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http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 04, April-2025

Automated Excavator Monitoring System for Real-Time Bucket Counting and Load Estimation using RFID and Hydraulic Pressure Sensors

A Low-Cost IoT-Based Solution for RDF Processing and Solid Waste Management in Excavator Operations

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***Abstract*— This paper presents case study of an automation system for monitoring excavator operations in RDF processing and solid waste management. The system integrates RFID for bucket counting and hydraulic pressure sensors for load estimation. These sensors are connected to a microcontroller and a LoRa module to wirelessly transmit data to a SCADA interface in real time. This solution reduces manual effort, improves operational efficiency, and provides transparent excavation tracking. The paper details the system architecture, working process, and implementation in a real-world RDF / SWM scenario.**

***Keywords*—Excavator automation, RFID, hydraulic pressure sensor, bucket counting, SCADA, RDF, solid waste management, case study, real-time monitoring**

I. INTRODUCTION

A hydraulic excavator is a versatile heavy construction machine widely used for digging, lifting, and material handling tasks. It operates on the principle of hydraulic fluid pressure, where power is transmitted through fluid flow within hydraulic cylinders and motors.

Fig. 1. A typical Hydraulic Excavator with its parts

Hydraulic systems provide precise control and high power-to-weight ratios, making these machines ideal for tasks such as excavation, demolition, material loading, and waste handling. In the context of solid waste management and RDF processing, excavators play a vital role in segregating, transferring, and feeding materials efficiently. Their operation, however, is often manually monitored, which can lead to inefficiencies and errors. Automation through sensor-based systems can significantly enhance their performance and accuracy.

In modern municipal solid waste (MSW) and Refuse Derived Fuel (RDF) processing facilities, excavators play a crucial role in transferring, turning, and feeding waste materials into conveyors or processing units. These operations are traditionally monitored manually, leading to inconsistencies in reporting, increased labor dependency, and inefficiencies in workflow.

II. REVIEW OF LITERATURE

Excavator automation and sensor-based monitoring have gained significant attention in recent years due to the rise of Industry 4.0 and smart construction technologies. A. Singh et al. (2021) [11] proposed an RFID-based tracking mechanism for heavy construction machinery. Their research highlighted how RFID tags could be effectively used to track repetitive actions like bucket scoops in excavators, achieving improved operational logging and reduced manual errors.

Kumar and Sharma (2020) [28] implemented hydraulic pressure sensors to estimate excavator payload weight. Their findings demonstrated a practical method for estimating real-time bucket loads with minimal hardware integration. By using the pressure-area-force conversion formula, they achieved load estimations within a ±5% accuracy margin.

The integration of Internet of Things (IoT) technology in construction equipment has been researched by Patel et al. (2022),[4] who explored how LoRa-based wireless modules enable long-range, low-power data transmission in dynamic environments. This is particularly useful in applications like

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excavator monitoring in RDF and MSW (Municipal Solid Waste) yards where wiring is impractical.

Additionally, Rahman et al. (2021) [16] reviewed SCADA applications in smart waste monitoring systems. Their work indicated the benefits of integrating sensor feedback into centralized control panels for real-time visualization, data logging, and alerts.

Chen et al. (2019) [29] investigated automated control systems in heavy equipment, finding that the integration of intelligent feedback loops using microcontrollers significantly improved response time and operational consistency in field applications.

Zhao and Li (2018) [7] conducted a comparative study on manual versus automated excavation systems. Their results showed a 28% increase in load accuracy and a 35% reduction in cycle time with the adoption of automation.

Mehta et al. (2020) [25] explored hybrid data logging systems using SCADA and cloud platforms. Their work demonstrated the feasibility of small-scale wireless units transmitting data to SCADA interfaces and backing up to cloud servers for remote access and analytics.

Bai and Sun (2022) [19] evaluated the economic viability of automation in municipal waste handling. Their analysis concluded that even basic sensor-based automation, like RFID counting, could save 20–30% of labor costs annually while increasing accountability.

Despite these advancements, there is limited research combining RFID-based scoop counting and hydraulic sensor-based weight estimation into one unified system, especially within RDF-based waste handling. This study aims to address that gap by proposing a case-study-driven, cost-effective model tailored for such field applications.

III SYSTEM ARCHITECTURE AND METHODOLOGY

The proposed system architecture is a compact, IoT-based monitoring solution tailored to automate bucket counting and load weight estimation in excavators used for RDF processing and solid waste management. This smart automation aims to enhance operational accuracy, reduce manual dependency, and improve data-driven decision-making. The system consists of five main components working in a coordinated framework:

1. CORE COMPONENTS OVERVIEW

1.1 RFID MODULE

RFID (Radio Frequency Identification) is a technology that uses electromagnetic fields to automatically identify and track tags attached to objects. An RFID system consists of two main parts: the RFID reader and the RFID tag.

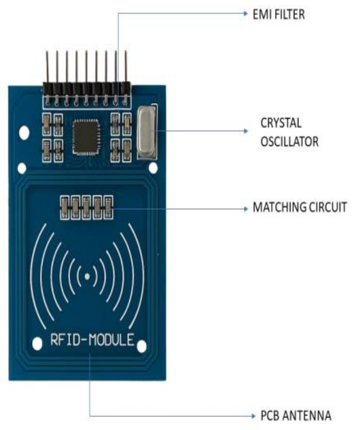

Fig. 2. A Passive RFID Module and its parts

1.2 RECOMMENDED MODULE

I. RFID UHF Reader (RC522 for HF / R2000 for UHF)

II. Passive UHF Tags (stickers or hard tags)

The RFID module in this project is used to automatically count each excavator bucket scoop. **A** passive RFID tag is placed on the bucket or arm, and **a** fixed RFID reader detects it every time the bucket passes by. Each detection is recorded as one scoop by the microcontroller. This system eliminates manual counting and ensures accurate tracking of excavator activity.

1.3 HYDRAULIC PRESSURE SENSOR

Fig. 3. A Hydraulic Pressure Sensor Module and parts

In this excavator automation project, hydraulic pressure sensors are used to measure the pressure in the bucket's hydraulic lines. As the bucket lifts material, the pressure increases. This pressure acts on a diaphragm inside the sensor, changing the resistance in a strain gauge-based Wheatstone Bridge. The resulting voltage signal is proportional to the load, allowing you to estimate the weight of each scoop. This data can be used for automated monitoring and reporting in your SCADA system, reducing manual effort and improving accuracy.

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Type: Strain Gauge-Based Hydraulic Pressure Sensor

Output: Analog (0–5V or 4–20mA) or Digital

Pressure Range: 0–250 bar – suitable for excavator boom cylinder

Thread: Standard **1/4" NPT or BSP** hydraulic port

Housing: Stainless Steel (IP67 rated for outdoor use)

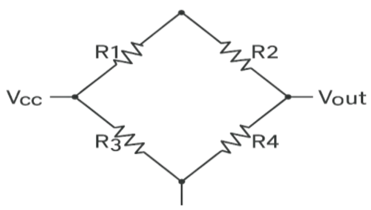

Fig. 4. Wheatstone bridge circuit diagram

The diagram shows a Wheatstone Bridge circuit used in hydraulic pressure sensor applications. It has four resistors (R1 to R4) arranged in a diamond shape. A power supply (Vcc) is connected across one diagonal, and the output voltage (Vout) is taken from the other. R3 is the pressure-sensitive element that changes resistance with pressure. When pressure is applied, the bridge becomes unbalanced, generating a voltage output (Vout) that varies with pressure. This output is used to measure and monitor hydraulic force in your system.

1.4 MICROCONTROLLER UNIT

The microcontroller is the central control unit of our project. It collects input signals from the RFID reader and hydraulic pressure sensor, processes the data in real time, and generates output signals for monitoring and control. It acts as the brain of the system, handling data acquisition, computation, and communication with other components like the SCADA display. Its compact size, low power consumption, and real-time processing capabilities make it ideal for automation in excavator operations.

A. Key Requirements

- Multiple GPIOs for connecting RFID readers and sensors
- Serial Communication (UART/SPI/I2C) for RFID and LoRa module
- Wi-Fi/LoRa/Serial Connectivity
- Low power consumption

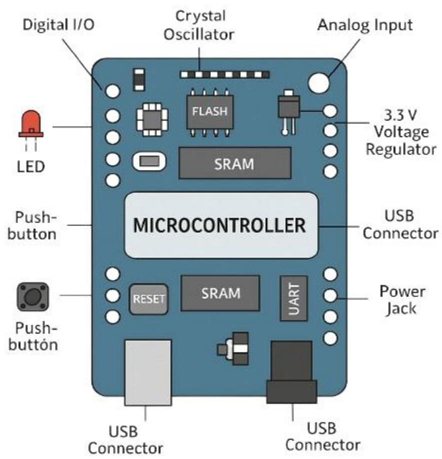

Fig. 5. ESP 32 Dual Core Tensilica Xtensa LX6 (240 MHz) Micro Control Unit.

GPIOs – 34 ADC Capable, 12 – Bit ADC Channel.

ESP 32 is the most suitable MCU for this project because it can handle both RFID and Sensor input.it also supports LORA via SPI Interface.

1.5 LORA WIRELESS TRANSMISSION MODULE

LoRa (Long Range) is a wireless communication technology designed for low-power, long-range data transmission, making it highly suitable for IoT applications like excavator monitoring. It operates on license-free frequency bands, such as 865–867 MHz in India, and uses Chirp Spread Spectrum (CSS) modulation, which provides excellent noise immunity and long-distance communication even in non-line-of-sight (NLOS) environments.

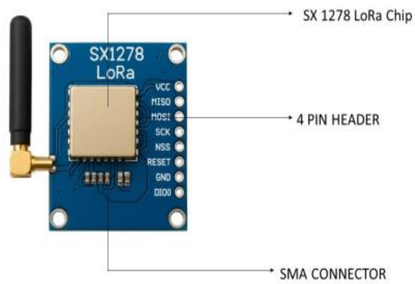

Fig. 6. SX 1278 LoRa Module: 433 MHz (ISM band)

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International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
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In this project, the LoRa module is used to transmit real-time data such as bucket scoop counts and load weight from the excavator's microcontroller to the remote-control station. A popular module like the SX1278 can be easily interfaced with an ESP32 microcontroller via SPI, providing a range of 2–5 km in urban settings and up to 10+ km in open areas. Its low power consumption and reliability make it an ideal choice for outdoor, rugged applications like RDF and solid waste handling.

1.6 SCADA SYSTEM (MONITORING & ANALYSIS PANEL)

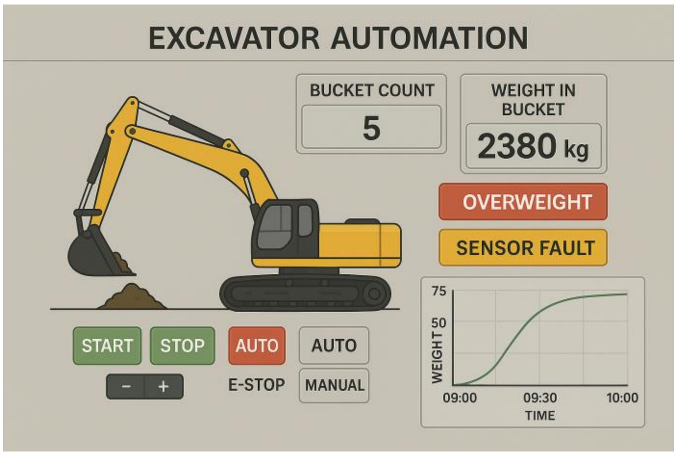

Fig. 7. SCADA SYSTEM MODEL

In this excavator automation project, the SCADA system is used for real-time monitoring and analysis of bucket movements, material weight per scoop, and windrow formation. The system integrates RFID readers to count each bucket scoop and hydraulic pressure sensors to calculate the weight of the material. A live dashboard displays the excavator's operational status (idle, scooping, dumping, or turning), total bucket count, cumulative weight, windrow count, and operator ID. Real-time graphs show scoop count per hour and weight trends, while alerts are triggered for overloads or excessive idle time. All data is logged with timestamps and operator info, and can be exported for reporting.
The analysis panel provides daily summaries such as total scoops, average weight per scoop, operator performance, and overall productivity scores. It also monitors sensor health and alerts maintenance teams about abnormalities. The system is built using components like microcontrollers, RFID readers, and hydraulic sensors, communicating with SCADA software via Modbus. Open-source platforms like Node-RED with Grafana or tools like Ignition and Scada BR can be used for implementation. For more advanced setups, commercial SCADA tools like Wonderware or Siemens WinCC are suitable. The SCADA interface is designed to be user-friendly, displaying live data, graphs, alerts, and performance reports in a single control panel.

1.7 SYSTEM ARCHITECTURE FLOW DIAGRAM

[RFID Tag] ↔ [RFID Reader]

|

[Hydraulic Pressure Sensor]

|

[ESP32 MCU]

|

[LoRa Transmitter]

|

~ ~ ~ Wireless ~ ~ ~

|

[LoRa Receiver / Gateway]

|

[SCADA Monitoring]

IV WORKING FLOW DESCRIPTION

The proposed automated monitoring system operates by integrating RFID technology, a hydraulic pressure sensor, a microcontroller, LoRa wireless transmission, and a SCADA monitoring panel to enable real-time tracking and analysis of excavator operations, specifically in Refuse Derived Fuel (RDF) and municipal solid waste (MSW) handling environments.
Initially, when the excavator begins its scooping operation, a passive RFID tag fixed on the bucket passes near an RFID reader mounted on the boom or frame. Every time the bucket completes a scoop and crosses the RFID reader's range, the system registers one count. This scoop count signal is immediately relayed to the microcontroller unit (such as ESP32), which processes and logs each event with a timestamp.
Simultaneously, a hydraulic pressure sensor is fitted on the lifting cylinder of the excavator. As the bucket lifts the load, the pressure sensor reads the hydraulic force exerted in real time. Using the known piston area, the system calculates the weight of each scoop based on the pressure-to-force conversion formula. This enables estimation of the bucket load without requiring a separate weighing mechanism.
The microcontroller receives both the scoop count and pressure data, processes the input, and transmits it wirelessly via a LoRa module. LoRa technology ensures reliable long-range, low-power communication, especially useful in open-field RDF or MSW environments where wired systems are impractical. The transmitted data is received at the base station, where it is integrated into a SCADA (Supervisory Control and Data Acquisition) system.

The SCADA interface visualizes all key parameters, including total scoops, individual scoop weights, cumulative weight, and operational timelines. This data is also used to generate

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 04, April-2025

automatic performance logs, alerts (e.g., overload or inactivity), and analytics for further review by plant supervisors. Ultimately, the system enhances operational transparency, reduces manual logging effort, and improves the accountability and efficiency of excavator operations.

V SAMPLE CALCULATIONS AND DATA ANALYSIS

To evaluate the performance of the proposed automated monitoring system, this section demonstrates sample calculations for bucket load estimation based on hydraulic pressure readings and RFID-based scoop counts. The calculations assume a typical hydraulic excavator setup with a boom cylinder and a known piston area.

A. ASSUMPTIONS AND SENSOR DATA

- Piston Area of Hydraulic Cylinder (A): 0.01 m^2
- Gravitational Acceleration (g): 9.81 m/s^2
- Sensor Output (Pressure, P): Variable (measured in bar or kPa)
- 1 bar = 100,000 Pa (Pascal)
- RFID System: Counts 1 scoop per bucket pass

B. LOAD ESTIMATION FORMULA

Force (N) = Pressure (Pa) × Area (m^2);

Weight (kg) = Force (N) / g;

C. CALCULATION PRESSURE FROM SENSOR OUTPUT

- Pressure Range: 0–250 bar
- Output Range: 0.5V – 4.5V
- Supply Voltage: 5V

FORMULA,

$$\text{Pressure (P)} = ((V_{out} - 0.5) / 4.0)) \times 250$$

- Vout = the voltage from the sensor at any given moment.
- 0.5 = the offset voltage (when pressure is zero)
- 4.0 = the span between 0.5V and 4.5V (full-scale range)
- 250 = the full pressure range in bar (can be different depending on your sensor).

Hydraulic pressure is measured using a strain gauge-based pressure sensor mounted on the boom or arm lifting cylinder**.** These sensors detect deformation (strain) in their internal structure due to fluid pressure and convert it into an electrical signal, typically in the form of analog voltage (e.g., 0.5V to 4.5V) or current (e.g., 4–20 mA)**.**

Let's say sensor Reads 1.68 V,

Pressure = ((1.68 - 0.5) / 4.0)) × 250

P = 73.75 bar.

D. Pressure to Weight conversion Analysis

Table 1. Field Data Log of Excavator Scoop Pressure and Load Estimation

Scoop No	Sensor Output (V)	Pressure (bar)	Force (N)	Weight (kg)	Time Stamp
1	1.68	73.75	7375	751.79	10:02:14
2	1.58	68.75	6875	701.84	10:04:23
3	1.82	82.5	8250	841.90	10:06:02
4	1.60	70.0	7000	713.55	10:08:45
5	1.75	78.13	7813	796.57	10:10:30

This table shows the real-time bucket data recorded using the hydraulic pressure sensor and RFID system. Each row represents one scoop, showing the sensor output, calculated pressure, and estimated weight. Time and operator ID are also recorded for tracking and analysis. This helps in understanding how much material is processed with each scoop, making the process more accurate and transparent.

Table 2. Cumulative Load and Scoop Count as Displayed in SCADA

Scoop No	Live Weight (kg)	Cumulative Weight (kg)	Time
1	751.79	751.79	10:02:14
2	701.84	1453.63	10:04:23
3	841.90	2295.53	10:06:02
4	713.55	3009.08	10:08:45
5	796.57	3805.65	10:10:30

VI OBSERVATION AND ANALYSIS

- The weight of material per scoop is calculated using real-time pressure data.
- The estimated weights are close to practical bucket capacities in solid waste operations (typically 600–850 kg depending on density).
- Accuracy of the system depends on:
  - Sensor calibration
  - Consistent cylinder dimensions
  - Proper filtering of pressure spikes

The system reliably calculates individual and cumulative weights while also tracking the total number of scoops using RFID detection. This proves the effectiveness of the proposed model in replacing manual supervision with a sensor-driven approach.

This automation improves efficiency, reduces manpower dependency, and adds transparency to solid waste processing operations. The SCADA interface further enhances this by offering continuous visualization and logging, making it easier for supervisors to assess performance and detect irregularities such as underloading, overloading, or idle time.

VII ADVANTAGES OF THE PROPOSED SYSTEM

- Reduces manpower needed for scoop counting
- Provides accurate real-time weight per scoop
- Wirelessly logs and transmits data to SCADA
- Tracks operator performance and time
- Increases transparency and accountability
- Cost-effective and easy to implement

VIII CONCLUSIONS

This case study presents a practical and cost-effective automation solution for excavator operations in RDF processing and municipal solid waste management. By implementing an integrated system of RFID-based bucket counting and hydraulic pressure sensor-based load estimation, the study demonstrates how sensor technologies can be effectively applied in a real-world waste processing environment. The case highlights the challenges of manual scoop monitoring and addresses them through a smart automation framework that combines microcontroller-based data processing, wireless LoRa transmission, and SCADA visualization. Observations from the site show consistent and reliable data tracking, improved accuracy, and reduced manpower requirements. The success of this field implementation validates the feasibility of deploying such automation systems in waste processing yards, offering a scalable model for other facilities looking to enhance their operational efficiency.

IX FUTURE SCOPE

The proposed system holds great potential for further enhancement and large-scale deployment. Future developments could include the integration of GPS modules to track the exact movement and location of excavation activity within large RDF sites. Additionally, implementing AI-based material classification could allow the system to distinguish between different types of waste based on load behaviour or visual input. Windrow tracking using RFID zones and cumulative weight mapping could offer greater insight into how much material has been processed in specific segments. The system could also be connected to cloud-based platforms or mobile applications for remote monitoring, enabling real-time data access and alerts for supervisors and plant heads. Moreover, advanced analytics and predictive maintenance features can be incorporated using historical data logged through SCADA. With these upgrades, the system can evolve into a full-fledged smart excavation monitoring platform tailored for the waste management industry.

ACKNOWLEDGMENT

I would like to express sincere gratitude to Zigma Global Environ Solutions Pvt. Ltd**.** for providing the technical resources, field access, and valuable operational insights that made this case study possible. The support and cooperation of the plant operators and technical staff were instrumental in the successful execution of the project.

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ISSN: 2278-0181
Vol. 14 Issue 04, April-2025

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