IMPLEMENTATION OF IOT SOLUTIONS TO MINIMIZE UNDERLOADING AND OVERLOADING ISSUES OF WAGON

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ABSTRACT:

This paper presents an IoT-based system designed to address the critical issue of load management in railway transportation by providing real-time weight monitoring for railway wagons. In modern logistics, recognizing the impact of improper load distribution and incorrect wagon loading is crucial. These issues contribute to operational inefficiencies, higher maintenance expenses, and increased safety hazards.

This study integrates approaches from multiple disciplines, such as sensor technology, wireless data transmission, and automated load monitoring, to provide a practical, data-driven solution for managing load distribution. The proposed system employs calibrated load cells installed in the railway wagons to collect precise weight data, which is wirelessly transmitted using ESP32 modules to a central monitoring hub. This comprehensive approach improves safety, ensures regulatory compliance, and enhances resource allocation and operational efficiency, establishing a new benchmark in railway logistics.

Keywords: Internet of Things, Railway Transportation, Load Management, Real-Time Monitoring, Wireless Data Transmission.

1. Introduction:

In today's logistics-centric economy, railway transport plays a vital role in moving large quantities of goods due to its high capacity and lower environmental impact. However, managing the load within railway wagons remains a significant challenge, affecting both operational efficiency and safety. Issues such as overloading, underloading, and uneven load distribution contribute to increased wear on wagons and infrastructure, leading to higher maintenance costs and safety risks. Current load management methods are often manual and inconsistent, lacking the real-time monitoring needed to ensure proper load distribution and compliance [1]. Recent advancements in the Internet of Things (IoT)

now enable real-time load tracking, presenting a transformative opportunity for railway logistics. This paper presents an innovative IoT-based solution for enhancing railway wagon load management. The system utilizes calibrated load cells and ESP32 modules to capture weight data, which is wirelessly transmitted to an OLED display. By addressing the limitations of traditional load management practices, this system promotes safer and more efficient railway operations.

2. Experimental setup:

2.1 Load-cell:

A load cell, a type of transducer, produces an electrical signal directly proportional to the force it senses. Several types of load cells are available, including hydraulic, pneumatic, and strain gauge models. The number of load cells required depends on the load configuration. For example, a single load cell can measure small concentrated forces, such as those from cables or point loads. For longer beams, two load cells are usually placed at the ends, while three load cells are typically used for vertical cylinders. Load cells are used to measure forces by converting a force into an electrical signal. For measuring small, concentrated forces, a strain gauge-based load cell is commonly used. The relationship between the force applied and the electrical signal is governed by a mathematical formula derived from Hooke's Law and the Wheatstone bridge circuit, as depicted below:

Strain (ε) is proportional to the applied force 'F' via Hooke's Law as

$$\varepsilon = \frac{\sigma}{E} = \frac{F}{A.E}$$

where σ is Stress, E is Young's modulus and A is Cross-sectional area

The Wheatstone bridge produces an output voltage proportional to the strain as

$\Delta V = G.\ K.\ \varepsilon$

Where K is a Gauge factor (relates strain to resistance change) and G is excitation voltage.

Combining these equations and isolating F, we get

$F = \frac{\Delta V}{S.G}$,

where S accounts for the sensitivity of the load cell and its physical properties. The rectangular objects generally require four load cells for accurate measurements and for large platforms, containers, or extremely high loads, additional sensors are required. In symmetrical loading situations, pivots can replace some load cells to reduce cost, although this may reduce accuracy. Load cells can also be connected in parallel, where the corresponding signals (e.g., Ex+ to Ex+, S+ to S+) are connected. This setup generates an average output signal from all load cells, making parallel configurations ideal for devices such as personal scales and multipoint weight measurement systems. The most common colour coding for the wires is red for Ex+, black for Ex-, green for S+, and white for S-, but other variations such as red for Ex+, white for Ex-, green for S+, and blue for S-, or red for Ex+, blue for Ex−, green for S+ and yellow for S−, can also be used [2].

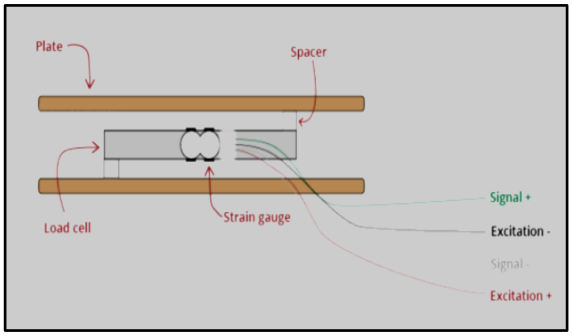

Fig 2.1.1: Load-cell Structure

2.2 HX711

The HX711 is a high-precision 24-bit analog-to-digital converter (ADC) designed specifically for use in load sensing and weighing applications. The HX711 converts the analog voltage (Vout) into a digital output value. The relationship is given by

$\text{Digital Output} = \frac{Vout\ .2^{24}}{Vref\ .G}$

Where, Vout = Output voltage from the load cell (mV), Vref = Reference voltage of the HX711, G = Gain factor of the HX711 (default options: 32, 64, or 128) and 2^{24} = Resolution of the 24-bit ADC. It is particularly effective for working with load cells or strain gauges, providing exceptional accuracy and minimal noise. The module has two channels: channel A, which provides selectable gain settings of 128 or 64, offering flexibility in handling different signal strengths, and channel B, which is fixed at a gain of 32. This versatility allows the HX711 to be used in various configurations, depending on the load cell manufacturer. With its simple 2-wire interface with DAT and CLK pins, the HX711 is easily connected to widely used microcontrollers such as Arduino or ESP32 [3]. Its energy-efficient design makes it perfect for battery-powered systems. The module converts low-millivolt analog signals from a load cell into digital data, which the microcontroller processes to provide accurate weight measurements in a variety of applications. The HX711's reliability and ease of integration have made it a preferred choice for many industrial and consumer-level weight measurement solutions. Its wide compatibility with various sensors makes it adaptable to diverse load-sensing requirements.

2.3 ESP32

The ESP32, developed by Espressif Systems, is a high-performance microcontroller with integrated Wi-Fi and Bluetooth, ideal for Internet of Things (IoT) applications that require robust wireless connectivity and efficient data management. Powered by a dual-core processor clocked at up to 240 MHz, it can multitask and handle complex processes efficiently. The ESP32's low-power modes allow for extended battery life, making it suitable for portable and energy-conscious designs.

Equipped with multiple GPIO pins, the ESP32 supports a wide range of sensors and peripherals, and it is compatible with communication protocols such as SPI, I2C, UART, and PWM. It also has integrated analog-to-digital converters (ADC) and digital-to-analog converters (DAC), expanding its potential for sensing and control applications [4].

Dual connectivity via Wi-Fi and Bluetooth makes the ESP32 versatile when it comes to communication, supporting both remote network-based applications and short-range Bluetooth configurations. Its adaptability, accessibility, and support for open-source development make the ESP32 popular in various industries, from home automation to industrial IoT, allowing developers to create innovative and connected solutions efficiently.

2.4 OLED display / serial monitor

The I2C OLED display is a small, energy-efficient display that uses the I2C (Inter-Integrated Circuit) communication protocol to interface with microcontrollers such as the ESP32. I2C allows multiple devices to communicate with just two wires: one for data (SDA) and one for clock (SCL), minimizing the number of connections required. OLED (Organic Light Emitting Diode) technology offers high contrast, deep blacks, and wide viewing angles, making it ideal for compact, low-power applications. THESE displays are commonly used in IoT projects to visually present data such as sensor readings, status updates, or system information in a clear, readable format.

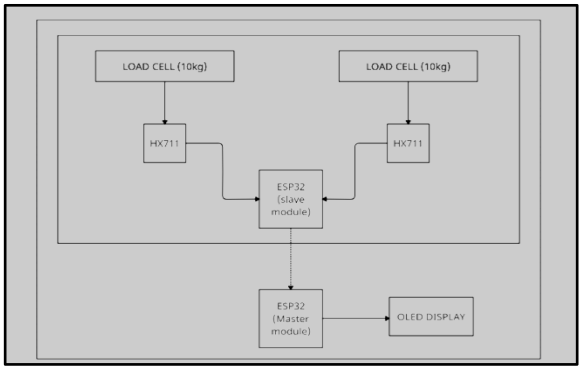

Fig 2.4.1: Proposed Block Diagram

3. Objective:

The main objective of this research is to create a reliable and real-time monitoring system to improve the safety and efficiency of loading railway wagons. By avoiding issues such as under loading and overloading [1], the system aims to improve operational accuracy and compliance with safety regulations. Accurate load monitoring helps reduce potential risks to the infrastructure and minimize safety risks, contributing to a more resilient rail logistics network.

This work offers an advantage by integrating IoT technology into a traditional manual and error-prone process. Real-time load weight data allows for immediate feedback and adjustments, optimizing load distribution and operational workflow. The wireless communication setup provides an efficient and automated solution that reduces human error and increases accuracy. Aligned with modern IoT standards, the research work lays the foundation for predictive maintenance, data-driven decision-making, and long-term cost reduction, positioning the rail sector toward greater safety and efficiency.

4. Methodology:

4.1 Load Cell Array Setup

This system incorporates an array of two highly sensitive 10 kg load cells, carefully calibrated and positioned to measure the weight distribution of the moving wagon with a high degree of accuracy. Calibration of the load cells is crucial to ensure consistent and repeatable data, accounting for minor variances that can arise due to environmental factors or mechanical shifts. The deliberate alignment of the cells allows them to detect the load evenly across the entire setup, making the array capable of accurately tracking any variations in load distribution as the wagon moves across. This configuration reduces the risk of inaccurate readings and ensures the system captures reliable weight data, even under dynamic conditions like the passage of a large, moving object. By achieving precise load distribution measurement, the array also enhances the accuracy and dependability of the weight data collected.

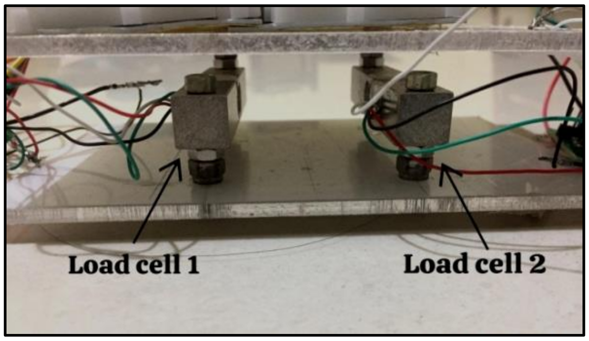

Fig 4.1.1: Load-cell Array set-up

4.2 Signal Amplification

Load cells produce analog signals in response to weight, but these signals are often too weak to be processed directly. To make these signals readable, the HX711 signal amplifier is used to amplify and convert them into a stronger digital format. The HX711 is specifically designed for load cell applications, providing amplification and analog-to-digital conversion (ADC) functions. By amplifying the signal, the HX711 ensures that even small fluctuations in weight are recorded accurately, which is essential for detecting subtle changes in load. The amplified digital signal makes the data more accurate and stable because it maintains clarity and responsiveness even with slight weight changes [3]. This amplification step is essential for reliable data collection, especially in environments where temperature or other conditions can affect signal quality. With support for the HX711, the system can continuously produce accurate weight data, ready for further processing and analysis.

4.3 ESP32 Slave Module

The ESP32 slave module is responsible for collecting and initially processing the load cell weight data. Located next to the load cells, this module handles the timing, synchronization, and data preprocessing before transmission to the master module. By handling these tasks locally, the ESP32 slave module ensures that the data from each load cell is synchronized, which is essential for stable and reliable data collection. The module operates in real time, collecting amplified digital signals and preparing them for transmission. This localized data management reduces latency and allows accurate and synchronized data to be sent quickly to the master module. This initial process also allows the slave module to efficiently manage and prepare data for smooth transfer, ensuring smooth operation of the overall system. Using this module, weight data can be collected and processed in real time, contributing to efficient and responsive monitoring.

4.4 ESP32 Master Module

The ESP32 master module is strategically positioned near the track, allowing it to be wirelessly connected to the ESP32 slave module on the moving railcar. As the railcar passes through the designated measurement area, the master module establishes a real-time connection with the slave module to receive the weight data captured by the load cells. The master module then collects this data and transmits it to a central monitoring system, where it can be analyzed or stored as needed. Its location is chosen to maximize the reliability of communication as the railcar moves through the area, ensuring stable data transmission even at higher speeds. The instantaneous transmission of data from the master module to the monitoring system allows for rapid analysis and decision-making. The role of this module is crucial in maintaining a smooth and continuous flow of data, ensuring that no information is lost and that the central system receives the data quickly.

4.5 Wireless Communication

ESP32 modules use wireless protocols, such as Wi-Fi or Bluetooth, to enable transparent data transmission between slave and master modules. This eliminates the need for complex wiring and allows for real-time data transfer from the load cells on the wagon to the master module and then to the central monitoring system. Wireless communication also ensures that the system is flexible and scalable, as the modules can be placed in different configurations depending on the application environment. Wi-Fi is generally chosen for its robust connectivity and speed over short distances, making it suitable for real-time monitoring needs. Bluetooth provides a low-power alternative that can be useful for mobile configurations where battery conservation is important. Wireless communication between modules provides instant data transmission, allowing rapid access to weight measurements, and enabling responsive monitoring and analysis. This configuration offers flexibility in terms of deployment and maintenance while maintaining efficient and reliable data transmission in a busy railway environment [5].

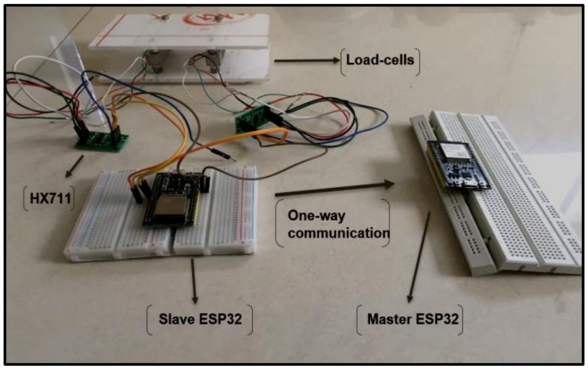

Fig 4.5.1: Wireless Data Transmission

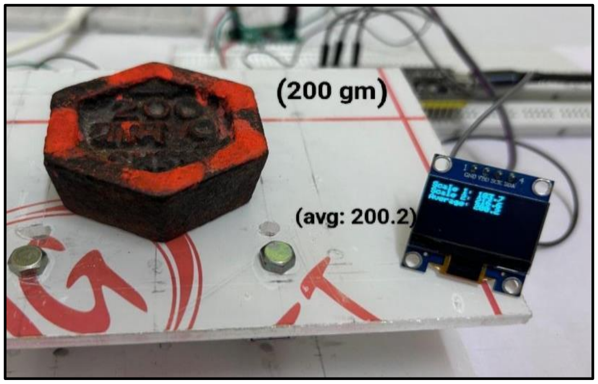

Fig 4.5.2: Displaying the weight in Oled display

5. Future Scope:

The future potential of this load cell-based weight measurement system presents many opportunities for improving functionality and adaptability. Expanding the load cell network would allow for accurate weighing of larger or heavier objects, increasing the adaptability of the system for various industrial and transportation applications. The inclusion of automated calibration and self-diagnostics can simplify maintenance and improve the reliability of measurements, adapting to environmental changes over time. The integration of edge computing in the ESP32 slave module will allow for local data processing, reducing transmission requirements and improving system speed. In addition, by using advanced communication protocols such as LoRa or 5G, data can be transmitted over longer distances with greater stability, supporting applications that require faster movements or larger coverage areas. Predictive maintenance features can be added to monitor system health and identify potential issues at an early stage, ensuring stable functionality. AI-based load distribution analysis can help optimize load distribution, which is essential for safety and operational efficiency. Cloud integration will enable centralized storage and remote monitoring of data, allowing for immediate analysis and insight generation, as well as tracking historical trends. IoT integration can improve logistics coordination, enabling interoperability with automated loading, tracking, and scheduling systems. Adding environmental adaptability with additional sensors can improve accuracy in different conditions. Finally, a real-time user interface can provide operators with immediate data feedback, allowing them to make informed decisions on the spot. These future enhancements will increase the system's versatility, reliability, and scalability for a wide range of industrial applications.

6. Conclusion:

The IoT-based weight monitoring system developed for rail wagons represents a valuable advance in cargo management, improving the safety and efficiency of rail logistics. Integrating calibrated load cells, HX711 signal amplifier, ESP32 modules, and wireless communication, this system enables accurate real-time weight measurement that promotes best practices in load distribution. Unlike traditional methods, this automated, data-driven approach minimizes human error, reduces maintenance costs, and helps maintain safety standards. Real-time weight monitoring allows for immediate intervention in the event of load imbalance, helping to mitigate the risks associated with overloading, underloading, and uneven weight distribution. This system offers future potential for scalability and connectivity to larger IoT networks, enabling functions such as predictive maintenance, long-term data analysis, and improved coordination with automated logistics.

Table 6.1 Comparison with traditional method

Criteria	**Traditional Methods**	**Proposed Solution**
Accuracy	Low	High
Real-Time Monitoring	No	Yes
Scalability	Limited	High
Cost-Effectiveness	High (long-term)	Low

As depicted in the table 6.1, the proposed solution offers advantages like low cost with minimum errors, scalability and real time monitoring. With rail transport still essential for the movement of large volumes of goods, the implementation of such a system could significantly contribute to a safer, more efficient, and technologically sophisticated rail industry.

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