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The Surface Crack Concrete Sleeper Detection System Using Arduino

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Abstract

The safety and efficiency of railway operations rely heavily on the condition of concrete sleepers, which provide structural stability by distributing loads and maintaining track alignment. This study proposes a Surface Crack Concrete Sleeper Detection System using Arduino to address challenges posed by traditional manual inspection methods. The system integrates a high-resolution camera for capturing detailed images and a rotary encoder for precise measurement of sleeper chainage, all controlled by an Arduino-based platform. The system was tested at the Labu-Tiroi Section and successfully demonstrated its ability to detect cracks autonomously. This innovative approach enhances the efficiency and accuracy of railway maintenance, reduces costs, and ensures safety.

1. Introduction

The integrity and functionality of railway infrastructure depend significantly on the condition of concrete sleepers, which serve as a stable base for distributing rail loads and maintaining track alignment. Aging railway tracks and environmental factors increase the susceptibility of concrete sleepers to surface cracks, which, if left undetected, can lead to severe structural issues, operational inefficiencies, and safety hazards. Traditional inspection methods, such as manual inspections, are labor-intensive, time-consuming, and prone to human error. While existing automated systems offer improvements, they often lack the precision required for accurate detection and measurement of subtle cracks. To address these challenges, the Surface Crack Concrete Sleeper Detection system using Arduino is proposed as an innovative solution. The system integrates a high-resolution camera to capture detailed images of sleeper surfaces and a rotary encoder for precise measurement and location mapping of detected cracks. Controlled by an Arduino-based platform, the system automates crack detection and provides remote monitoring capabilities, significantly reducing reliance on manual inspections while enhancing accuracy, efficiency, and response times. This research aims to bridge the gaps in existing inspection methods by providing a cost-effective and user-friendly system that ensures the safety and reliability of railway operations. By automating the crack detection process, the proposed solution not only improves the efficiency of maintenance activities but also reduces operational risks and costs, offering a sustainable approach to maintaining railway infrastructure.

1.1 Problem Statement and Objectives

The safety and reliability of railway infrastructure are crucial for the efficient transportation of goods and passengers. However, aging railway tracks, particularly concrete sleepers, are increasingly prone to surface cracks due to environmental stress, wear and tear, and material degradation.[1] These cracks, if undetected, can compromise track stability, posing significant safety risks and increasing maintenance costs. Traditional methods of inspection, such as manual assessments, are labor-intensive, time-consuming, and prone to human error, while existing automated systems often lack the precision needed for effective crack detection.[2] To address these challenges, this research focuses on developing the Surface Crack Concrete Sleeper Detection system using Arduino, an innovative and cost-effective solution to enhance railway maintenance practices. The system integrates a high-resolution camera for remote monitoring, a rotary encoder for precise length measurement, and an Arduino-based control unit to automate the detection and measurement of surface cracks. The objectives of this study include investigating key parameters for surface crack detection, developing an autonomous detection system, and analyzing its performance. The prototype system was successfully developed and tested, demonstrating its ability to detect surface cracks accurately and provide precise location data. By automating the crack detection process, the system significantly reduces reliance on manual inspections, enhances efficiency, and lowers maintenance costs. While the system shows great potential, challenges such as limited internet connectivity, operational difficulties in adverse weather conditions, and insufficient battery capacity remain. Recommendations for improvement include integrating renewable energy solutions such as solar panels, enhancing weatherproofing, and utilizing 3D printing to create durable components for field deployment. These advancements will ensure the system's robustness and reliability for real-world applications, contributing to safer and more efficient railway operations worldwide.

1.2 Literature Review

Surface crack detection in concrete sleepers is essential for maintaining the safety and longevity of railway infrastructure. Concrete sleepers, critical for supporting rails and distributing loads, are vulnerable to surface cracks caused by environmental stress, wear and tear, and material defects.[3] Traditional manual inspection methods, though cost-effective, are labor-intensive, subjective, and prone to human error, making them unsuitable for large railway networks. To address these challenges, non-destructive testing (NDT) techniques such as Ultrasonic Testing (UT), Impact Echo (IE), Ground Penetrating Radar (GPR), Infrared Thermography (IRT), Acoustic Emission (AE), and Electrical Impedance Spectroscopy (EIS) offer more accurate and objective alternatives. However, these methods also have limitations, such as the need for skilled operators and specific equipment.[4] Innovative solutions, including Internet of Things (IoT)-based systems and deep learning techniques, have emerged to enhance crack detection efficiency and reliability. IoT systems integrate sensors, controllers, and communication technologies for real-time monitoring, while deep learning approaches, such as convolutional neural networks (CNNs), automate the detection process with high precision. These advancements hold the potential to revolutionize railway maintenance by enabling proactive and efficient infrastructure management.[5] Additionally, stringent quality standards for concrete sleepers, as established by organizations like KTMB, underscore the importance of defect-free surfaces, precise dimensions, and proper alignment for ensuring track stability and safety. Such standards emphasize the need for advanced and reliable crack detection technologies. This study contributes to the development of an Arduino-powered Surface Crack Concrete Sleeper Detection system, integrating a high-resolution camera and rotary encoder to autonomously detect and measure cracks.[6] The system's successful prototype demonstrates its potential to improve railway maintenance by enhancing detection accuracy, reducing operational risks, and minimizing costs. While challenges such as internet connectivity, weatherproofing, and battery capacity remain, proposed improvements like 3D printing, solar integration, and full-scale fabrication can transform the prototype into a robust, deployable solution. These innovations pave the way for safer and more efficient railway operations globally.[7]

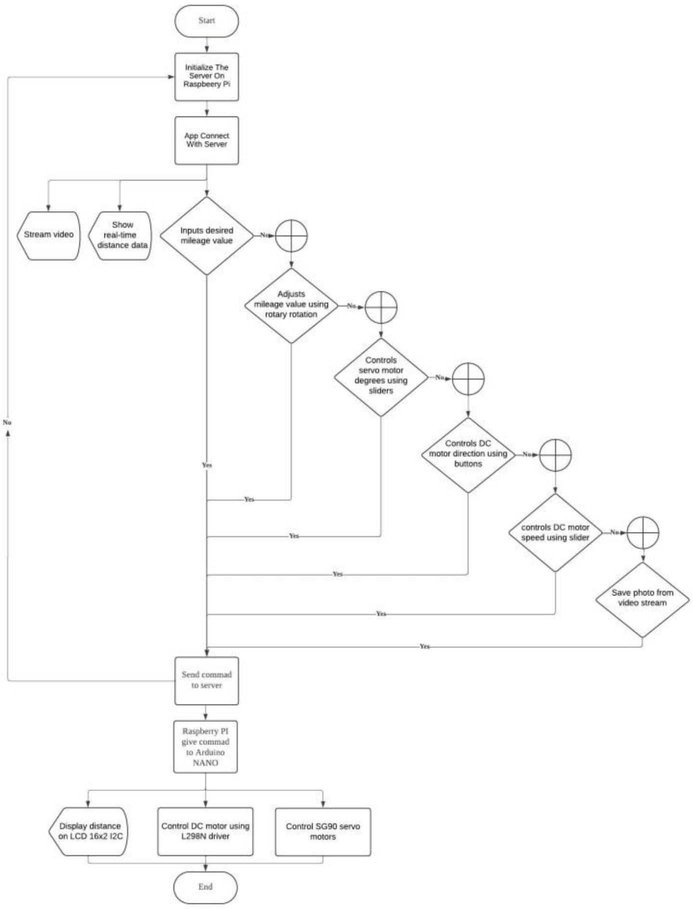
2. Methodology

The Surface Crack Concrete Sleeper Detection system using Arduino is designed to address critical challenges in railway maintenance by providing an innovative and automated approach to detecting surface cracks in concrete sleepers. Railway infrastructure relies on the integrity of concrete sleepers to ensure safety and efficiency.[8] Aging tracks and environmental factors increase the risk of surface cracks, which can lead to severe structural and operational failures if undetected. Traditional manual inspection methods are labor-intensive, time-consuming, and prone to human error, while existing automated solutions often lack precision. This project aims to enhance crack detection accuracy, reduce costs, and improve the reliability of railway maintenance. The system integrates a high-resolution camera for capturing detailed images, ultrasonic sensors for crack detection, and a GPS module for precise location mapping, all controlled via an Arduino microcontroller. Supporting components such as a Bluetooth module, OLED display, SD card module, and stable power supply ensure effective operation, real-time monitoring, and data storage. The system is further enhanced using Raspberry Pi for processing and integration with a mobile application developed through MIT App Inventor, enabling remote control and monitoring.

2.1 Project Flowchart

Figure 1 shows the project follows a structured methodology, including planning, designing, fabrication, testing, and iterative refinement, as outlined in the detailed flowchart. Several design iterations were considered, ranging from simple vertical movement to advanced 2D camera movement, balancing cost, complexity, and functionality. The final prototype incorporates full 2D movement, ensuring comprehensive monitoring with minimal blind spots. The coding, developed using Arduino IDE and Raspberry Pi, orchestrates sensor data processing, image analysis, and communication with external devices.

***Fig. 1*: Project Flowchart**



The system was constructed with high-quality components, including the HC-SR04 sensor, OV7670 camera, L298N motor driver, and LM2596 voltage regulator, to ensure precision and reliability.[8] The circuit diagram outlines the integration of all hardware components, highlighting the collaboration between Arduino and Raspberry Pi for seamless operation. Challenges such as power management, environmental durability, and user accessibility were addressed through thoughtful design and component selection.

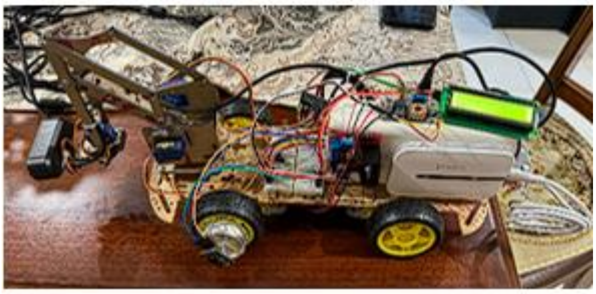
2.2 Final Product

The Surface Crack Concrete Sleeper Detection system using Arduino is an innovative solution for identifying surface cracks in railway sleepers, enhancing safety and efficiency in railway maintenance. The project involves a systematic design process, culminating in a prototype that integrates Arduino, ultrasonic sensors, a GPS module, and a camera for accurate crack detection and location mapping [9]. Three design iterations were explored, progressing from basic vertical movement to comprehensive 2D camera movement in the final product. The system ensures real-time monitoring, data storage, and ease of use through Bluetooth communication and an SD card module. By automating crack detection, this cost-effective and efficient system minimizes manual effort, reduces risks, and supports timely maintenance, contributing to safer and more reliable railway operations.

Figure 2 shows that the final product is designed to provide enhanced functionality similar to the Third Sketch Project, featuring full 2D camera movement with the ability to move up, down, left, and right. This comprehensive movement ensures thorough coverage of complex environments. While it retains the extensive camera movement capabilities of the Third Sketch, the final product aims to simplify the Arduino coding process, making it more accessible to users with varying programming skills. Efforts will be made to keep costs reasonable, potentially using cost-effective components or streamlined design, without compromising performance. Additionally, the final product may incorporate refined features or improvements based on user feedback and technological advancements, enhancing its overall effectiveness and practicality for diverse monitoring applications. The figure includes (a) the final project deployed at a railway construction site, showcasing its real-world application, and (b) the prototype product developed during the initial phase, refined through user feedback and technological advancements to enhance effectiveness. This final design balances functionality, affordability, and practicality, offering a robust solution for improving railway maintenance operations.

Fig. 2: The Surface Crack Concrete Sleeper Detection system using Arduino

(a) Final Project in Construction Railway



(b) Prototype Product

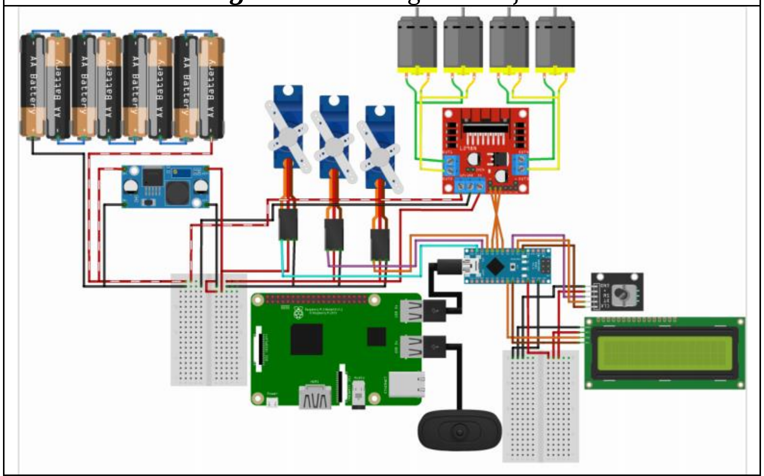
2.3 Coding

The Arduino and Raspberry Pi coding integration in the Surface Crack Concrete Sleeper Detection system serves as the backbone for automating hardware control, data processing, and real-time monitoring. The Arduino code focuses on managing the hardware components, including servos, a DC motor, an encoder, an ultrasonic sensor, and an LCD display. It enables precise control over the system's movement, mileage calculation, and crack detection. The program incorporates user-friendly features such as distance measurement updates on the LCD and real-time input handling via a serial interface, making it an efficient tool for physical operations. On the other hand, the Raspberry Pi code functions as the central server, facilitating communication between the Arduino and a mobile application through a Flask web interface. It also handles advanced tasks such as video streaming, command processing, and image saving, leveraging Python's threading and queue modules for efficient multitasking.[10] The Raspberry Pi processes user commands received through HTTP requests, relays them to the Arduino for execution, and provides real-time feedback on system operations. Additionally, it integrates camera functionality to capture and stream images, further enhancing the system's monitoring capabilities. Together, the Arduino and Raspberry Pi coding frameworks create a seamless interaction between hardware and software components, enabling autonomous monitoring, efficient communication, and precise control. This integration ensures a robust and scalable platform for railway maintenance, addressing challenges such as real-time crack detection, efficient monitoring, and timely intervention.

2.4 Circuit Diagram

Figure 3 show the circuit diagram of Surface Crack Concrete Sleeper Detection system using Arduino integrates Raspberry Pi and Arduino Nano to automate the detection of surface cracks in railway sleepers, ensuring seamless operation and efficient maintenance. The Raspberry Pi serves as the central hub, connected to a mobile app via Wi-Fi or Bluetooth, and communicates with the Arduino Nano through GPIO pins or serial communication. The system features a rotary encoder for mileage adjustment, an L298N motor driver to control a DC motor's speed and direction, and SG90 servo motors for precise movement. Real-time data from a distance sensor is processed by the Arduino Nano and displayed on an LCD screen using I2C communication. The Raspberry Pi manages video streaming and image capture via a camera module, enhancing crack detection accuracy. Power is shared between the Raspberry Pi and Arduino Nano, with additional external power for the DC motor and servos. This setup enables efficient data flow, precise control of hardware components, and real-time monitoring, making the system a cost-effective and reliable solution for improving railway safety and maintenance operations.

Fig. 3: Circuit Diagram Project

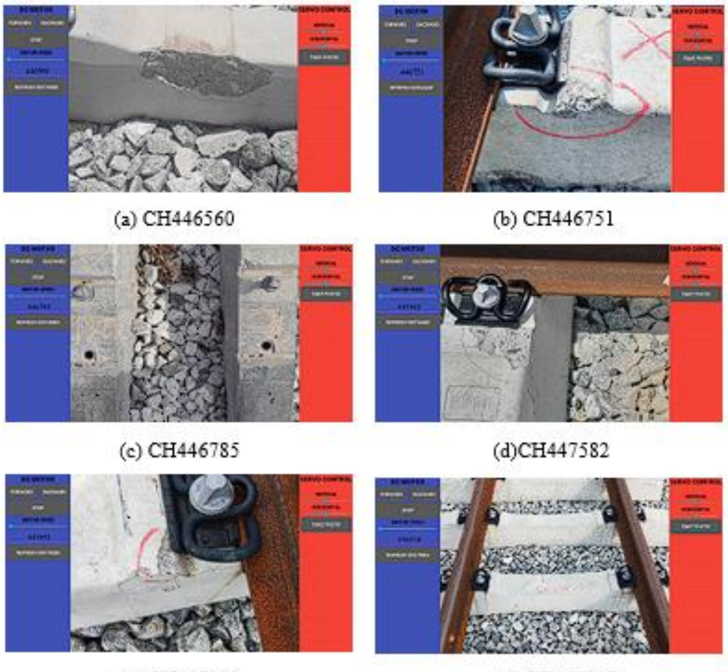


3. Result

The Surface Crack Concrete Sleeper Detection System using Arduino is a cost-effective, efficient, and innovative solution for enhancing railway maintenance. The system integrates advanced components such as an Arduino Nano, Raspberry Pi, rotary encoder, servo motors, and a camera module to automate the detection of surface cracks in railway sleepers. Tested at the Labu-Tiroi section, the system demonstrated its ability to identify defective sleepers accurately, ensuring timely interventions and maintenance. The rotary encoder provided precise chainage measurements, while the camera module captured high-resolution images of cracks for further analysis. The system's cost totaled RM 746.00, offering an affordable solution with long-term benefits, including reduced labor costs and increased inspection efficiency. Compared to human inspection, the system completed 1 km of track inspection in less than an hour, unaffected by fatigue or adverse weather conditions, highlighting its superior speed, consistency, and reliability. This automated system also supports detailed data collection and analysis, surpassing manual inspection in accuracy and repeatability. With features such as remote control via Flask API, real-time monitoring, and integration of OpenCV for crack detection, the system significantly improves railway safety and operational efficiency. The Surface Crack Concrete Sleeper Detection System represents a valuable advancement in railway infrastructure maintenance, combining automation, precision, and cost-effectiveness to ensure the longevity and safety of railway tracks.

Figure 4 shows that the results obtained from the Surface Crack Concrete Sleeper Detection system using Arduino, applied at the Labu-Tiroi section, which spans from chainage CH446000 to CH457500. The figure shows several sleepers identified by their chainage (CH) numbers: CH446560, CH446751, CH446785, CH447582, CH447852, and CH456219. Each sleeper exhibits cracks in different locations, indicating structural damage. These cracks compromise the integrity of the sleepers, making them unsuitable for continued use in railway operations. As a result, all the sleepers shown in the images have been rejected and will need to be replaced to ensure the safety and reliability of the railway track. This demonstrates the effectiveness of the detection system in identifying defective sleepers, allowing for timely intervention and maintenance.

Fig. 4: Result from Image Analysis



(a) CH446560 (b) CH446751 (c) CH446785 (d)CH447582 (e) CH447852 (f) CH456219

3.1 Comparison using Arduino and Human Inspection

Table 1 shows that the Surface Crack Concrete Sleeper Detection System outperforms human inspectors in terms of speed and efficiency, covering 1 km in significantly less than an hour with continuous operation. It delivers consistent, repeatable results without the impact of fatigue and offers detailed, precise image capture and analysis. Although it requires a high initial setup and maintenance investment, it reduces long-term operational costs and labor expenses. Conversely, human inspectors typically need around 1 hour to inspect 1 km, with productivity potentially decreasing due to physical fatigue, weather conditions, and the need for breaks. Their manual data collection relies on subjective analysis and can be interrupted by rain. While human inspection incurs ongoing labor costs without significant initial investment, these costs add up over time, and inspections must be paused during adverse weather.

Table 1: Surface Crack Concrete Sleeper Detection System vs Human Inspection

Aspect	Surface Crack Concrete Sleeper Detection System	Human Inspector
Speed and Efficiency	Can cover 1 km in significantly less than 1 hour; operates continuously.	Takes around 1 hour to inspect 1 km without breaks.
Consistency and Accuracy	Provides consistent, repeatable results; not subject to fatigue.	Takes around 1 hour to inspect 1 km without breaks.
Coverage and Productivity	Capable of covering large areas efficiently; automation allows for frequent inspections.	Limited by physical endurance; productivity may decline with fatigue and hot weather. When rainy inspection need to stop.
Data Collection and Analysis	Automatically captures and processes images; detailed records with precise measurements.	Manual data collection; relies on subjective analysis and experience.
Cost and Resource Management	High initial setup and maintenance costs; lower long-term operational costs; reduces labor costs.	Ongoing labor costs; no high initial setup costs but involves wages and breaks.

3.2 Calculation Rotary Encoder for Chainage Measurement

The Surface Crack Concrete Sleeper Detection System using Arduino employs a rotary encoder to calculate precise chainage measurements, ensuring accurate tracking of sleeper locations. The system calculates the wheel's circumference, based on a 4 cm diameter, to determine the distance traveled with each rotation. The encoder measures approximately 4.78 rotations to cover the standard 600 mm distance between sleepers, enabling precise correlation of chainage increments to the physical track layout. Starting from an initial chainage, such as CH446000, the system updates the chainage in 0.6-meter increments as the encoder records rotations. The accurate measurement of distance ensures proper alignment with the sleeper spacing, enhancing reliability and precision in railway maintenance operations. This approach automates chainage calculations, reduces manual effort, and provides real-time data, making it an effective and practical solution for ensuring railway track integrity.

To calculate chainage measurements using the rotary encoder, the following formulas can be used:

1. Wheel Circumference:

$$Rotations\ per\ Sleeper = \pi r^2$$

Where:

π≈3.1416
Diameter is the wheel diameter in meters.

2. Rotations per Sleeper:

$$Rotations\ per\ Sleeper = \frac{Sleeper\ Distance}{Circumference}$$

Where:

Sleeper Distance is the distance between two sleepers in meters.

3. Distance Traveled:

$$Distance\ Traveled = Rotations \times Circumference$$

Where:

Rotations is the total number of wheel rotations recorded by the encoder.

4. Chainage Update:

$$New\ Chainage = Initial\ Chainage + Distance\ Traveled$$

Where:

Initial Chainage is the starting chainage value.
Distance Traveled is calculated from the encoder.

5. Encoder Pulses to Distance: If the encoder outputs P pulses per rotation:

$$Distance\ per\ Pulse = \frac{Circumference}{P}$$

$$Distance\ Traveled = Pulses\ Counted \times Distance\ per\ Pulse$$

4. Conclusion

The Surface Crack Concrete Sleeper Detection system using Arduino has successfully achieved its objectives of detecting and mapping surface cracks on railway sleepers autonomously. The system integrates a high-resolution camera, rotary encoder, and Arduino-based control unit, providing accurate crack detection and precise location mapping. Tested at the Labu-Tiroi Section, the prototype demonstrated its ability to enhance railway maintenance by automating crack detection, improving efficiency, and reducing reliance on manual inspections. Despite its success, the system has limitations, including limited internet connectivity in remote areas, operational challenges in adverse weather due to exposed cables, insufficient battery capacity, and a lack of durability for field deployment. To address these challenges, several recommendations are proposed: enhancing connectivity through satellite or mesh networks, improving weatherproofing, increasing battery capacity, and integrating renewable energy solutions such as solar panels. Utilizing 3D printing and full-scale fabrication is also recommended to develop a more durable and deployable system. With further refinement, including extensive field testing and design optimization, the Surface Crack Concrete Sleeper Detection system can evolve into a reliable and cost-effective solution for railway maintenance, significantly contributing to the safety and efficiency of railway operations globally.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The author confirm contribution to the paper as follows: **The Surface Crack Concrete Sleeper Detection System Using Arduino:** Aiman Muhammad Aqil Bin Kamarudzaman, **Supervisor:** Prof. Madya Ir. Ts. Dr. Musli Nizam bin Yahya and Norhidayah Binti Sabtu. All authors reviewed the results and approved the final version of the manuscript.

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