IoT-Based Smart Bin Waste Management System with Real-Time Capacity Monitoring

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Abstract— Conventional waste management in Indonesia faces the challenge of inefficiency due to static transportation schedules, causing waste to pile up in crowded locations and becoming a source of environmental problems. This study aims to design and implement a smart trash can system based on the Internet of Things (IoT) as a solution to this problem. This system was developed using the Design and Build approach with the Waterfall model, integrating a Wemos microcontroller, infrared sensors for automatic opening and closing mechanisms, ultrasonic sensors for waste volume monitoring, and a web dashboard for centralized data visualization. The results of the study showed the success of the implementation of a functional prototype, starting from hardware assembly, firmware development on the microcontroller, to the backend system and database. System testing using the Black Box method showed that all main functional scenarios including user detection, automatic closing control, volume measurement, and sending data to the dashboard were 100% successful according to the design. This functional success proves that the developed prototype is a valid and potential solution to realize a more efficient, hygienic, and real-time monitorable waste management system, so that it can support better operational decision making.

Keywords— IoT, smart waste management, real-time monitoring, Wemos D1 R32, ultrasonic sensor

I. INTRODUCTION

Indonesia's rapid population growth and urbanization have had serious consequences for the increasing volume of waste generated. Data from the National Waste Management Information System (SIPSN) of the Ministry of Environment and Forestry (KLHK) shows that in 2023, Indonesia will produce around 35.9 million tons of waste, with the largest composition coming from food waste (41.5%) and plastic (18.5%) [1] [2], [3]. This massive volume puts tremendous pressure on existing urban waste management infrastructure and systems, demanding smarter and more efficient solutions.

The root of the problem of current waste management lies in the conventional, static operational model, where waste transportation is carried out based on fixed routes and schedules. [4], [5].

On the other hand, and this is a crucial problem, TPS in densely populated locations or commercial areas often experience a buildup of waste that exceeds its capacity (overload) long before the next collection schedule arrives. [6], [7], [8]. This phenomenon of garbage accumulation not only damages the aesthetics of the city, but also becomes a source of serious environmental and health problems. Garbage that rots in open spaces produces methane gas (CH_4), one of the greenhouse gases whose contribution to global warming is much stronger than carbon dioxide.[9].

Answering these challenges, Internet of Things (IoT) technology offers a new paradigm in waste management. By integrating sensors and internet connectivity into waste infrastructure, passive objects such as trash cans can be transformed into smart assets that can provide real-time operational data [10], [11]. So there needs to be an IoT-based system to help manage waste so that monitoring carried out by officers becomes more efficient. [12], [13], [14], [15].

Therefore, this study aims to design, build, and test the functionality of a prototype IoT-based three-compartment smart trash bin system. This system not only addresses hygiene issues through an automatic opening-closing mechanism, but also fundamentally addresses transportation inefficiencies by providing real-time waste height data through ultrasonic sensors. Data from each trash bin unit is visualized on a scalable web dashboard, allowing centralized monitoring of multiple locations. Thus, this system is designed as a concrete solution for optimizing transportation routes, preventing waste accumulation, and improving the overall effectiveness of urban waste management.

II. METHOD

This study uses the application design approach to produce a technological product in the form of a prototype of a smart trash can system integrated by IoT and a trash height monitoring dashboard. The system development process adopts a waterfall model that is sequential and structured. This model was chosen because the functional needs of the system have been clearly defined at the beginning, thus allowing systematic development through the stages of IoT device development, waste monitoring dashboard software development, and system testing.

The hardware requirements for building the prototype are detailed in Tables 1.

Table 1. Hardware Requirements

No.	Component	Spec.	Function
1	Process Unit	Wemos D1 R32 (ESP8266)	System Control, and Wifi Connectivity
2	Distance Sensor	Ultrasonik HC-SR04	Measuring the level of waste
3	Presence Sensor	Infrared Sensor FC-51	Detecting user presence
4	Actuator	Motor Servo MG90	Actuating the open-close mechanism
5	Physical Container	3 Compartment Trash Can	Main structure of the prototype
6	Power Supply	Adaptor DC 5V 2A	Power source for the circuit
7	Support	Jumper Cable	Electronic assembly component

The selection of components for this prototype was based on a balance between functionality, cost-effectiveness, and ease of integration. The Wemos D1 R32 (ESP32) was chosen as the main processing unit due to its integrated Wi-Fi module essential for IoT connectivity and ease of programming via Arduino IDE. For sensory functions, the HC-SR04 ultrasonic sensor is ideal for non-contact waste level measurement with sufficient accuracy, while the FC-51 infrared sensor provides reliable and responsive near-field user detection. As an actuator, the MG90 servo motor is used due to its ability to provide precise angular control for the opening-closing mechanism. The entire system is powered by a 5V 2A adapter to ensure power stability, especially for the servo motor, and is implemented in a three-compartment container to functionally support the main purpose of waste sorting at source.

In addition to hardware requirements, the development of smart trash bins also requires support from system development. In this study, system development used several existing tools and can be seen in Table 2.

Table 2. Software Requirements

No	Software	Function
1	Arduino IDE	Firmware programming for Wemos D1 R32
3	PHP & MySQL	Backend server (API) and database management
4	HTML, CSS, JavaScript	Front End Monitoring Dashboard

This research stage is carried out by identifying the functional needs of the system where the system will be developed by developing a sensor device controlled by a wemos microcontroller, then it can send a percentage height signal to the server and provide notification when the barrel is full.

The testing stage is carried out using the blackbox method, namely a software testing method that focuses on application functionality without requiring knowledge of the internal structure or program code.

The system development flow can be seen in the flowchart diagram below.

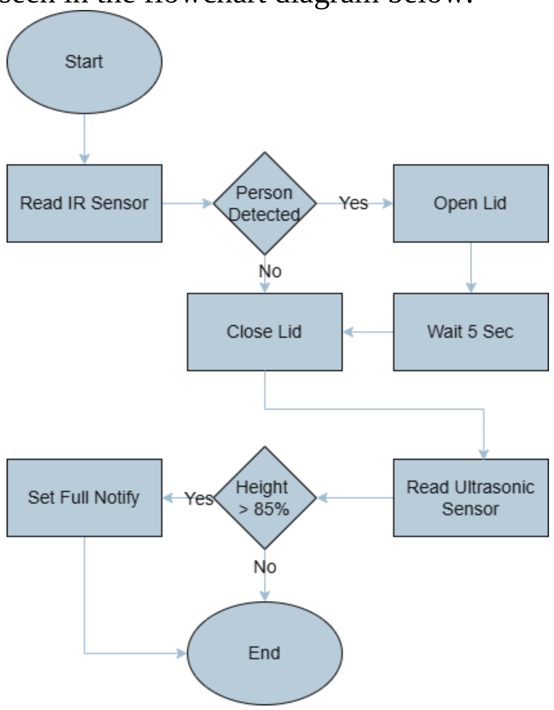

Figure 1 Systems Flowchart

III. RESULTS AND DISCUSSION

In this section, the results of each stage of system development are presented, starting from IoT hardware assembly, software development (firmware and backend), to dashboard interface implementation.

A. RESULT

The results of this research can be seen from the hardware and software development that has been carried out, the results are divided into several parts, namely

1. IoT Hardware Development

IoT development uses the Wemos D1 R32 device as a microcontroller used to send data on the height of the trash and control the components used in the trash can.

The sensors used include the FC-51 infrared sensor to detect the movement of people who are about to throw away trash, and provide a signal to the microcontroller to open the bin if movement is detected around the trash can.

The MG90 servo motor is used to open the trash can lid after receiving a signal from the infrared sensor and make the trash can lid rotate 90 degrees, and close it again after the movement signal from the infrared is lost.

The HC-SR04 Ultrasonic Sensor is used to measure the height of the trash from the top to the bottom of the trash can. The height obtained from this ultrasonic sensor is then formulated into a percentage that will be sent to the database to be displayed on the application dashboard. The following is an illustration of the series of tools used can be seen in Figure 2.

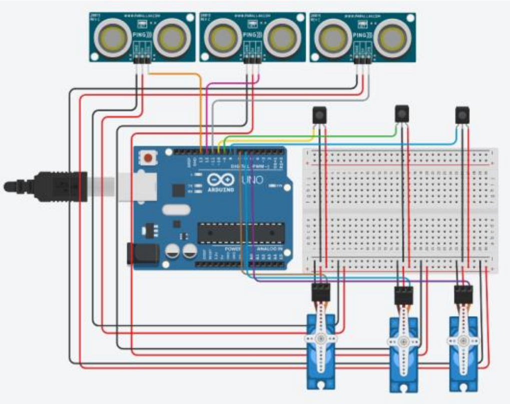

Figure 2. IoT Sensor Illustration

2. Microcontroller Code Development

The development of the microcontroller code consists of several developments of functions required for the microcontroller, including the development of the "handleLidControl" function which is used to open the trash can lid when receiving a signal from the infrared sensor. Then the "handleDataSending" function is used to measure the height of the trash can using an ultrasonic sensor. And the last function is "sendDataToServer" which is used to send the measured data to the database server. Then these functions are called periodically through the basic loop function in the program. An illustration of the Arduino code used can be seen in Figure 3.

```
void loop() {
  // Mengelola kontrol tutup untuk setiap tong sampah
  handleLidControl(0, IR_PIN_1, servo1);
  handleLidControl(1, IR_PIN_2, servo2);
  handleLidControl(2, IR_PIN_3, servo3);

  // Mengelola pengiriman data ke server secara periodik
  handleDataSending();
}
```

Figure 3. Ilustrasi Kode Arduino

3. System Database Development

The next development that was done was to develop a database to accommodate data from the existing microcontroller. The data needed for the application concerns the location of the bin and the percentage of numbers sent by each trash can, so that the table created in Figure 4 can be seen as follows.

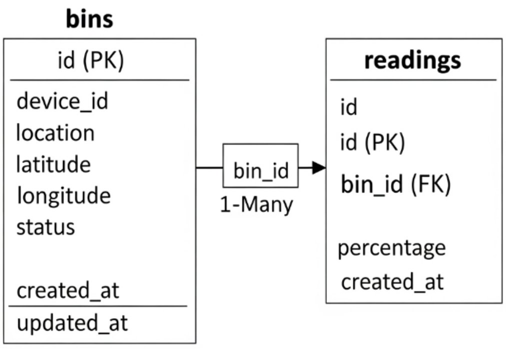

Figure 4. Database Table

4. Dashboard System Development

The next stage is the development of a dashboard to monitor the contents of each trash can that is equipped with an IoT device. The development of the dashboard uses the native php programming language using the bootstrap framework to provide a responsive display to monitor the height of the trash can. The dashboard is developed by taking data through a database that has been created, then with a time interval of 5 seconds it will refresh the web page to update data in real time.

```
async function fetchAndUpdateData() {
    try {
        const response = await fetch('get_data.php');
        if (!response.ok) {
            throw new Error('Failed to get data from server. Status: '
                + response.status);
        }

        const dataFromServer = await response.json();

        tongSampahData = dataFromServer;

        renderDashboard();
    } catch (error) {
        console.error('An error occurred while retrieving data:', error);
    }
}
fetchAndUpdateData();
setInterval(fetchAndUpdateData, 5000);
```

Figure 5. Backend Code Illustration

The display results can be seen in Figure 6. Where the dashboard can display data on the height of the waste taken from each trash can that has been equipped with an IoT sensor.

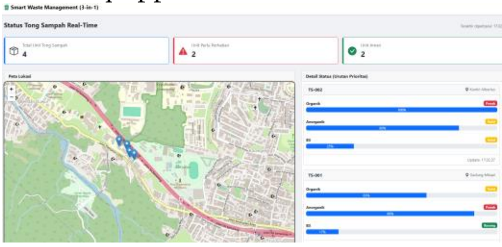

Figure 6. Monitoring Dashboard Illustration

B. DISCUSSION

After developing the application and system, assembly is carried out on existing trash bins, then testing is carried out on the bins.

Figure 7 Implementation of Smart Trash Bin

Application Testing

After the development of the tool and dashboard application is completed, then testing is carried out on the existing system. Testing is carried out using the Black Box method to validate the system's functionality as a whole.

Table 3. Blackbox Testing

Scenario	Input	Expected	Observed	Result
Automatic Lid Opening Mechanism	Placing a hand approx. 10 cm in front of the infrared sensor of one sub-bin.	The corresponding sub-bin's lid opens automatically. Other lids remain closed.	The tested sub-bin's lid opened in under 1 second.	Pass
Automatic Lid Closing Mechanism	After the lid opens, the hand is moved away from the sensor.	The lid closes automatically after the specified duration (e.g., 5 seconds).	The lid closed automatically after 5 seconds.	Pass
Sub-bin Data Update	Filling the 'Organic' sub-bin in unit 'TS-001' to a level >85%.	On the next update cycle, the dashboard displays: 'Organic' progress bar >85%. Its status becomes 'Full' with a red badge.	The display for the 'TS-001' card on the dashboard updated as expected. The progress bar and 'Full' status appeared correctly.	Pass
Summary Card Update	Continuing from scenario FUNC-003 (making one compartment full).	The number on the 'Unit Needs Attention' summary card increments by one.	The number on the 'Unit Needs Attention' card was updated accurately.	Pass

The success of all Black Box test scenarios confirms that the developed smart trash can system has met all functional requirements formulated at the analysis stage. Thus, it can be concluded that the prototype of this system is functionally ready and valid for further testing at the performance testing stage (such as accuracy) and real environment trials.

IV. CONCLUSION

This comprehensive research has successfully designed, implemented, and validated a functional prototype of an IoT-based smart trash bin system, which has proven to be a valid technological solution to transform conventional waste management. The success of this system is demonstrated through its main functionalities that work optimally, including an automatic open-close mechanism via infrared sensors that improve hygiene, as well as the ability to monitor waste volume accurately using ultrasonic sensors. Supported by a scalable web-based monitoring dashboard, this system effectively provides crucial real-time data for the implementation of a dynamic and efficient transportation scheme, thus being able to answer the challenges of inefficiency and waste accumulation in urban areas.

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