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Development of a Compact Eddy Current Separator for Industrial Waste Recycling

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Abstract **– Efficient separation of non ferrous metals from mixed waste streams is important for improving recycling efficiency and resource recovery. This paper presents the development of an IoT enabled Eddy Current Separator integrated with a Digital Twin based monitoring framework for aluminum recovery applications. The proposed system consists of a conveyor belt mechanism, an Eddy Current Separator rotor, a NodeMCU ESP8266 controller, encoder based speed monitoring, and a web based dashboard for remote supervision and control. Real time operating data, including conveyor and rotor speeds, are continuously transmitted to the monitoring platform, enabling improved operational visibility. The Digital Twin framework compares reference operating conditions with real time system parameters and assists operators in evaluating system performance. Experimentally derived operating guidelines are also incorporated to support the selection of suitable operating conditions for different waste categories, contributing to efficient energy utilization. The developed prototype demonstrates the feasibility of integrating Eddy Current Separation technology with IoT connectivity and Digital Twin assisted monitoring, providing a foundation for future enhancements in intelligent waste management systems.**

Keywords - Eddy Current Separator, Digital Twin, Internet of Things, Industrial Waste Recycling, Web Based Monitoring, Aluminum Recovery

I. INTRODUCTION

Efficient recovery of recyclable materials is an important requirement in modern waste management systems. Non-ferrous metals such as aluminum possess significant economic value and can be reused through proper separation and recycling processes. As waste generation continues to increase, there is a growing need for reliable and energy-efficient material recovery systems.

Eddy Current Separators (ECS) are widely used for separating non ferrous metals from mixed waste streams. However, conventional ECS systems generally operate with fixed settings and limited monitoring capabilities, which may affect performance under varying waste conditions and lead to unnecessary energy consumption.

Recent developments in the Internet of Things (IoT) and Digital Twin technologies have enabled improved monitoring and management of industrial systems. These technologies provide real-time access to operational data and support better decision-making during system operation.

This paper presents an IoT-enabled Eddy Current Separator integrated with a Digital Twin-based monitoring framework. The proposed system enables real-time monitoring of operating parameters through a web-based interface and supports the selection of suitable operating conditions for different waste categories. By combining ECS operation with IoT connectivity and Digital Twin technology, the system aims to improve operational visibility, energy utilization, and overall separation efficiency.

II. SYSTEM ARCHITECTURE

The proposed system integrates an Eddy Current Separator (ECS) with IoT-based monitoring and a Digital Twin framework to enable efficient separation of non-ferrous metals from mixed waste streams. The overall architecture consists of four major components: the mechanical separation unit, motor control system, web-based monitoring platform, and Digital Twin module. Fig. 1. System Architecture illustrates the overall system architecture.

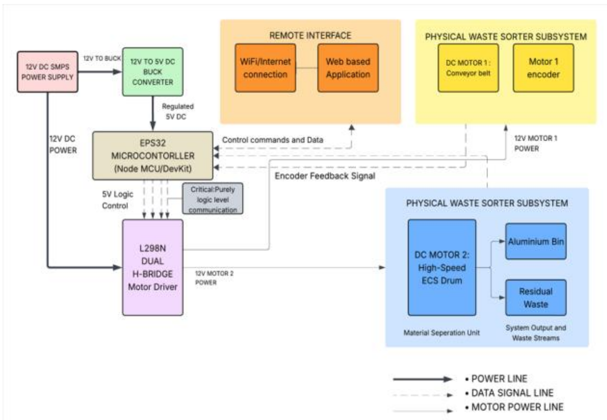

Fig. 1. System Architecture

1. Mechanical Design: The mechanical section consists of a conveyor belt assembly and an ECS rotor unit as shown in Fig. 2. Conveyor Belt and Fig. 3. ECS Rotor. Mixed waste materials are fed onto the conveyor and transported towards the separation zone. The ECS rotor is positioned at the discharge end of the conveyor and is responsible for generating the alternating magnetic field required for metal separation. For prototype development, the rotor assembly is

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fabricated using a 3D-printed housing embedded with neodymium permanent magnets arranged in alternating North-South polarity. Permanent magnets were selected due to their simplicity, low cost, and suitability for laboratory-scale validation. As conductive aluminum particles pass through the magnetic field, eddy currents are induced within them, resulting in a repulsive force that alters their trajectory and enables separation from non-conductive materials.

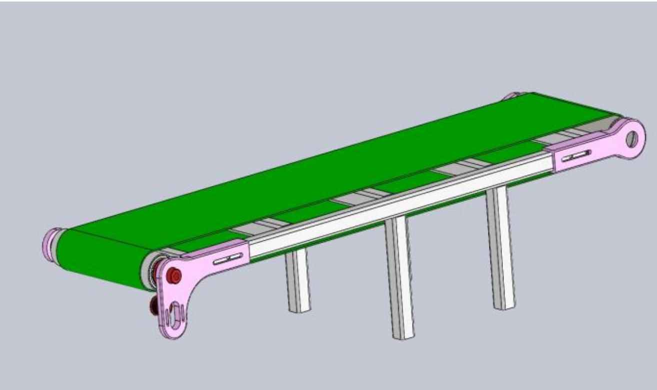

Fig. 2. Conveyor Belt

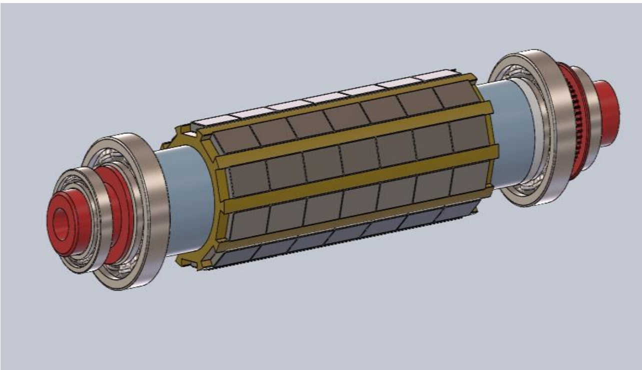

Fig. 3. ECS Rotor

2. Motor Control System: The conveyor belt and ECS rotor are driven independently using a planetary gear motor and a DC motor, respectively. Independent control of both motors allows suitable operating conditions to be established for different waste categories. A NodeMCU ESP8266 microcontroller serves as the central control unit and manages communication between the hardware components and the monitoring platform. Motor operation is controlled through PWM signals generated by the microcontroller and delivered through appropriate motor driver circuits. This arrangement enables remote operation and flexible adjustment of rotor and conveyor speeds.

3. Web-Based Monitoring Interface: A web-based dashboard which is shown in Fig. 5. Webpage is developed to provide real-time monitoring and control of the ECS system. The dashboard can be accessed through any device connected to the same network and allows the operator to monitor key operating parameters such as conveyor speed and rotor speed. A secure login page as shown in Fig. 4. Login page is incorporated into the dashboard to ensure that only authorized users can access the monitoring and control functions of the ECS system. The interface also provides system control functions, enabling convenient operation without direct physical interaction with the equipment. The continuous transmission of sensor data to the dashboard improves operational visibility and assists users in evaluating system performance during material separation.

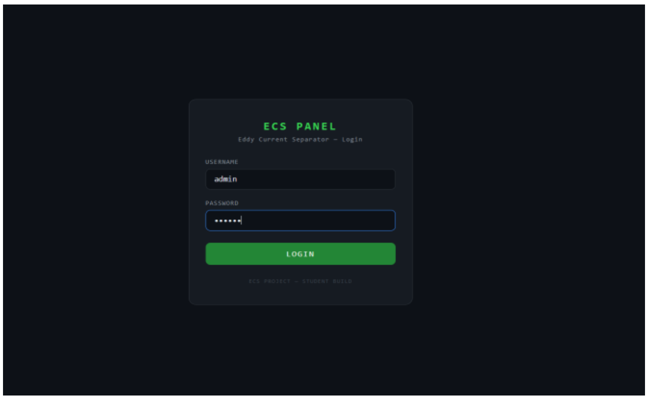

Fig. 4. Login Page

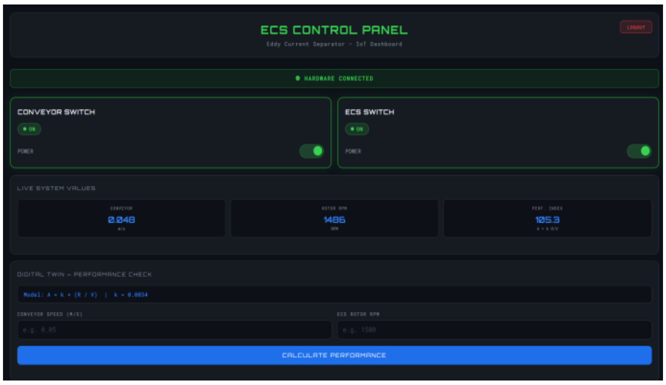

Fig. 5. Webpage

4. Digital Twin Framework: A Digital Twin framework is incorporated to create a virtual representation of the physical ECS system. The Digital Twin utilizes real-time operating data received from the sensors and compares it with expected operating conditions derived from experimentally established operating guidelines. Since different waste streams may contain aluminum particles of varying sizes and weights, different operating speeds may be required to achieve effective separation. The Digital Twin assists in selecting suitable operating conditions while supporting energy-conscious system operation. During operation, the framework continuously compares expected and actual system parameters. Any deviation between the predicted and real-time values is indicated on the dashboard, allowing operators to identify performance variations and take corrective action when necessary.

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III. METHODOLOGY

The proposed system integrates Eddy Current Separation (ECS), IoT-based monitoring, and Digital Twin technology to facilitate aluminum recovery from mixed waste streams while promoting energy-conscious operation. The overall methodology consists of material transportation, separation, real-time monitoring, operating parameter selection, and Digital Twin-based performance validation.

Initially, mixed waste materials are fed onto the conveyor belt, which transports them towards the separation zone. The conveyor is driven by a planetary gear motor that ensures stable and controlled material movement. At the discharge end of the conveyor, an ECS rotor embedded with neodymium permanent magnets generates an alternating magnetic field. As conductive aluminum particles pass through this magnetic field, eddy currents are induced within them, producing a repulsive force that alters their trajectory. Consequently, aluminum particles are separated from non-conductive materials such as plastics and glass, enabling efficient material recovery.

The conveyor motor and ECS rotor motor are interfaced with a NodeMCU ESP8266 microcontroller, which functions as the central control and communication unit. A web-based dashboard is developed to provide remote monitoring and control of the system. Through the dashboard, operators can access system information and observe important operating parameters in real time. Encoder sensors attached to the motors continuously measure rotational speed and transmit the collected data to the dashboard through the microcontroller.

Since different waste streams may contain aluminum particles of varying sizes and weights, different operating conditions are required to achieve effective separation. Therefore, experimentally obtained operating guidelines are incorporated into the monitoring platform. A reference table containing recommended operating parameters for different waste categories is displayed on the dashboard. Based on the type of waste being processed, the operator can select suitable operating conditions to reduce unnecessary energy consumption while maintaining effective separation performance.

A. Digital Twin Performance Estimation

To enhance monitoring and operational assessment, a Digital Twin framework is integrated into the proposed system. The Digital Twin acts as a virtual representation of the physical ECS setup and utilizes real-time operating data obtained from the encoder sensors. The framework estimates the favorability of the selected operating conditions using rotor speed and conveyor speed as key input parameters.

The relationship between the operating parameters and the separation performance index is expressed as:

$$A=k(R/V) \tag{1}$$

where A represents the separation performance index, R denotes the rotor speed (RPM), V represents the conveyor belt speed, and k is a system-specific calibration constant obtained experimentally. The calibration constant k is determined experimentally during initial system setup and remains fixed for a given operating configuration.

The Digital Twin continuously receives real-time speed data from the physical system and computes the corresponding performance index. The calculated value is used as an indicator of the suitability of the selected operating conditions for aluminum separation. Since the exact composition of incoming waste cannot be determined during practical operation, the calculated value is treated as a performance indicator rather than an absolute measure of separation efficiency.

The expected operating parameters stored within the Digital Twin are continuously compared with the actual values obtained from the encoder sensors. Whenever a deviation is observed between the reference and real-time operating conditions, an indication is generated on the dashboard. This enables operators to identify performance variations, verify system operation, and take corrective action when required.

The overall workflow of the proposed system is illustrated in Fig. 6. Workflow. By combining ECS operation, IoT-based monitoring, and Digital Twin-assisted validation, the developed system provides improved operational visibility, energy-conscious parameter selection, and enhanced decision-making for non-ferrous metal recovery applications.

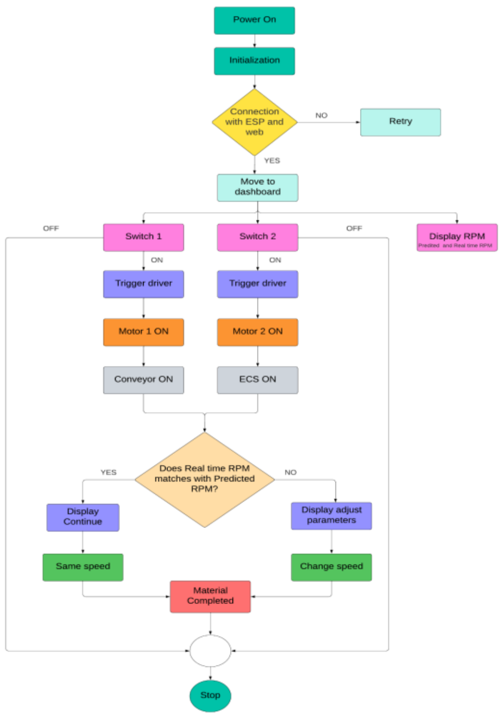

Fig. 6. Workflow

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IV. RESULTS AND DISCUSSION

Figure 7 shows the developed prototype of the proposed ECS system. The prototype successfully demonstrated the integration of Eddy Current Separation (ECS), IoT-based monitoring, and Digital Twin-assisted performance assessment within a unified platform. The primary objective of the experimental evaluation was to verify the functionality of the proposed architecture and assess the effectiveness of the interaction between the physical system and its virtual representation.

During operation, the ECS rotor generated the alternating magnetic field required for non-ferrous metal separation. The observed behavior of conductive aluminum particles within the separation zone was consistent with the fundamental principles of eddy current separation, wherein induced eddy currents generate a repulsive force that alters the particle trajectory. The prototype successfully demonstrated the separation mechanism and validated the feasibility of employing ECS technology within a compact, IoT-enabled framework.

The web-based monitoring platform established reliable communication with the NodeMCU ESP8266 controller and facilitated continuous observation of key operating parameters. Real-time speed information acquired from encoder sensors was successfully transmitted to the dashboard, providing operators with immediate visibility into system operation. The remote accessibility of the monitoring interface improved operational convenience and demonstrated the practicality of integrating web technologies into small-scale recycling systems.

The Digital Twin framework functioned as a virtual representation of the physical ECS setup by utilizing operating parameters obtained from the system. Expected operating conditions were continuously compared with real-time sensor data, enabling verification of system behavior during operation. The comparison mechanism provided an additional layer of operational awareness by assisting operators in identifying deviations between reference and actual conditions.

A significant outcome of the study was the development of operating guidelines for different categories of waste materials. Since aluminum fragments originating from household, commercial, and industrial sources may differ in size and mass, identical operating conditions may not always provide optimal separation performance. The proposed framework enables operators to utilize experimentally derived parameter recommendations when selecting rotor operating conditions, thereby supporting efficient system utilization and reducing unnecessary energy expenditure.

The overall results demonstrate the successful implementation of an IoT-enabled ECS system capable of real-time monitoring and Digital Twin-assisted performance evaluation. Although the current prototype focuses primarily on monitoring and operator-guided parameter selection, the developed architecture establishes a foundation for future enhancement through adaptive control, automated parameter optimization, and large-scale deployment in intelligent recycling applications.

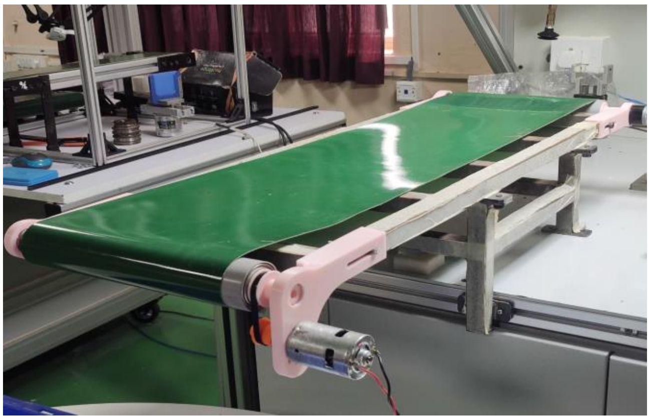

Fig. 7. Developed Prototype

V. ADVANTAGES OF THE PROPOSED SYSTEM

The proposed system offers several advantages over conventional prototype-scale Eddy Current Separator implementations. The integration of IoT technology enables real-time monitoring of key operating parameters through a web-based dashboard, improving operational visibility and accessibility. The incorporation of a Digital Twin framework provides an additional layer of system validation by comparing expected and real-time operating conditions.

The proposed architecture also supports energy-conscious operation through the use of experimentally derived operating guidelines. By selecting suitable rotor speeds based on the characteristics of the incoming waste stream, unnecessary energy consumption can be reduced while maintaining effective separation conditions. Furthermore, the use of low-cost hardware components such as the NodeMCU ESP8266 makes the system economically feasible for small-scale research and educational applications.

The modular design of the system allows future expansion through adaptive control algorithms, automated parameter optimization, and advanced monitoring capabilities, making it a scalable platform for intelligent recycling applications.

VI. CHALLENGES AND LIMITATIONS

Although the proposed system successfully demonstrates the integration of ECS, IoT monitoring, and Digital Twin technology, certain limitations remain. The current implementation is developed as a prototype-scale system utilizing permanent magnets for magnetic field generation. Industrial-scale ECS systems typically employ larger and more sophisticated magnetic assemblies to achieve higher throughput and separation capacity.

The effectiveness of separation may also vary depending on the composition, size, and distribution of materials within the incoming waste stream. In addition, the present Digital Twin

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framework primarily functions as a monitoring and validation tool, requiring operator intervention for parameter selection and adjustment. Future work will focus on incorporating adaptive control mechanisms capable of automatically modifying operating parameters based on real-time system conditions.

Despite these limitations, the developed prototype provides a practical platform for validating the proposed concept and investigating future advancements in intelligent waste separation systems.

VII. CONCLUSION

This paper presented the design and development of an IoT-enabled Eddy Current Separator integrated with a Digital Twin framework for non-ferrous metal recovery applications. The proposed system combines Eddy Current Separation technology, web-based monitoring, and real-time operational assessment within a single platform. Through the integration of a NodeMCU ESP8266 controller, encoder-based speed monitoring, and a web dashboard, the system enables remote observation of key operating parameters and improves operational visibility .The incorporation of a Digital Twin framework provides a virtual representation of the physical ECS system, allowing comparison between expected and real-time operating conditions. In addition, the use of experimentally derived operating guidelines supports the selection of suitable rotor speeds for different waste categories, contributing to more efficient system utilization and reduced unnecessary energy consumption. The developed prototype successfully demonstrates the feasibility of integrating IoT and Digital Twin technologies into ECS-based recycling systems. Although the current implementation focuses on monitoring and operator-assisted parameter selection, the proposed architecture establishes a foundation for future enhancements such as adaptive control, automated parameter optimization, and large-scale deployment in intelligent waste management applications.

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