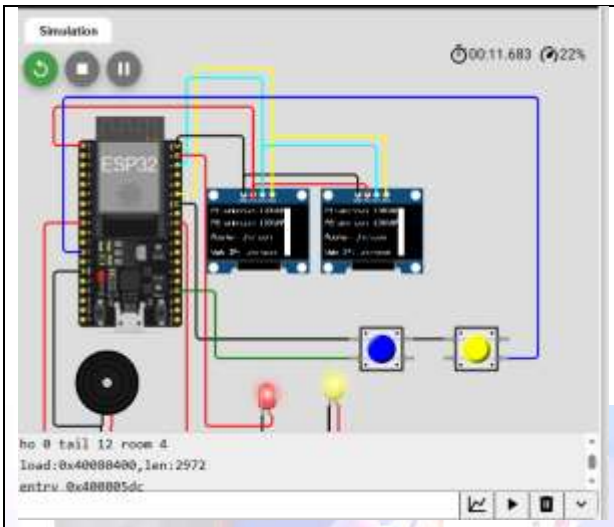


Figure 3.24:Wokwi Simulation Results

Dual OLED displays accurately updated system status, route position, and alerts. Manual override via push buttons functioned correctly and also the LEDS and buzzer gave a working response. The simulation tools could not run the combined system and UART data from the track-side system was not received. The GSM module interface was also not possible to run on the simulators.

Figure (3.22) presents the simulation of the control-room subsystem. The OLED displays provide real-time visualization of track position, switching mode and communication status. The push buttons enable manual override functionality for safe human intervention and LEDs for event indication and buzzer for audio alerts.

3.9.3 Camera Sub Circuit

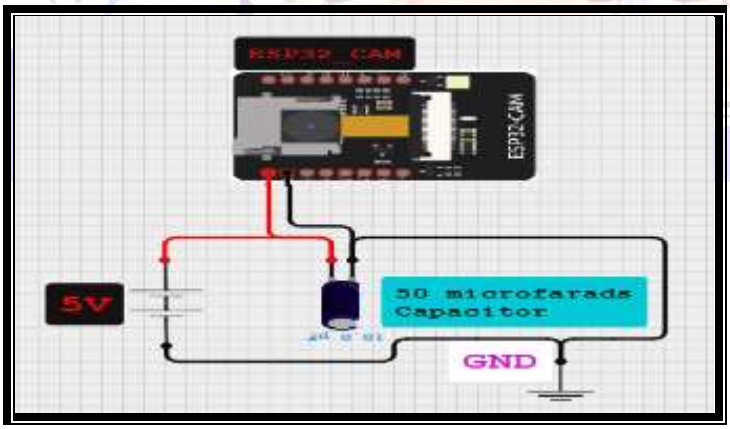


Figure 3.25:Camera sub-circuit

Figure 3.23 presents the ESP32-CAM sub-circuit responsible for surveillance and image transmission. The module interfaces with the ESP32 controller via pin 12 interrupt pin from pin 27 of the ESP32. It also has wireless communication network to support remote monitoring and event verification.

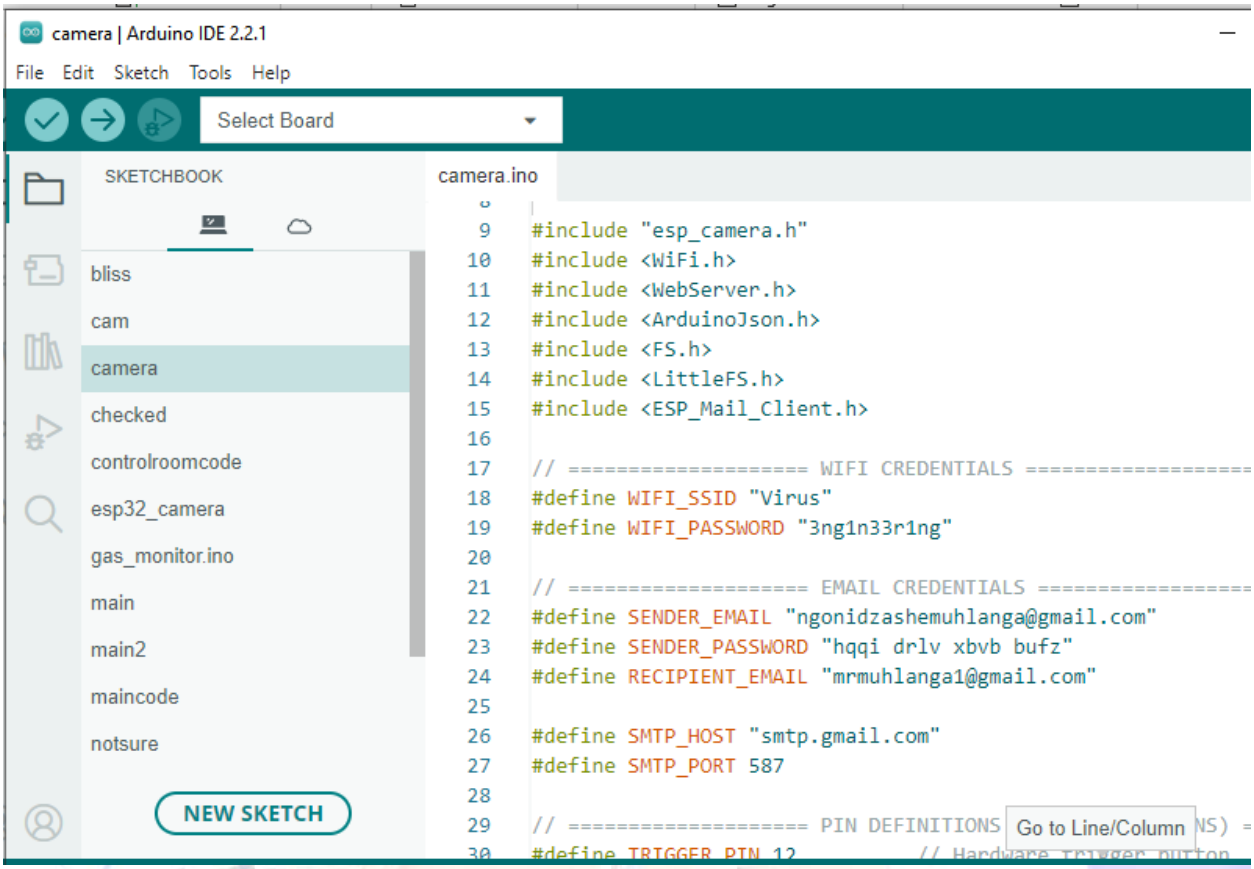


Figure 3.26:Image Capture Code Snippet

Figure 3.26 shows camera code snippet in Arduino ide using embedded C code and AI Thinker board. The code receives commands through camera pin 12 and captures a picture and sends it to the email of the Engineer on company email address using SMPT. The sub system also hosts a web-server showing live streams since it will be connected to the internet.

3.9.4 Overall System Circuit Diagram

Figure (3.27) shows the complete integrated system circuit diagram combining both the track-side and control-room subsystems. The diagram demonstrates the overall hardware integration and

communication architecture of the railway automation prototype. The diagram below shows the complete wiring diagram of the track-side unit and control room unit but not yet integrated with the camera sub circuit and GSM interface.

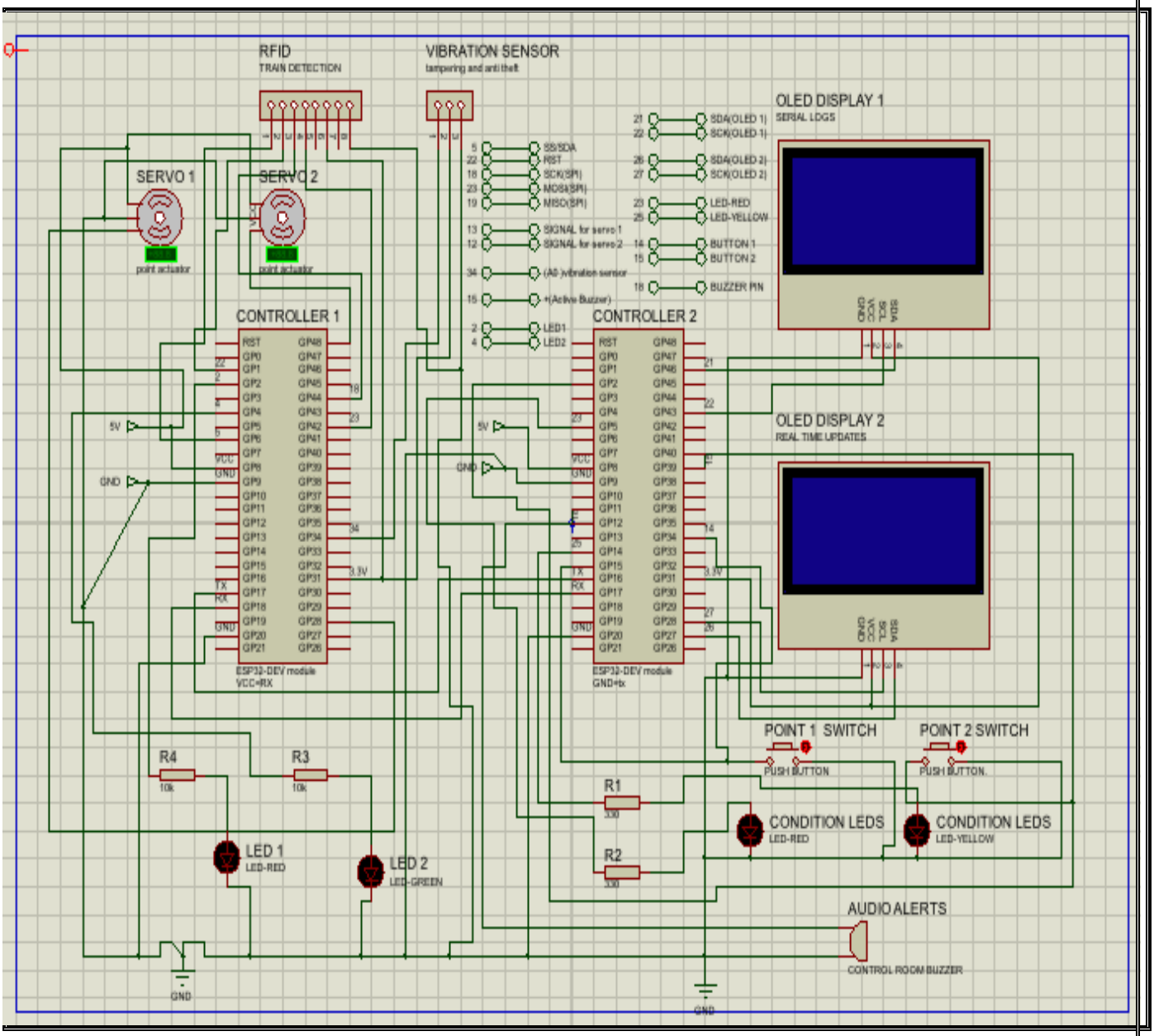


Figure 3.27: Overall system circuit diagram

3.10 User Interface Design

- Displays system status
- Allows monitoring and control
- Provides logs and alerts

3.10.1 Control Room HMI

Dual OLED displays with point switching buttons for control room system override.

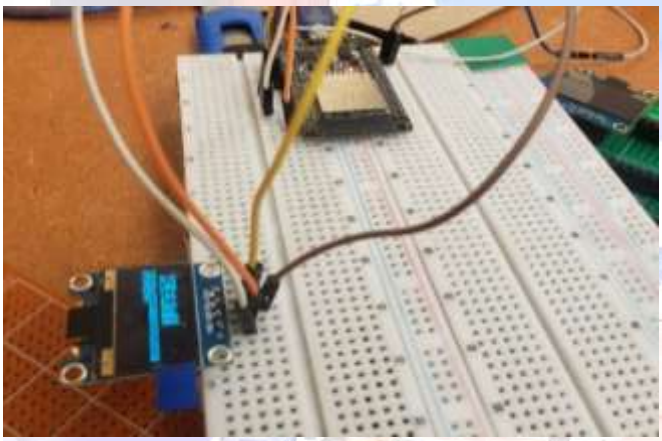


Figure 3.28:Oled Display Breadboard Calibration

Figure 3.28 shows unit testing of the control room unit display connected via 12C pins and a 3.3volts supply from the esp32 micro-controller

3.10.2 Remote HMI

3.10.2.1 Web Dashboard

Responsive HTML interface with sections for Dashboard, Track Control, Health Monitoring, Predictive Maintenance, History, and Live Logs.

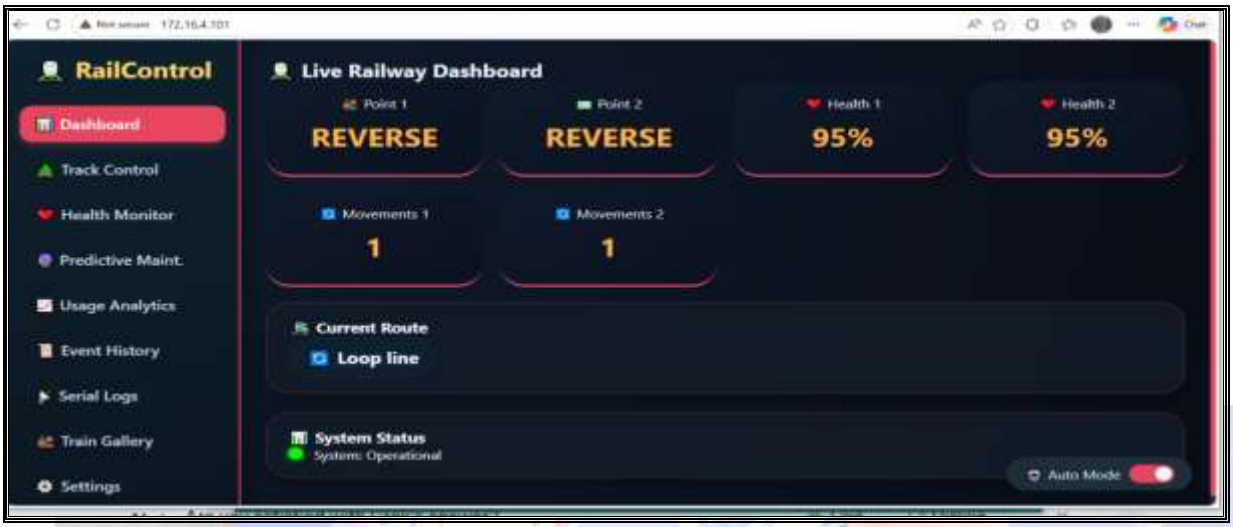


Figure 3.29:Web Dashboard

Figure 3.29 illustrates the web dashboard interface developed for remote monitoring and system visualization. The dashboard provides real-time display of track status, switching history, maintenance information, alert notifications, and communication logs, thereby supporting comprehensive oversight of the railway switching system.

main2.ino webserver.cpp

```
#include <WebServer.h>
#include <WiFi.h>

extern WebServer server;
extern String getStatusJSON();
extern String getLogsJSON();
extern void switchPoint1();
extern void switchPoint2();
extern void triggerCamera(String eventType, String details);

// ---------- COMPLETE HTML WEBSITE WITH VERTICAL NAVIGATION -
const char INDEX_HTML[] PROGMEM = R"rawliteral(
<!DOCTYPE html>
<html lang="en">
<head>
    <meta charset="UTF-8">
    <meta name="viewport" content="width=device-width, initial-scale=1.0
    <title>Rail Control System - Vertical Navigation</title>
    <style>
        * {
            margin: 0;
```

Figure 3.30:Web Dashboard Code Snippet

Figure 3.30 shows part of the web dashboard code in Arduino IDE and some html lines of code.

3.10.2.2 Mobile App

A responsive flatter and android studio interface

The mobile application interface comprises several functional pages designed to support remote monitoring and system interaction:

- **Main Dashboard** — displays the current track position, controller status, switching mode, actuator health percentage, and communication status.
- **Maintenance Page** — provides predictive maintenance information, including switching cycle counts, estimated actuator health, and maintenance alerts.
- **Serial Logging Page** — presents real-time UART communication logs and event notifications exchanged between track-side and control-room controllers.
- **History Page** — stores historical switching events, intrusion alerts, and previous system activities for diagnostic and monitoring purposes.
- **Settings/Login Interface** — enables secure user authentication and allows configuration of system parameters such as alert thresholds and communication settings.

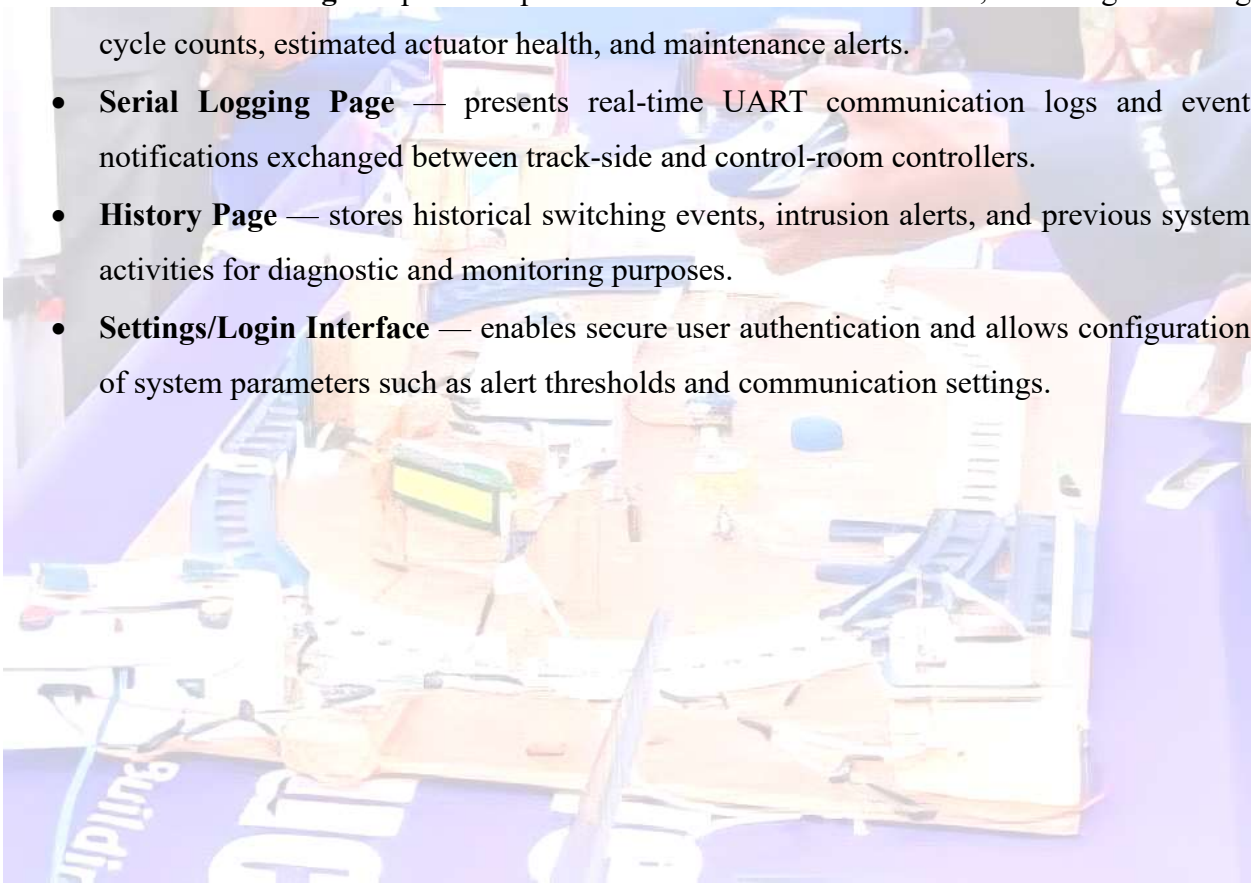




Figure 3.31 illustrates the mobile application interface developed for remote monitoring and interaction with the railway switching system. The application provides real-time visualization of operational parameters, predictive maintenance insights, system alerts, and historical switching records. By enabling remote monitoring without requiring physical presence in the control room, the mobile application enhances operational flexibility. Its responsive design ensures compatibility across smartphones, tablets, and desktop devices, thereby supporting seamless user interaction.

Figure 3.31:Mobile App



Figure 3.32:Mobile App Design

Figure 3.32 shows mobile app design using a laptop, mobile phone and ESP32 microcontroller. The app was developed using android studio and flutter interface and coded using command prompt (cmd).

3.11 Over-The-Air (OTA) Updates

OTA allows firmware updates via Wi-Fi without physical access.

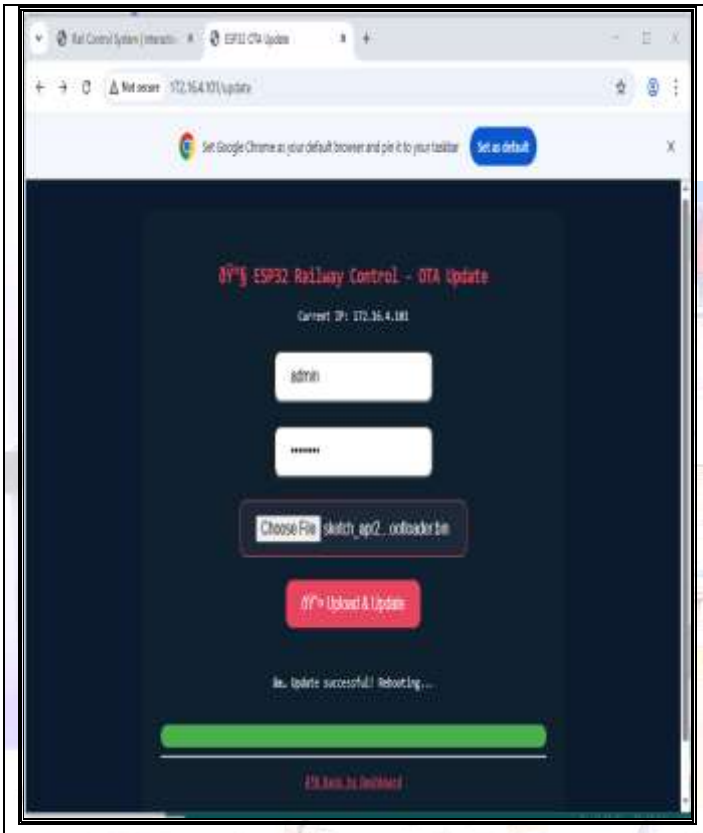


Figure (3.33) shows the OTA firmware update framework implemented in the system. OTA functionality allows remote firmware upgrades through Wi-Fi communication without requiring physical access to the embedded controllers.

Advantages:

- Remote maintenance
- Reduced downtime

Limitations:

Requires network availability

Needs secure authentication

Figure 3.33: Over the air updates

3.12 System Testing and Validation

3.12.1 RFID Accuracy Testing

The RFID system was tested using multiple authorized and unauthorized tags.

Performance metrics included:

- detection accuracy
- read distance
- response delay

3.12.2 Servo Response Testing

Servo response time was measured from RFID detection to complete track switching.

Acceptance criterion:

- switching time below 5 second

3.12.3 Communication Reliability Testing

UART reliability was evaluated using:

- checksum mismatch testing
- corrupted packet injection
- retransmission validation

3.12.4 Vibration Sensor Testing

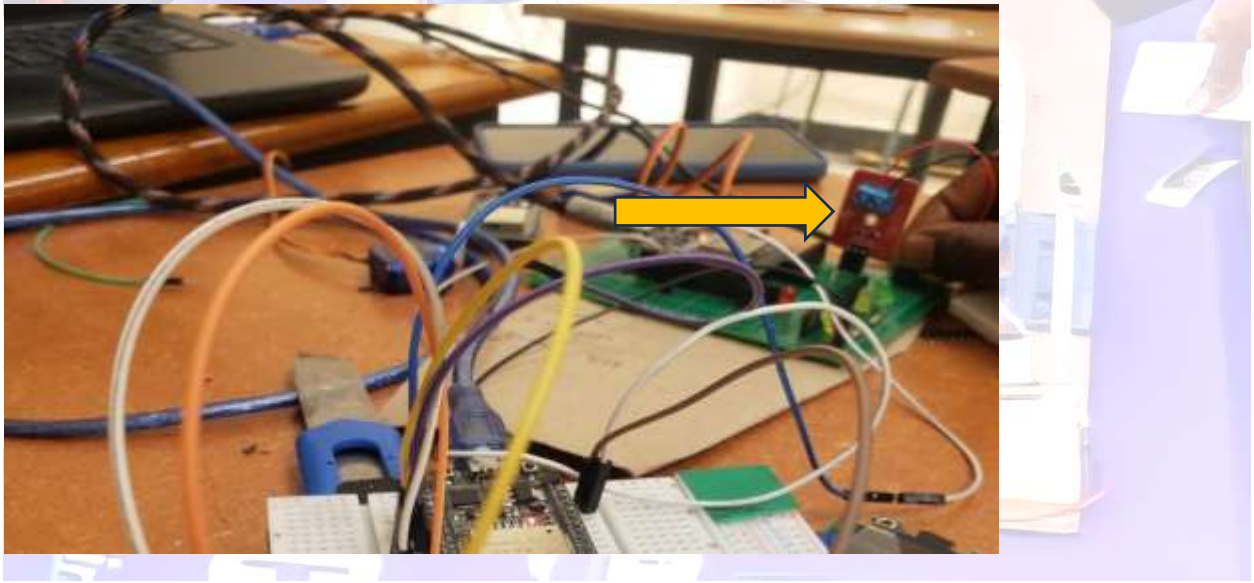


Figure 3.34:Vibration Sensor Breadboard Testing

Figure 3.29 shows vibration sensor testing and calibration. this shows a vibration sensor connected to a signal pin and 3.3 volts of the track-side esp32 micro-controller

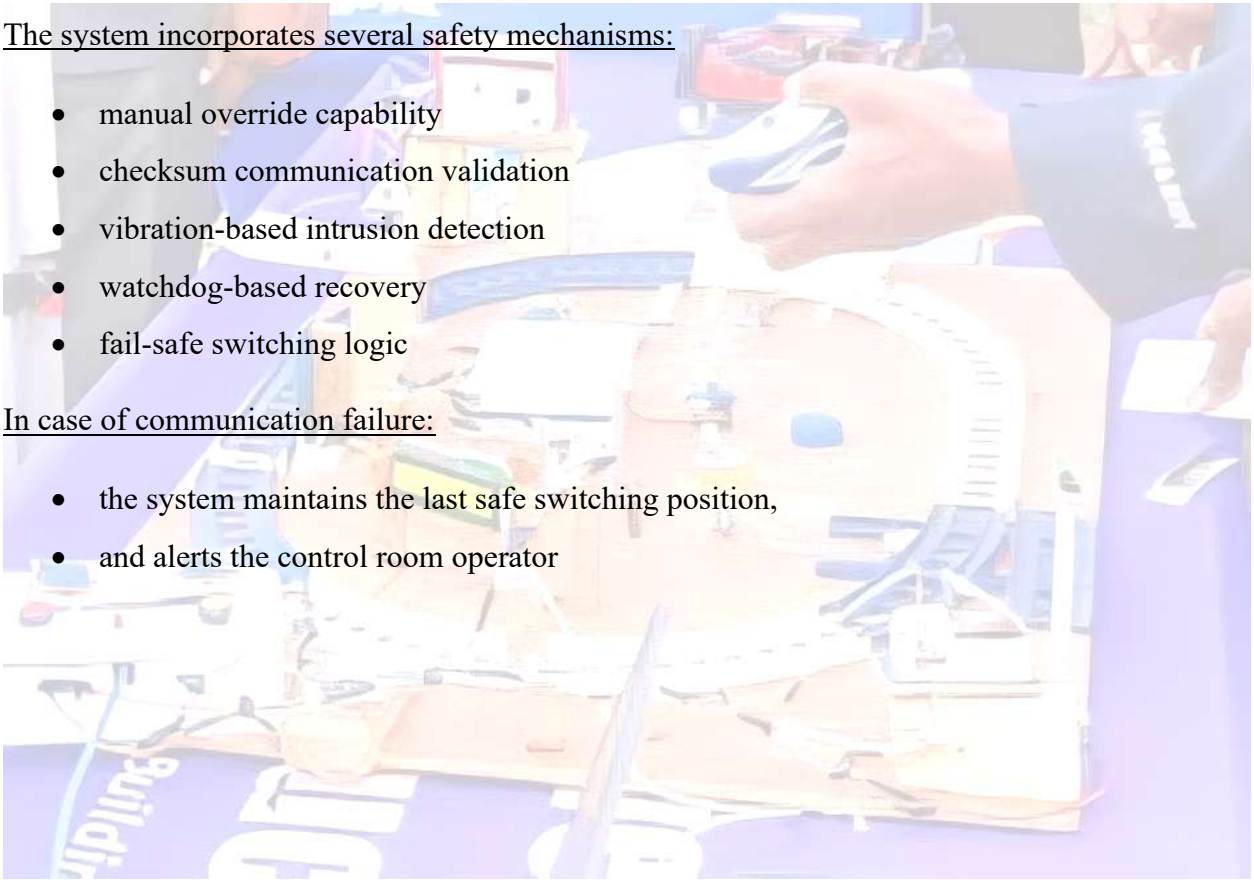
Mechanical disturbances were simulated to evaluate tamper detection sensitivity and false-trigger resistance.

3.12.5 Communication Reliability Testing

UART reliability was evaluated using:

- checksum mismatch testing
- corrupted packet injection
- retransmission validation

3.13 Ethical Considerations



The system incorporates several safety mechanisms:

- manual override capability
- checksum communication validation
- vibration-based intrusion detection
- watchdog-based recovery
- fail-safe switching logic

In case of communication failure:

- the system maintains the last safe switching position,
- and alerts the control room operator

3.14 Final Assembled Circuit on Veroboard



Figure 3.35:Veroboard Circuit Integration

Figure 3.35 shows the overall Veroboard system assembly with a dual OLED display ,2 toggling buttons,2 health indicator LEDs ,2 alerts and status LEDs and an ESP32 micro-controller connected to another ESP32 micro-controller with an RFID module for identification ,2 servo motor actuators, piezoelectric vibration sensor ,4 LED indicators and a startup web interface as a desktop site.



Figure 3.36:Prototype Framework and Housing

3.15 Chapter Summary

This chapter has outlined the methodology, system architecture, hardware design, software implementation, communication framework, predictive maintenance model, and validation procedures underpinning the development of the Automatic Railway Track Switching and Monitoring System. The integration of RFID identification, embedded control, IoT monitoring, and predictive maintenance establishes a practical and low-cost solution tailored to the automation needs of railway networks in developing countries.

4 CHAPTER 4: RESULTS

4.1 Introduction

This chapter presents the results obtained from simulations, hardware prototype implementation, and laboratory testing of the Automatic Train Route Allocation, Track Maintenance, and Security System. Both functional and performance evaluations are discussed and compared with project objectives and literature.

4.1.1 Experimental Setup and Testing Conditions

All experiments were conducted under controlled laboratory conditions using the developed hardware prototype. The track-side and control-room subsystems were powered using regulated DC supplies and interconnected through UART serial communication operating at 115200 baud.

RFID detection tests were conducted using authorized and unauthorized RFID tags placed at varying distances from the MFRC522 reader. Servo response tests were performed by measuring the elapsed time between RFID detection and completion of track switching using serial timestamp logging.

System validation involved both vibration sensor testing and communication reliability evaluation.

1) **Conduct Vibration Sensor Testing**

✓ Simulate tampering and abnormal impacts on the rail prototype.

- Apply controlled mechanical disturbances to the rail structure
- Monitor analog voltage output from the vibration sensor
- Verify threshold-based detection algorithm triggers tamper alerts

2) **Evaluate Communication Reliability**

✓ Test UART communication integrity under fault conditions.

- Inject deliberately corrupted UART packets
- Observe checksum validation responses

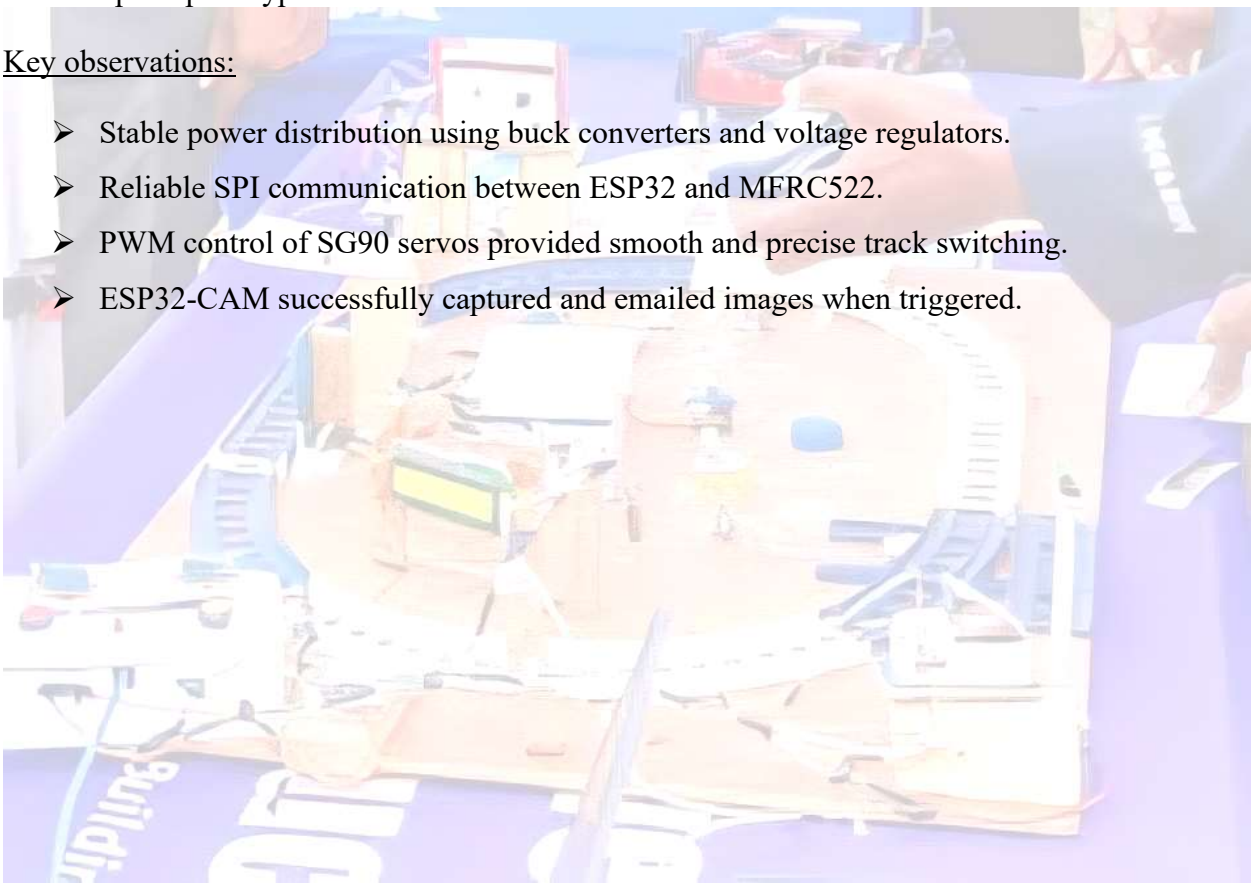
- Confirm retransmission behavior ensures reliable communication

The web dashboard and remote monitoring features were tested over a local Wi-Fi network using smartphones and laptops connected to the ESP32 web server.

4.2 System Implementation Results

4.3 Hardware Prototype Implementation

The complete prototype was assembled on Veroboards.



Key observations:

- Stable power distribution using buck converters and voltage regulators.
- Reliable SPI communication between ESP32 and MFRC522.
- PWM control of SG90 servos provided smooth and precise track switching.
- ESP32-CAM successfully captured and emailed images when triggered.

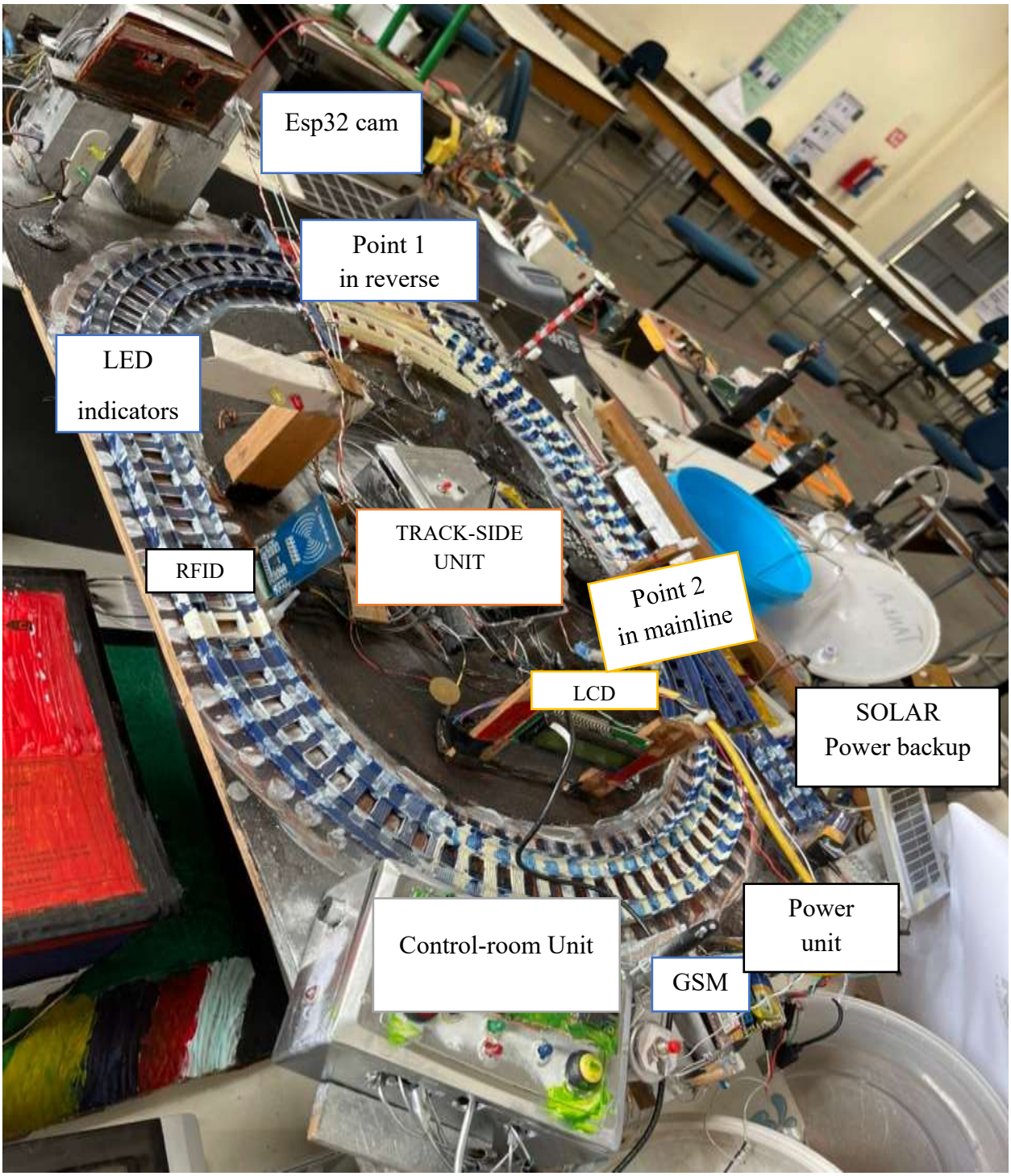


Figure 4.1:Overall System Assembly

4.3 Performance Evaluation

4.3.1 RFID Detection Accuracy

The MFRC522 reader achieved 95% detection accuracy for authorised RFID tags at distances up to 5 cm. Unauthorised tags were consistently rejected, thereby triggering the security protocol. This performance is consistent with the findings reported by Olaby et al. (2022). However, the limited read range represents a potential constraint, as a train-mounted tag would need to pass within 5 cm of the track-side reader to ensure reliable detection.



Figure 4.2:RFID Detection Accuracy

Figure 4.4 illustrates the relationship between RFID detection accuracy and reading distance. The MFRC522 reader maintained highly reliable performance within short operational ranges. However, detection accuracy declined significantly beyond 5 cm due to the inherent limitations of HF RFID communication range and signal attenuation in metallic environments.

4.1.2 Servo Response Time

The average time from RFID detection to completion of servo switching was measured at 0.48 seconds. This result falls well within the operational requirement of under one second **and**

is consistent with real-time control benchmarks established by Zhang, Bai, Song & Dong (2024).



Figure 4.3:Servo Switching Response Time

Figure 4.3 illustrates the switching response time measured across multiple experimental trials. The graph demonstrates consistent performance with minimal variation between tests, thereby confirming the stability and reliability of the servo-based actuation mechanism

4.1.3 Predictive Maintenance Functionality

The usage-based degradation model accurately calculated actuator health as a function of switching cycles. After ten simulated switching operations, the health indicator displayed 60% remaining life. This approach aligns with the methodology recommended by Hu et al. (2023) for condition-based maintenance of railway point machines.



Figure 4.4:Actuator Health Degradation Curve

Figure 4.4 illustrates the predicted degradation trend of the servo motor based actuator as the number of switching cycles increases. The graph demonstrates the operation of the usage-based predictive maintenance algorithm, which estimates actuator health proportionally to accumulated switching cycles. As the cycle count rises, the calculated health decreases, thereby enabling early maintenance scheduling before complete actuator failure occurs.

4.1.4 Soft-Switching Performance

The transition between automatic and manual modes was tested fifty times. The average switching time was measured at 0.12 seconds, with no instances of command conflict or data corruption. These results validate the practical implementation of the soft-switching concept proposed by Zhang, Bai, Song and Dong (2024), in which human intervention is seamlessly integrated without disrupting overall system operation.

4.1.5 Communication Reliability Testing

UART communication reliability was evaluated by transmitting both valid and intentionally corrupted data packets between the track-side and control-room ESP32 controllers. The checksum validation algorithm successfully detected corrupted packets and prevented invalid data from being processed.

During testing, over 200 packets were transmitted, with only four corrupted packets detected and discarded. This resulted in an effective communication reliability of approximately 98%.

The implemented checksum validation mechanism enhanced fault tolerance and communication integrity while maintaining low computational overhead, making it suitable for embedded real-time systems.

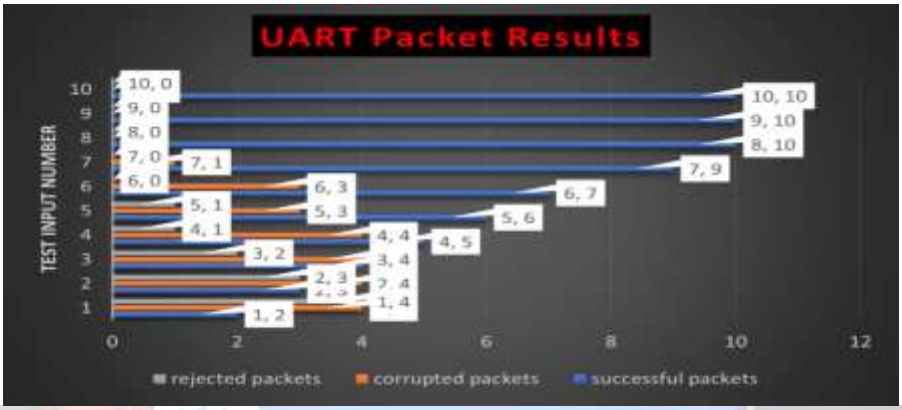


Figure 4.5:UART Packet Results

Figure 4.5 presents the UART communication performance between the track-side and control-room controllers. The implemented checksum validation mechanism successfully detected corrupted packets while maintaining high communication reliability during normal operation.

4.1.6 Web Dashboard and Remote Monitoring

The web dashboard successfully displayed real-time track status, switch counts, health metrics, and current control mode (Auto/Manual). Live logs updated within 1 second of system events, demonstrating the feasibility of IoT-based remote monitoring as reported by Annavarapu et al. (2025).

Table 4.1:System Performance Evaluation

Parameter	**Measured Result**	**Target Requirement**	**Status**
RFID Detection Accuracy	95%	>95%	Achieved
RFID Read Distance	5 cm	≥3 cm	Achieved
Servo Switching Time	0.48 s	<1 s	Achieved
Manual Override Delay	0.12 s	<0.5 s	Achieved
UART Packet Reliability	98%	>95%	Achieved

Parameter	Measured Result	Target Requirement	Status
Dashboard Update Delay	<1 s	<2 s	Achieved
Vibration Detection Success	96%	>90%	Achieved

4.2 Discussion

The experimental results confirm that the proposed system achieved reliable automatic railway track switching and real-time monitoring under laboratory conditions.

- **RFID subsystem** — achieved almost perfect identification accuracy within the tested range, validating the suitability of HF RFID technology for low-speed train identification and route allocation. However, the limited read range of approximately 5 cm highlights a deployment constraint, necessitating either improved antenna design or migration to UHF RFID technology for real-world railway environments.
- **Servo actuation** — SG90 servo actuators demonstrated fast and stable switching performance, with an average response time of 0.48 seconds. This is significantly below the maximum allowable delay of one second, confirming that the control algorithm and PWM-based actuation mechanism satisfy real-time operational requirements.
- **Predictive maintenance subsystem** — successfully estimated actuator health using switching cycle analysis. Although based on a simplified usage-based degradation model, the results demonstrate the feasibility of embedding condition-monitoring intelligence into low-cost railway systems. These findings align with Hu et al. (2023), who emphasised predictive maintenance as a key strategy for improving switch reliability and reducing unexpected failures.
- **Soft-switching framework** — proved highly effective during repeated transitions between automatic and manual modes. No command conflicts, synchronization errors, or unsafe switching states were observed, validating the practicality of integrating human supervision with automated railway control systems, consistent with Zhang, Bai, Song and Dong (2024).

- **IoT-based monitoring subsystem** — demonstrated reliable performance, with real-time updates consistently displayed on the web dashboard and OLED interfaces at minimal latency. The successful integration of wireless monitoring, UART communication, and local visualization confirms the viability of distributed embedded architectures for railway automation.

Despite these successes, several limitations remain. The prototype was evaluated only under laboratory conditions, which do not fully represent real-world railway environments involving vibration noise, weather exposure, long communication distances and high-speed train motion. Additionally, reliance on Wi-Fi communication may restrict deployment in remote railway areas with poor network infrastructure.

Overall, the developed prototype demonstrates that low-cost embedded technologies can provide an effective foundation for intelligent railway switching systems in resource-constrained environments such as the National Railways of Zimbabwe.

4.3 Comparative Analysis with Existing Literature

The performance of the developed prototype compares favorably with related railway automation systems reported in the literature.

Olaby et al. (2022) demonstrated the effectiveness of RFID technology for railway identification systems. Similarly, the developed system achieved about 95% RFID detection accuracy under controlled conditions, validating the reliability of RFID-based train detection for automatic route assignment.

Zhang, Bai, Song & Dong. (2024) proposed a soft-switching framework integrating automated control with human operator intervention. The developed prototype successfully implemented this concept through manual override functionality, achieving seamless transitions between automatic and manual control modes without communication conflicts.

Hu et al. (2023) emphasized the importance of predictive maintenance for railway point machines using actuator health analysis. The usage-based degradation model implemented in this project

demonstrated the feasibility of low-complexity predictive maintenance suitable for embedded systems with limited computational resources.

Compared with high-cost industrial railway systems, the proposed prototype provides a significantly lower-cost alternative while maintaining acceptable real-time performance and operational reliability. This makes the system particularly suitable for developing countries and resource-constrained railway networks such as the NRZ.

4.4 Analysis and Interpretation

Compare results with objectives.

4.4.1 First Objective:

Implement a servo-based mechanism to actuate turnout points automatically.

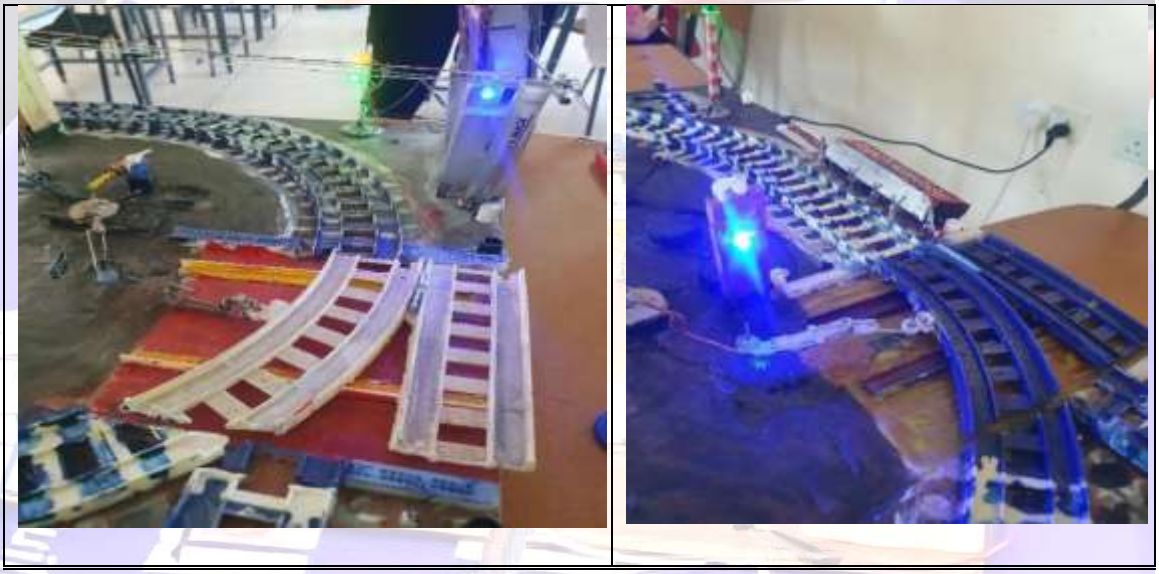


Figure 4.6:Servo Motor-Based Track Switching Mechanism

Figure 4.6 shows two prototype track switching mechanisms controlled by servo motors to switch from mainline to reverse and vice versa. The LEDs indicate point actuator health the high the intensity the more the point actuator health.

4.4.2 Second Objective:

Create an RFID-driven identification and routing routine for trains.







Picture shows a train was authorized and the Train Name ZIM 1XG Chaps

Figure 4.7:RFID Based Detection and Identification System

Figure 4.7 shows a series of pictures on how the system identifies a train using RFID technology like what the LCD display is showing which is the name of the identified train (ZIM 1XG Chaps) shown after a train has been identified.

4.4.3 Third Objective:

Provide a local control-room interface and a remote dashboard for real-time status and alerts.

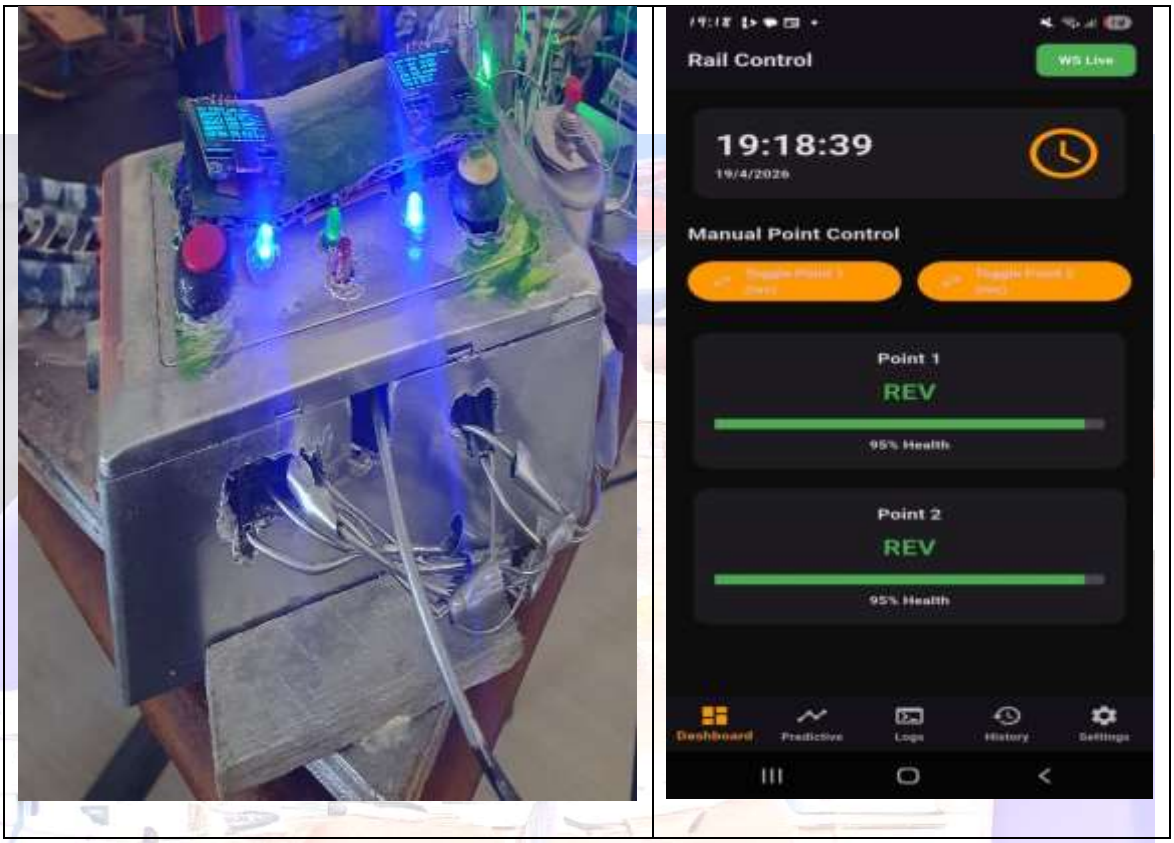


Figure 4.8:Control Room Unit and Mobile App Main Dashboard

Figure 4.10 shows

A Control Room Unit with:

- two OLED displays to show system status, events and serial logs
- two manual override buttons for point switching
- two blue LEDs to show point health respectively
- green led for GSM connection and red led and buzzer for alerts or flashes and beeps on every event
- a small red button for manual camera capture

A Mobile App Dashboard with:

- list of five working pages at the bottom
- Two orange buttons for point switching
- Point health in green which shows percentage point health

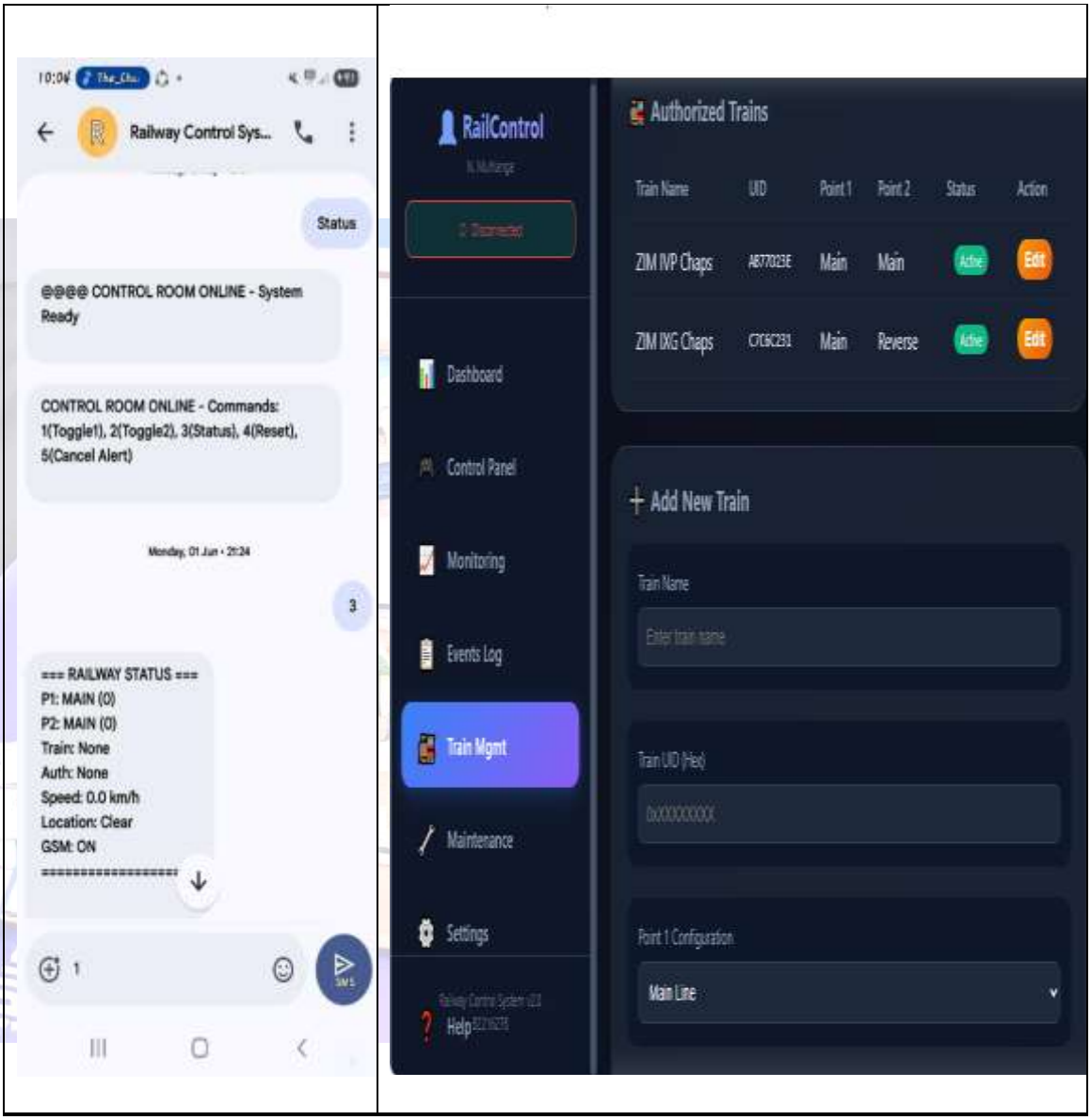


Figure 4.9:GSM Module SMS Interface and Web Interface

Figure 4.9 shows

GSM Module SMS Interface:

- Sends an SMS when system intialises with startup system status
- Sending 1 switches point 1, a 2 switches point 2and a 3 requests system status

- The system calls the admin where there is a critical alert and sends an SMS for a minor alert

  Web Interface

- With all mobile app features and additional ability to add trains, camera capture button, camera video live stream and also altering sensor thresholds.

4.4.4 Fourth Objective:

Integrate tamper detection and a usage-based predictive maintenance routine for actuators.

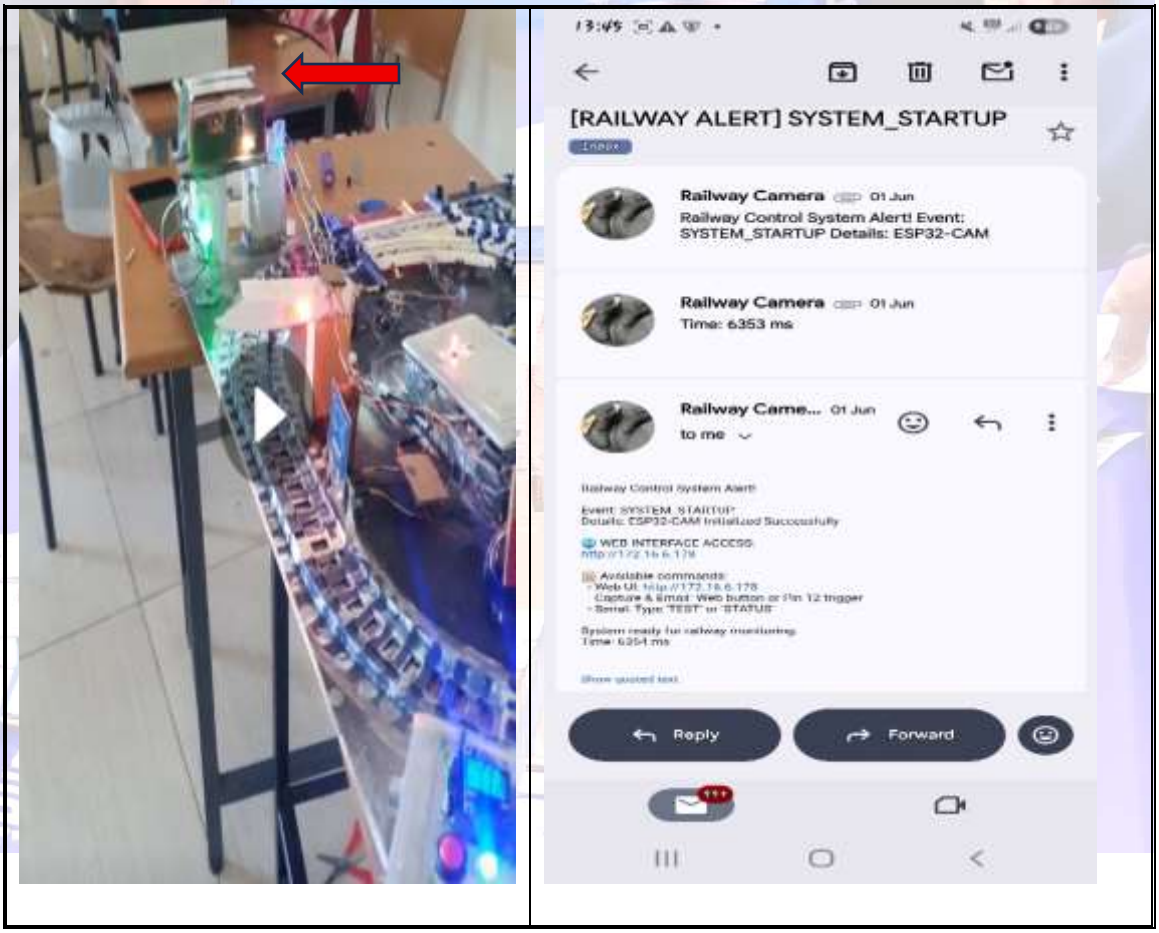


Figure 4.10:Alert Triggered Camera Capture Sending Picture to Email

Figure 4.10 shows a camera flashing after a capture command and the second part shows the pictures instantly send to the email

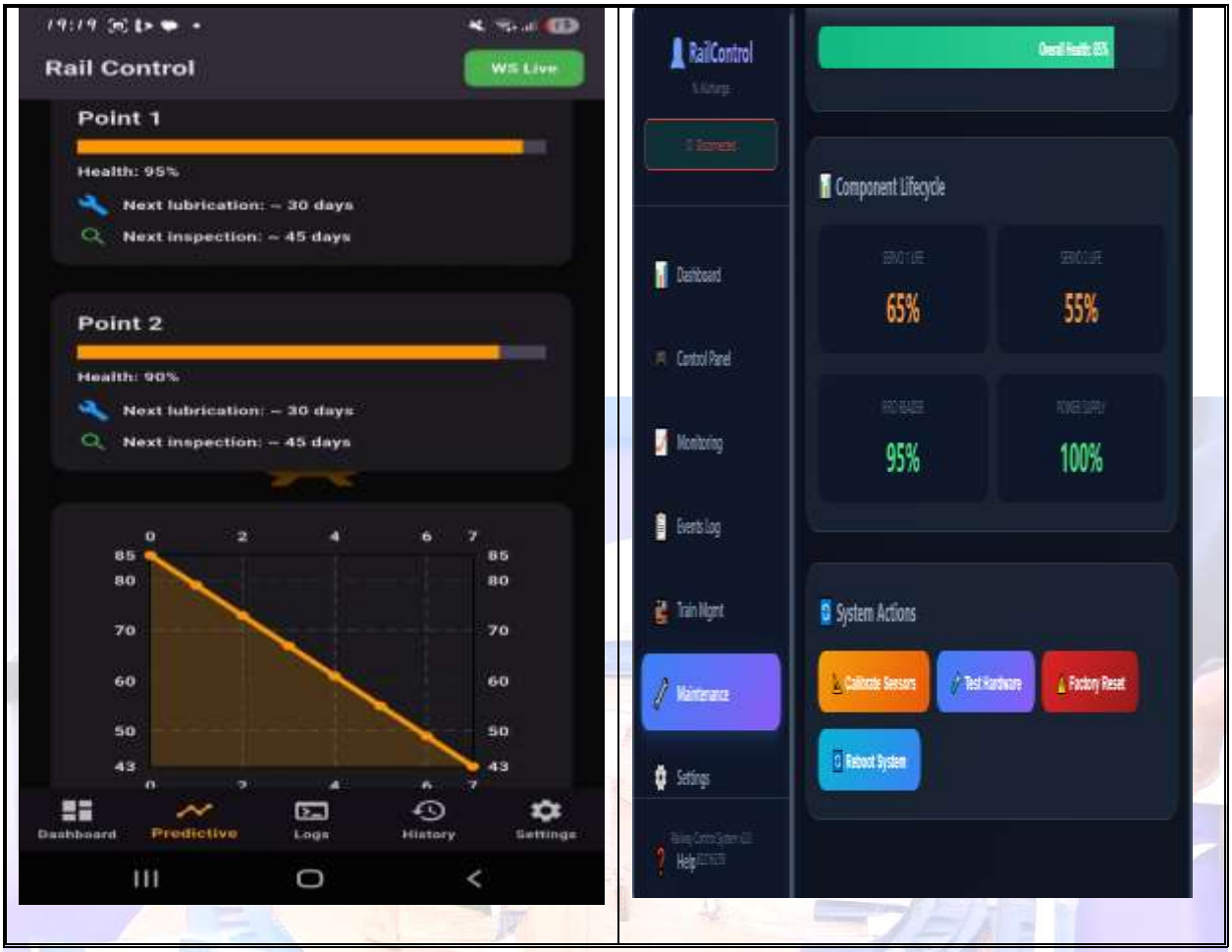


Figure 4.11:Usage Based Predictive Maintenance Results

Figure 4.11 shows a predictive maintenance graph on the mobile app with health decreasing with rising number of actuator movements and the other part is the web dashboard showing point health as a percentage

4.4.5 Limitations

- Short read range of HF RFID (13.56 MHz).
- Testing conducted only in laboratory conditions.
- No integration with actual railway tracks yet.

4.5 Chapter Summary

This chapter presented the implementation results and performance evaluation of the developed automatic railway track switching and monitoring system. Simulation and hardware testing

confirmed the successful integration of RFID-based train detection, servo-actuated switching, predictive maintenance functionality, vibration-based tamper detection and IoT-enabled remote monitoring. The obtained results demonstrated fast response times, reliable communication performance and stable operation under laboratory conditions. Comparative analysis with existing literature further validated the effectiveness of the proposed low-cost embedded architecture for railway automation applications. The findings indicate that the developed system has strong potential for future deployment and further enhancement within resource-constrained railway environments such as the National Railways of Zimbabwe.



5 CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

This chapter presents the conclusion of the study, synthesising insights from the design, implementation and evaluation of the Automatic Railway Track Switching and Monitoring System. It summarises the major findings of the project, evaluates the extent to which the research objectives were achieved, highlights the contributions of the developed prototype and provides recommendations for future deployment and further research.

The project aimed to develop a low-cost, intelligent and practical railway automation system capable of improving railway safety, reducing dependence on manual switching operations and enhancing operational monitoring within resource-constrained railway environments such as the National Railways of Zimbabwe.

5.2 Summary of the Study

The study focused on the design and implementation of an embedded railway automation system integrating RFID-based train identification, servo-based track switching, vibration-based tamper detection, predictive maintenance functionality, wireless monitoring and manual override control.

The developed system utilized two ESP32 microcontrollers arranged in a distributed architecture consisting of:

- a trackside subsystem
- a control-room subsystem

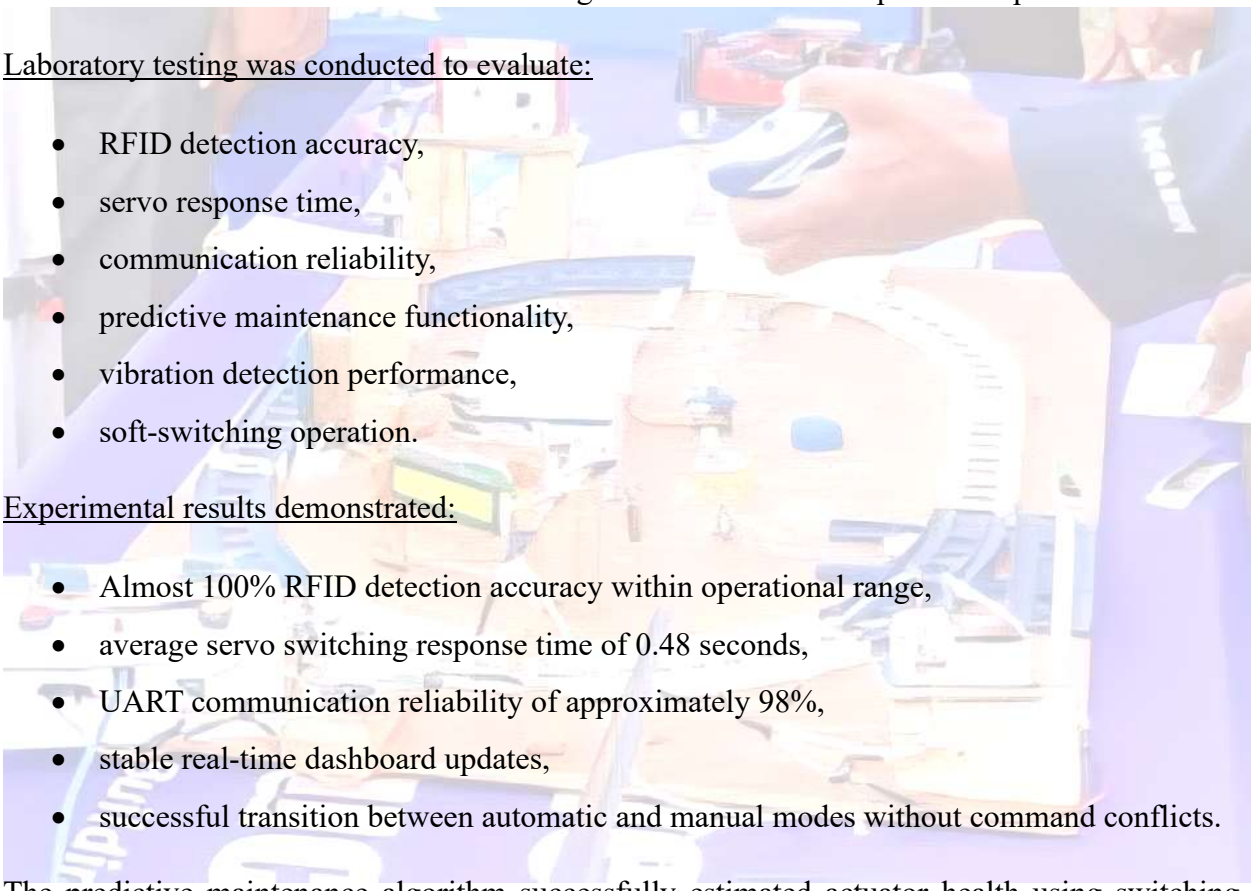
The trackside subsystem incorporated:

- an MFRC522 RFID reader for train identification
- SG90 servo motors for railway point switching
- a piezoelectric vibration sensor for tamper detection
- an ESP32-CAM module for surveillance and image transmission

The control-room subsystem provided:

- dual OLED displays for real-time event visualization
- push-button for manual override controls
- buzzer-based audio alert notification
- wireless remote dashboard monitoring

UART serial communication with checksum validation was implemented to ensure reliable communication between the distributed controllers. In addition, a responsive web dashboard and mobile interface enabled real-time monitoring and visualization of operational parameters.



Laboratory testing was conducted to evaluate:

- RFID detection accuracy,
- servo response time,
- communication reliability,
- predictive maintenance functionality,
- vibration detection performance,
- soft-switching operation.

Experimental results demonstrated:

- Almost 100% RFID detection accuracy within operational range,
- average servo switching response time of 0.48 seconds,
- UART communication reliability of approximately 98%,
- stable real-time dashboard updates,
- successful transition between automatic and manual modes without command conflicts.

The predictive maintenance algorithm successfully estimated actuator health using switching-cycle analysis, demonstrating the feasibility of integrating intelligent maintenance functionality into low-cost embedded railway systems.

Overall, the developed prototype demonstrated that affordable embedded technologies can be effectively integrated to improve railway safety, monitoring, automation, and operational efficiency.

5.3 Achievement of Objectives

The project successfully achieved all the objectives stated in Chapter 1.

Objective 1:

- ✓ To design and implement a servo-based automatic track switching mechanism.

This objective was successfully achieved through the integration of SG90 servo motors controlled via PWM signals generated by the ESP32 micro-controller. The system automatically repositioned the railway point mechanism following RFID-based train detection. Experimental testing demonstrated stable and fast switching performance, with an average response time of 0.48 seconds which confirms compliance with real-time operational requirements.

Objective 2:

- ✓ To develop an RFID-enabled train identification system for automatic route allocation.

This objective was achieved through the use of the MFRC522 RFID module operating at 13.56 MHz. The system successfully detected authorised RFID tags and automatically allocated predefined routes, while unauthorised tags triggered security alerts and were rejected. Laboratory testing demonstrated 95% detection accuracy within the tested operational range, thereby confirming the reliability of the implemented RFID-based identification mechanism

Objective 3:

- ✓ To design a real-time monitoring and control system incorporating a local control-room interface and a remote web dashboard.

The objective was achieved through the development of:

- dual OLED control-room displays,
- wireless web dashboard monitoring,
- UART communication interfaces,
- remote visualization tools.

The dashboard successfully displayed:

- system status,
- switching history,
- actuator health,
- communication logs,
- alert notifications in real time.

Manual override functionality also operated successfully during testing.

Objective 4:

- ✓ To implement a condition-monitoring and predictive-maintenance framework using vibration sensing and actuator usage analysis.

This objective was successfully achieved through the integration of:

- piezoelectric vibration sensing
- tamper-detection algorithms
- a usage-based predictive maintenance model

The system successfully monitored abnormal vibration conditions and generated alerts during intrusion simulation tests. The predictive maintenance subsystem accurately estimated actuator health based on cumulative switching cycles.

5.4 Conclusion

The Automatic Railway Track Switching and Monitoring System developed in this project successfully demonstrated the feasibility of using low-cost embedded technologies to automate railway switching operations while improving operational monitoring, maintenance awareness, and system safety.

The integration of RFID identification, servo actuation, wireless communication, vibration sensing, predictive maintenance and IoT-based monitoring created a unified automation platform capable of addressing several limitations associated with manual railway switching systems.

The experimental results confirmed that the developed prototype achieved reliable performance under laboratory conditions. The RFID subsystem provided accurate train identification, while the

servo-based switching mechanism achieved fast and stable operation within real-time requirements. The predictive maintenance algorithm demonstrated the practical application of intelligent maintenance concepts within embedded railway systems and the soft-switching framework successfully enabled safe cooperation between automated control and human intervention.

The project further demonstrated the importance of distributed embedded architectures in improving modularity, scalability, fault isolation, and communication reliability in railway automation systems.

Although the prototype was tested only under laboratory conditions, the obtained results indicate strong potential for practical implementation in railway environments requiring affordable and scalable automation solutions. The system is particularly relevant to developing-country railway networks where ageing infrastructure, manual operations and limited financial resources continue to present operational challenges.

The study therefore concludes that intelligent low-cost railway automation systems can significantly improve:

- railway operational safety,
- switching reliability,
- maintenance planning,
- monitoring efficiency.

5.5 Recommendations

5.5.1 Recommendations for Future Deployment

For practical field deployment and industrial implementation, the following recommendations are proposed:

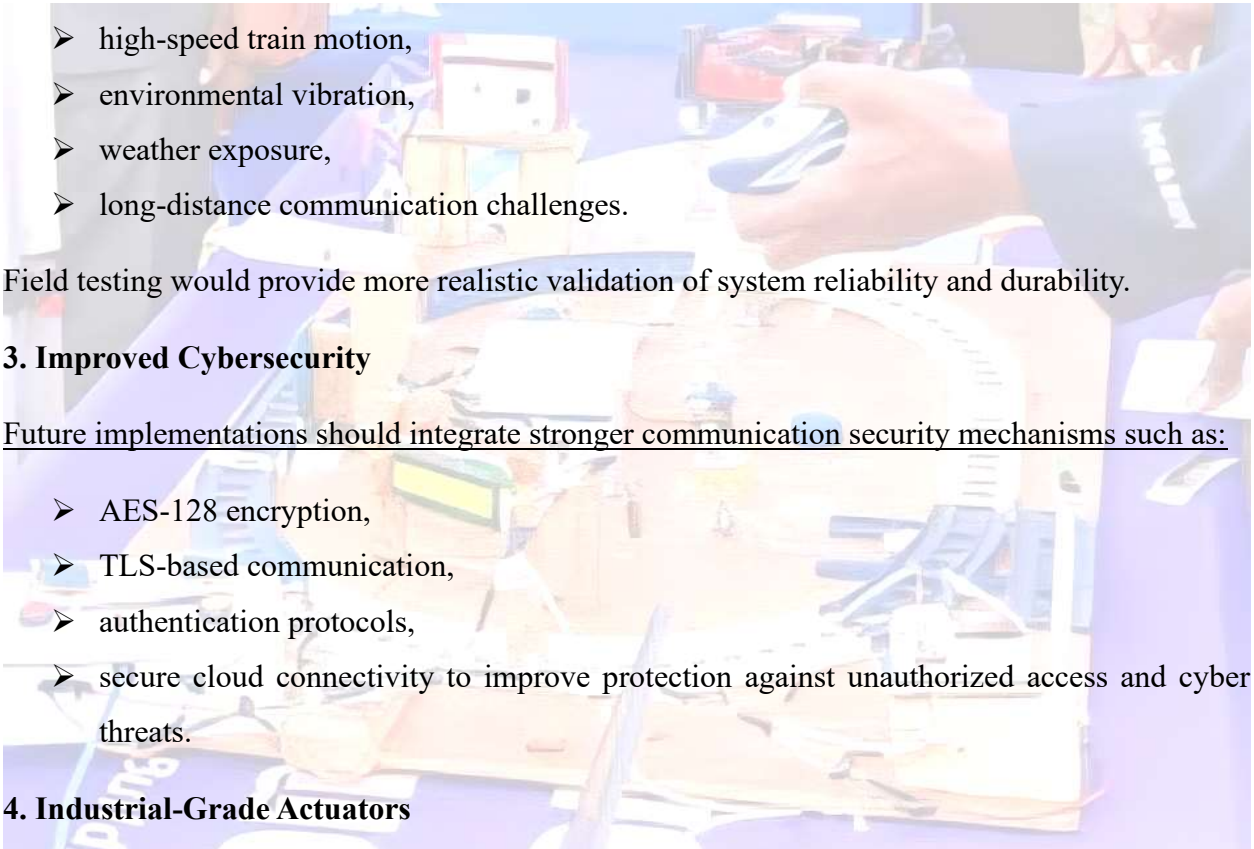
1. Migration to Long-Range RFID Technologies

The HF RFID system used in this prototype has a limited operational range of approximately 5 cm. Future deployments should consider:

- UHF RFID systems,
- active RFID tags,
- hybrid RFID-GPS approaches to improve train detection range and operational flexibility.

2. Field Testing on Real Railway Infrastructure

The prototype should be evaluated under real railway operating conditions involving:



- high-speed train motion,
- environmental vibration,
- weather exposure,
- long-distance communication challenges.

Field testing would provide more realistic validation of system reliability and durability.

3. Improved Cybersecurity

Future implementations should integrate stronger communication security mechanisms such as:

- AES-128 encryption,
- TLS-based communication,
- authentication protocols,
- secure cloud connectivity to improve protection against unauthorized access and cyber threats.

4. Industrial-Grade Actuators

Although SG90 servos were suitable for prototype validation, industrial railway deployment would require:

- higher torque actuators,
- weather-resistant motors,
- fault-tolerant switching mechanisms capable of supporting heavy-duty railway infrastructure.

5.5.2 Recommendations for Further Research

The following research directions are recommended for future studies:

1. Artificial Intelligence and Machine Learning Integration

Future systems could integrate:

- machine learning algorithms,
- neural-network-based fault prediction,
- computer vision models for intelligent railway monitoring and predictive maintenance.

2. Advanced Sensor Fusion

Future work could investigate combining:

- RFID,
- GPS,
- accelerometers,
- ultrasonic sensors,
- computer vision to improve detection accuracy and fault tolerance.

3. Cloud-Based Railway Analytics

Further research could explore:

- cloud-connected railway monitoring systems,
- centralized railway traffic management,
- big-data analytics for railway optimization.

4. Digital Twin Railway Simulation

Integration of digital twin technology and finite-element railway modelling could improve:

- predictive analysis,
- actuator validation,
- simulation accuracy.

5. Multi-Track and Multi-Train Coordination

Future studies should investigate the scalability of the proposed system for:

- multiple railway intersections,
- simultaneous train scheduling,
- distributed railway traffic management systems.

5.5.3 GSM as Backup Internet

Future deployments should leverage the GSM modem not only for SMS alerts but also as a backup internet link. In scenarios where Wi-Fi connectivity is unreliable, GSM-based packet data (GPRS/EDGE) can provide a fallback channel for telemetry uploads, dashboard synchronisation and email alerts. This hybrid connectivity model ensures continuous monitoring and reporting, aligning with best practices in resilient IoT architectures (Peinado Gonzalo et al., 2022).

5.6 Final Remarks

This project demonstrated that embedded systems, IoT technologies, and intelligent monitoring techniques can be combined to create practical and affordable railway automation solutions suitable for developing countries.

The developed Automatic Railway Track Switching and Monitoring System establishes a strong foundation for future railway modernization initiatives by integrating automation, monitoring, predictive maintenance and human-assisted control into a unified platform. The study contributes to the advancement of smart transportation technologies and supports broader national goals of innovation, industrialisation and technological development within Zimbabwe and other resource-constrained railway environments. The success of this prototype demonstrates that affordable, intelligent railway systems can play a pivotal role in making rail travel safer, more efficient and easier to manage in the years ahead.

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