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Design and Implementation of an IoT-based Automatic Waste Sorting System using ESP-32, Proximity Sensors, and Firebase

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Abstract

Waste management remains a significant environmental challenge due to the low level of public awareness in sorting waste according to its type. Improper waste segregation reduces recycling efficiency and increases the amount of waste disposed of in landfills. This study proposes the design and implementation of an Internet of Things (IoT)-based automatic waste sorting system using an ESP32-S microcontroller. The system is capable of classifying waste into three categories, namely metal, organic, and inorganic waste. Waste identification is performed using a combination of photoelectric, inductive proximity, and capacitive proximity sensors, while HC-SR04 ultrasonic sensors are utilized to monitor the capacity of each waste compartment. The sorting mechanism is controlled by MG996R servo motors, and the collected data are transmitted to Firebase Realtime Database for real-time monitoring through a Kodular-based Android application. The system was developed using the Agile methodology and evaluated through black-box testing. Experimental results show that the proposed system achieved a maximum classification accuracy of 85%. In addition, the ultrasonic sensor demonstrated stable distance measurement performance with an average error below 0.6 cm. The integration of Firebase and Kodular enabled real-time monitoring of waste classification results and bin status. Therefore, the proposed system can improve waste management efficiency and has potential applications in smart waste management for both household and public environments.

***Keywords**: ESP-32; Firebase; Internet of Things; Smart waste management; Waste sorting*

1. Introduction

Waste management has become one of the major environmental challenges faced by many countries, particularly in urban areas. Population growth and increasing human activities contribute to the continuous rise in waste generation. Improper waste management can lead to adverse health outcomes, for example through contamination of water, soil and air, as well as by creating hazardous conditions for those working in the waste management sector [1]. One of the main challenges in waste management is the lack of effective waste segregation at the source. Most people dispose of waste without separating it according to its type, causing recyclable materials to be mixed with other waste and eventually transported to landfills. This condition reduces recycling efficiency and increases environmental pollution.

The advancement of Internet of Things (IoT) technology has enabled the development of intelligent waste management systems capable of automating waste monitoring and classification processes. Several studies have proposed smart waste bins integrated with sensors and communication technologies. Syaljumairi et al. [2] developed an IoT-based smart waste bin using ultrasonic and rain sensors to classify wet and dry waste while providing monitoring through Telegram notifications. Ramadhan et al. [3] designed an automatic waste sorting system based on Arduino for separating metallic and non-metallic waste. Ismail et al. [4] implemented a smart waste monitoring system utilizing NodeMCU, ultrasonic sensors, Firebase, and Android applications to monitor waste levels in real time. Bahauddin and Munawaroh [5] proposed an automatic waste classification system based on Fuzzy Sugeno integrated with IoT technology. Meanwhile, Bahtiar et al. [6] employed inductive, capacitive, and infrared sensors to identify different waste materials.

Although previous studies have demonstrated the feasibility of automated waste sorting systems, several limitations remain. Most systems focus only on monitoring waste capacity, separating waste into two categories, or implementing computationally intensive fuzzy logic methods. In addition, some studies lack real-time monitoring features accessible through mobile applications. Therefore, there is still a need for a lightweight and practical waste sorting system capable of classifying waste into multiple categories while providing real-time monitoring functionality.

This study proposes an IoT-based automatic waste sorting system using an ESP32-S microcontroller, photoelectric sensors, inductive proximity sensors, capacitive proximity sensors, and ultrasonic sensors. The proposed system classifies waste into three categories: metal, organic, and inorganic waste. The classification results and waste bin status are transmitted to Firebase Realtime Database and displayed through a Kodular-based Android application. The system adopts a rule-based classification approach that reduces computational complexity while maintaining reliable sorting performance.

The main contributions of this study are as follows: (1) the development of an automatic waste sorting system capable of classifying metal, organic, and inorganic waste; (2) the integration of Firebase Realtime Database and a Kodular-based Android application for real-time monitoring; and (3) the implementation of a lightweight rule-based classification mechanism suitable for ESP32-based embedded systems.

2. Research Method

This study focuses on the design and implementation of an Internet of Things (IoT)-based automatic waste sorting system using an ESP32-S microcontroller. The proposed system integrates multiple sensors, servo motors, cloud-based data storage, and a mobile monitoring application to automate the waste classification process. The research methodology consists of system architecture design, workflow development, hardware and software implementation, and system evaluation through functional testing. The overall methodology adopted in this study is illustrated through the system architecture and operational workflow presented in the following subsections.

2.1. System Architecture

The proposed system consists of an ESP32-S microcontroller, multiple sensors, a servo motor, Firebase Realtime Database, and a Kodular-based Android application. The ESP32 is an integrated SoC (System on Chip) microcontroller equipped with 802.11 b/g/n Wi-Fi, Bluetooth version 4.2, and various peripherals. It is a highly capable chip featuring a processor, storage, and GPIO (General Purpose Input-Output) access. The ESP32 can serve as an alternative to the Arduino and possesses the capability to connect directly to Wi-Fi [7].The ESP32-S acts as the central controller responsible for processing sensor data, controlling the servo motor, and transmitting information to the cloud database. As you can see in Figure 1.

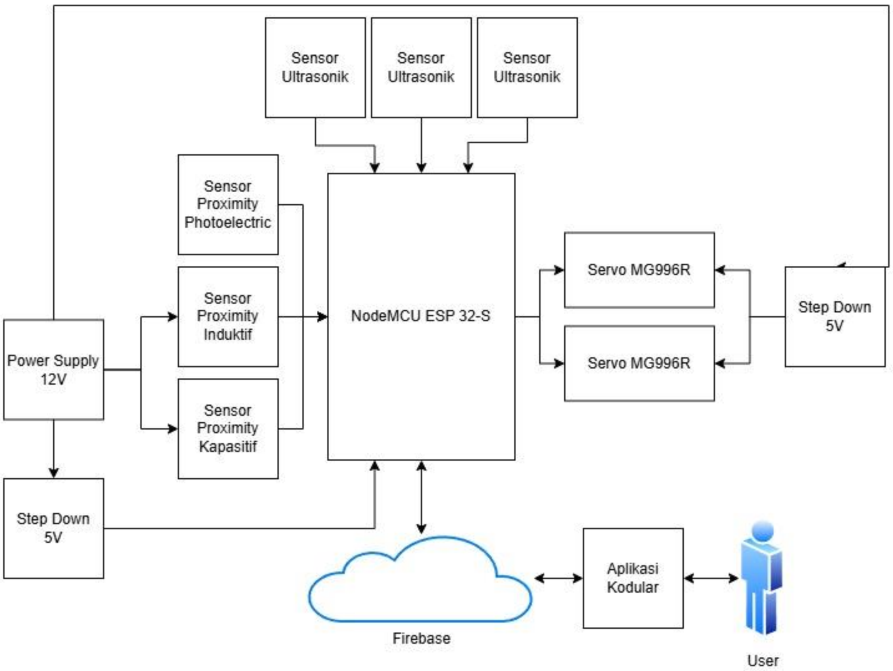


Figure 1: Architecture of the proposed system

A photoelectric sensor is used to detect the presence of waste objects entering the system. A photoelectric proximity sensor is a proximity sensor that utilizes light-sensitive components to detect the presence of an object[8]. Waste classification is performed using inductive and capacitive proximity sensors. While the inductive sensor identifies metallic materials, capacitive proximity sensors are similar to inductive proximity sensors. The main difference between the two types is that capacitive proximity sensors generate an electrostatic field instead of an electromagnetic field. Capacitive proximity switches detect both metallic and non-metallic materials, such as paper, glass, liquids, and fabric [9] with higher moisture content. HC-SR04 ultrasonic sensors operate based on the principle of sound wave reflection, enabling them to determine the distance to an object using a specific frequency[10]. An HC-SR04 ultrasonic sensor is installed in each waste compartment to monitor the waste level and determine whether the bin is full.

The sorting mechanism utilizes an MG996R servo motor, a metal gear servo motor with a maximum stall torque of 11 kg/cm [11], to direct waste into the appropriate compartment according to the classification result. All classification data and bin status information are transmitted to Firebase Realtime Database and displayed through a Kodular-based Android application, enabling real-time monitoring by users.

2.2. System Workflow

The operational workflow of the proposed system begins with the initialization of all hardware and software components, including the ESP32 microcontroller, sensors, servo motor, and Firebase connection. After initialization, the system continuously monitors the waste bin capacity using the HC-SR04 ultrasonic sensor. If the waste compartment reaches its maximum capacity, the sorting process is temporarily suspended until the bin is emptied.

When a waste object is detected by the photoelectric sensor, the classification process is initiated. First, the inductive proximity sensor determines whether the object contains metallic material. If detected, the waste is classified as metal and directed to the metal compartment using the servo motor. If no metallic material is detected, the capacitive proximity sensor evaluates the object. Waste identified by the capacitive sensor is categorized as organic waste. Otherwise, the object is classified as inorganic waste and directed to the corresponding compartment.

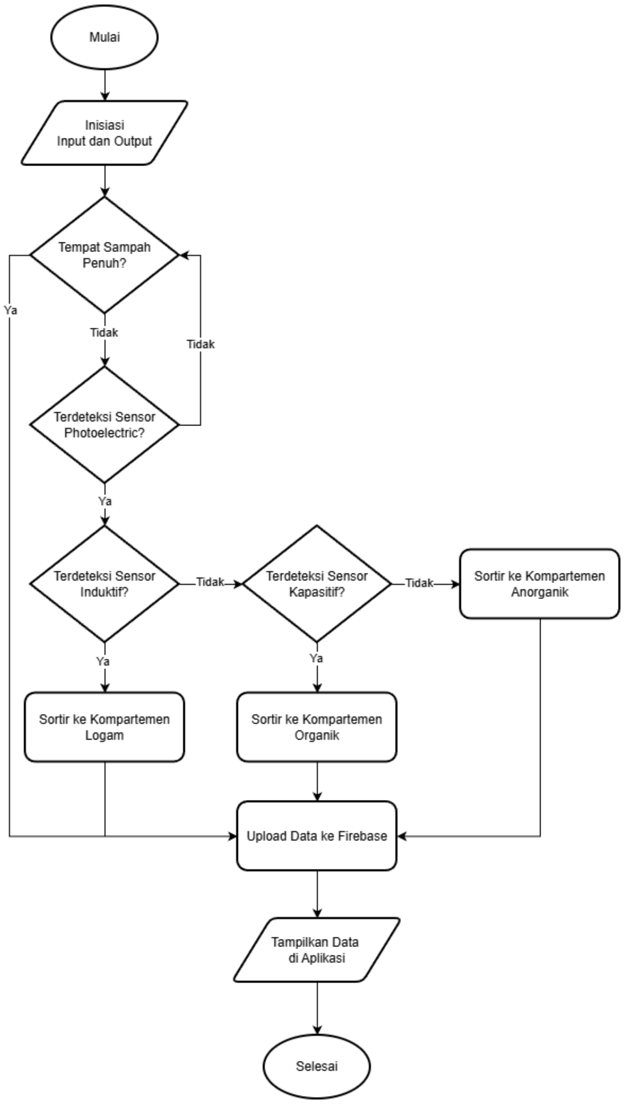


Figure 2: Workflow of the proposed system

After the sorting process is completed, the system records the classification result and transmits the data to Firebase Realtime Database. The stored information can then be accessed through a Kodular-based Android application, allowing users to monitor waste sorting activities and bin status in real time. The system subsequently returns to the monitoring state and waits for the next waste object..

3. Result and Discussion

3.1. Prototype Implementation

The proposed automatic waste sorting system was successfully developed by integrating an ESP32-S microcontroller, inductive proximity sensor, capacitive proximity sensor, photoelectric sensor, HC-SR04 ultrasonic sensors, servo motors, Firebase Realtime Database, and a Kodular-based Android application. The ESP32-S serves as the central controller responsible for processing sensor data, executing classification logic, controlling servo movements, and transmitting information to the cloud database.

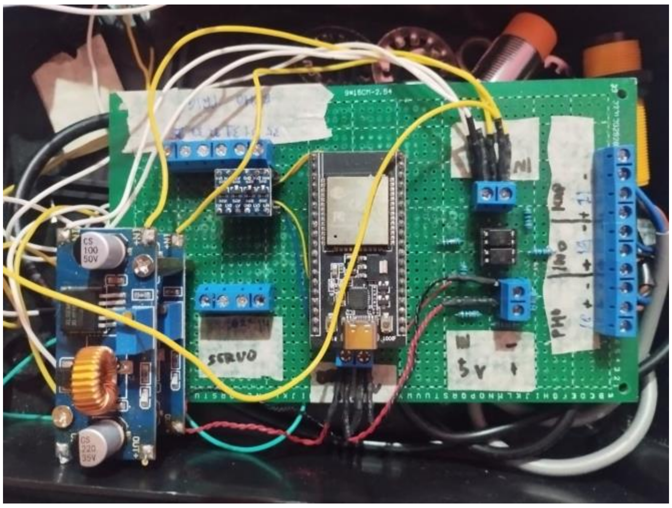
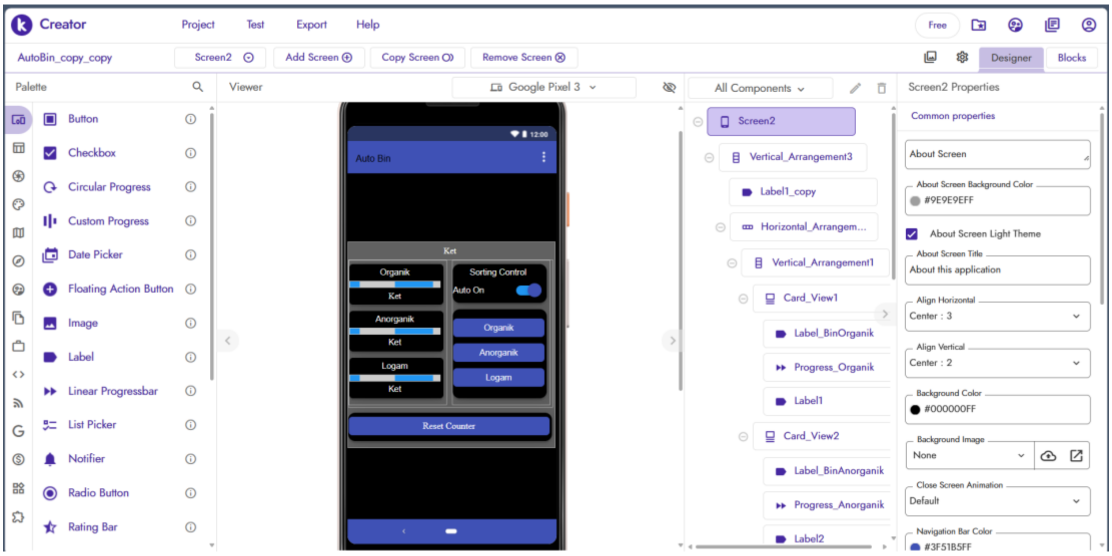


Figure 3: Prototype PCB

The hardware implementation was assembled on a custom PCB to simplify component integration and improve system reliability. The ultrasonic sensors were installed on each waste compartment to monitor bin capacity, while the inductive and capacitive sensors were positioned along the waste input path to identify material characteristics. The photoelectric sensor was used to detect the presence of incoming waste objects before the classification process was performed.



About Screen
About Screen Background Color: #9E9E9EFF
☑ About Screen Light Theme
About Screen Title: About this application
Align Horizontal: Center : 3
Align Vertical: Center : 2
Background Color: #000000FF
Background Image: None
Close Screen Animation: Default
Navigation Bar Color: #3F51B5FF

Figure 4: Monitoring App made by Kodular

Furthermore, a mobile monitoring application was developed using Kodular and connected to Firebase Realtime Database. The application enables users to monitor waste classification activities and waste bin status in real time. The successful integration of hardware and software components demonstrates the feasibility of implementing an IoT-based automatic waste sorting system for smart waste management applications.

3.2. HC-SR04 Testing

The HC-SR04 ultrasonic sensor was evaluated to determine its capability in measuring the distance between the sensor and the waste surface. The measured values were compared with manually measured reference distances to assess accuracy.

Table 1: HC-SR04 Testing Result

Measured Distance	Actual Distance	Error
9.8 cm	10 cm	0.2 cm
19.7 cm	20 cm	0.3 cm
29.5 cm	30 cm	0.5 cm
39.4 cm	40 cm	0.6 cm
49.6 cm	50 cm	0.4 cm

Based on the experimental results presented in Table 1, the sensor produced measurement errors ranging from 0.2 cm to 0.6 cm. The smallest error was observed at a distance of 10 cm, while the largest error occurred at a distance of 40 cm. Despite these variations, the sensor maintained stable performance throughout the testing process. The error distance is obtained using the following formula.

$$Error = |A - B| \qquad (1)$$

Definition 1 : A = Measured Distance; B = Actual Distance

The average measurement error obtained was approximately 0.4 cm, indicating that the sensor provides sufficient accuracy for monitoring waste bin capacity. Such accuracy is considered acceptable because the primary objective of the ultrasonic sensor is to determine whether the waste compartment is approaching its maximum capacity rather than performing precision distance measurements. Therefore, the HC-SR04 sensor is suitable for real-time waste level monitoring within the proposed system.

3.3. Proximity Sensor Testing

The waste classification mechanism relies on the combined operation of inductive, capacitive, and photoelectric proximity sensors. Each sensor performs a specific role in identifying the physical characteristics of waste materials.

Table 2: Proximity Sensor Testing Result

Material	Activated Sensor	Expected Result
Metal	Inductive, Capacitive, Photoelectric	Inductive, Capacitive, Photoelectric
Plastic	Photoelectric	Photoelectric
Glass	Photoelectric	Photoelectric
Fruit Skin	Capacitive, Photoelectric	Capacitive, Photoelectric
Paper	Photoelectric	Photoelectric

The testing results indicate that the inductive sensor successfully detected metallic materials such as iron and aluminum-based objects. The capacitive sensor demonstrated the ability to identify organic materials with relatively high moisture content, including fruit peels. Meanwhile, the photoelectric sensor consistently detected the presence of incoming objects regardless of material type.

The combination of these sensors enables the proposed system to distinguish between metal, organic, and inorganic waste categories. Experimental observations showed that metallic objects generated the most reliable detection results due to the strong response of the inductive sensor. In contrast, several organic materials exhibited varying detection performance because their moisture content directly influenced the capacitive sensor response. Nevertheless, the sensor configuration was able to support the classification requirements of the proposed waste sorting system.

3.4. Functional Testing

Functional testing was conducted using the black-box testing method to verify that all major system functions operated according to the design specifications. The testing covered Wi-Fi connectivity, Firebase authentication, operating mode control, waste classification logic, servo motor actuation, and real-time data communication.

Table 3: Functional Testing Result

Feature	Result
Wi-Fi Connectivity	Pass
Firebase Authentication	Pass
Automatic Mode	Pass
Manual Mode	Pass
Waste Classification	Pass
Servo Control	Pass
Rapid Switching	Fail
Sequential Routing	Fail

The results showed that the ESP32-S successfully connected to the Wi-Fi network within 15 seconds under normal conditions. When incorrect network credentials were provided, the system remained stable and continuously attempted reconnection without causing system crashes. Firebase anonymous authentication was also successfully performed, enabling real-time communication between the embedded system and the cloud database.

The automatic and manual operating modes functioned correctly. In automatic mode, the system classified waste and directed it to the appropriate compartment based on sensor readings. In manual mode, the system waited for user commands without executing automatic routing. The transition between operating modes occurred smoothly with a response time below 300 ms.

Servo motor testing demonstrated that the actuators successfully moved to the designated positions corresponding to organic, inorganic, and metal waste compartments. Most tested scenarios passed successfully. However, slight performance degradation was observed during rapid sequential routing commands and repeated mode-switching operations. These limitations were primarily caused by servo response delays and increased microcontroller processing load. Despite these minor issues, the overall system functionality remained stable and reliable.

3.5. Waste Classification Evaluation

To evaluate the performance of the proposed waste sorting system, repeated experiments were conducted using various waste materials representing organic, inorganic, and metal categories. A total of 100 classification tests were performed under real operating conditions. The results showed that inorganic waste materials, including plastic bags, bubble wrap, masks, and paper, were consistently classified correctly. These materials produced stable responses from the photoelectric sensor and did not activate either the inductive or capacitive sensors, allowing the rule-based classification algorithm to identify them as inorganic waste.

Table 4: Waste Classification Result

Waste Type	Correct	Incorrect
Plastic Bag	10	0
Mask	10	0
Bubble Wrap	10	0
Paper	10	0
Banana Peel	7	3
Leaves	5	5
Branches	4	6
Iron Piece	7	3
Beverage Can	6	4
Perfume Can	6	4

Organic waste materials such as banana peels and leaves achieved satisfactory classification results. However, several misclassifications occurred when the capacitive sensor failed to detect sufficient dielectric variation from the tested objects. This issue was particularly noticeable for dry organic materials such as branches, which frequently exhibited characteristics similar to inorganic waste due to their low moisture content. The following is the formula used to determine the success rate.

$$Success\ Rate = \frac{Total\ Test - Failed\ test}{Total\ Test} \times 100\% \qquad (2)$$

Metal waste objects, including iron pieces, beverage cans, and perfume cans, were generally classified correctly. The inductive sensor demonstrated high sensitivity toward conductive materials and provided reliable detection performance. Misclassifications mainly occurred when the object position reduced the effective sensing range of the inductive sensor. Additional experiments were conducted to investigate the influence of sensing distance on classification performance. The results indicate that classification accuracy decreases significantly as the distance between the object and sensors increases.

Table 5: Classification performance based on sensing distance

Distance	Success Rate
0 cm	85%
2 cm	52%
5 cm	40%

Table 5 shows that the proposed system achieved a maximum classification success rate of 85% when the waste object was positioned directly in front of the sensors. The success rate decreased to 52% at a distance of 2 cm and further dropped to 40% at a distance of 5 cm. These findings demonstrate that sensor placement is a critical factor affecting classification performance. Proper alignment between the waste object and sensing area is necessary to maintain reliable operation. Overall, the experimental results confirm that the proposed system is capable of performing automatic waste classification with satisfactory performance under optimal sensing conditions.

3.6. Firebase and Mobile Application Monitoring

The monitoring subsystem was implemented using Firebase Realtime Database and a Kodular-based Android application. The ESP32-S transmitted waste classification results and waste bin status information to Firebase through a wireless internet connection.

During testing, the communication process operated successfully without significant data transmission failures. Classification data generated by the system were immediately stored in Firebase and synchronized with the Android application. This functionality enabled users to monitor waste sorting activities remotely without direct interaction with the hardware system.

The developed mobile application displayed information regarding waste classification results and system status in real time. The user interface was intentionally designed to be simple and easy to understand, allowing users to access monitoring information efficiently. The successful integration between ESP32-S, Firebase, and Kodular demonstrates the feasibility of implementing cloud-based monitoring in smart waste management systems.

Furthermore, the use of Firebase Realtime Database provides scalability for future development, including historical data storage, notification services, and advanced analytics. Therefore, the proposed monitoring architecture not only supports current system requirements but also offers flexibility for future smart waste management applications.

4. Conclusion

This study successfully designed and implemented an ESP32-S-based automatic waste sorting system capable of classifying waste into metal, organic, and inorganic categories. The proposed system integrates inductive, capacitive, photoelectric, and ultrasonic sensors with servo motor actuators to perform automated waste sorting operations.

Experimental results showed that the HC-SR04 ultrasonic sensor provided stable distance measurements with an error below 0.6 cm, making it suitable for monitoring waste bin capacity. The combination of inductive, capacitive, and photoelectric sensors successfully supported waste classification according to the predefined rule-based algorithm. The waste classification evaluation demonstrated a maximum classification success rate of 85% under optimal sensing conditions.

Furthermore, the integration of Firebase Realtime Database and a Kodular-based Android application enabled real-time monitoring of waste sorting activities and waste bin status. Although minor limitations were observed, including reduced classification performance at larger sensing distances and slight delays during rapid servo operations, the overall system operated reliably and achieved the objectives of the study.

Future work may focus on improving sensor calibration, optimizing sensor placement, and implementing intelligent classification methods to further enhance system accuracy and performance.

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