Smart Waste Bin System: An Implementation of IoT Technology for Waste Management

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Abstract

This study aims to apply Internet of Things (IoT) technology to a smart trash bin system to address waste management inefficiencies and maintain user hygiene. System development was carried out using the Waterfall method, which includes the stages of needs analysis, design, implementation, and testing. The prototype was built using an ESP32 microcontroller, two HC-SR04 ultrasonic sensors to detect user presence and measure waste capacity, an MG996R servo motor as a door actuator, and integrated with the Firebase Realtime Database for remote monitoring purposes. System functionality testing was conducted using the Black Box Testing method, while user acceptance evaluation was measured using the System Usability Scale (SUS) questionnaire. The test results showed that the automation system and integration of real-time data delivery to the database operated with a 100% success rate. Furthermore, usability testing involving 10 respondents resulted in an average SUS score of 78.5. This value classifies the system into the good acceptance range (Grade B), indicating that this smart trash bin prototype is efficient, functional, and well-accepted by users.

Keywords: *Internet of Things, ESP32, Smart Waste Bin, Firebase, System Usability Scale*

Introduction

The problem of increasing waste volume every year requires serious and structured handling to avoid negative impacts on the environment and public health [1]. Currently, the system for managing and checking the capacity of waste bins in several institutional environments is still largely done manually based on a routine schedule. This conventional method often triggers inefficiencies in costs and operational manpower, where officers visit waste bins that are still empty, or conversely, there is an accumulation of waste that is not monitored due to delays in information [2].

To overcome these obstacles, the application of Internet of Things (IoT) technology is an innovative solution that allows for real-time monitoring of waste capacity remotely [3]. Therefore, this study aims to design a smart trash can prototype using an ESP32 microcontroller, combined with an ultrasonic sensor to detect the level of fullness, and a servo motor actuator so that the lid can open automatically to maintain user hygiene [4]. This system is fully integrated with the Firebase Realtime Database cloud service to ensure fast and accurate data synchronization. This innovation is expected to make it easier for cleaning staff to monitor and prioritize waste collection based on real data in the field, so that operational efficiency can be significantly increased.

Literature Study

The application of IoT technology in waste management systems has been widely explored by previous researchers. Research by Hanafie et al. designed a prototype of a smart trash can that can sort waste using an Arduino Uno [5]. Trisudarmo et al. also implemented an automatic opening and closing mechanism using an ultrasonic sensor and servo motor with an Arduino Uno R3 microcontroller [6]. Another study by Yama developed a waste volume monitoring system using a NodeMCU ESP8266 by utilizing the automatic notification feature via the Telegram messaging application [7], while Fitriani et al. utilized a third-party IoT platform, Blynk, to monitor the level of waste fullness in residential areas [8]. In line with this, Priyansah et al. proved that the use of an ESP32 microcontroller combined with an ultrasonic sensor is very stable and accurate for smart trash cans, even though the system they built is still standalone and relies on a local web server [4].

Unlike previous research, the novelty of this study lies in its collaborative system architecture, independent of the constraints of instant IoT platforms. The prototype was developed using an ESP32 microcontroller fully integrated with the Firebase Realtime Database cloud service. This database enables direct and accurate synchronization of waste capacity data. Furthermore, this study quantitatively measures user acceptance using the System Usability Scale (SUS) test, a technique rarely evaluated in previous hardware design research.

Methodology

Research approach The development of this smart trash bin system prototype was carried out using the Waterfall method approach adapted from Sommerville [9]. The implementation stages are sequential, including Requirements Definition (Needs analysis), System and Software Design (System and software design), Implementation and Unit Testing (Implementation and unit testing), and Integration and System Testing (Integration and system testing). The needs analysis stage begins with data collection through a semi-structured interview method involving 10 respondents (consisting of cleaning staff and students) in the Faculty of Industrial Technology, Islamic University of Indonesia to map the constraints of conventional systems.

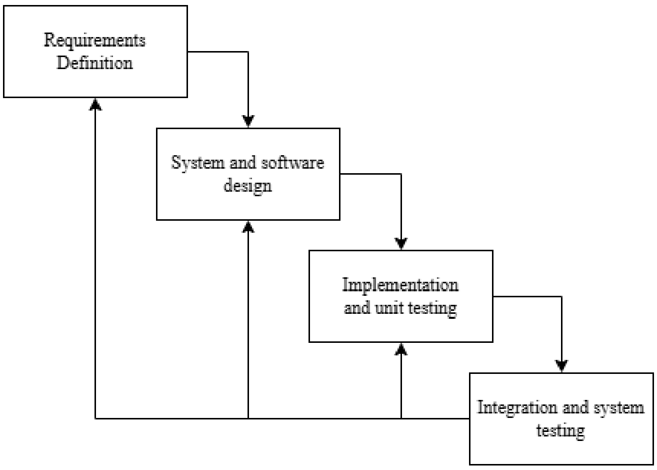

Figure 1. Steps in Waterfall Model

Hardware and software instruments The hardware architecture is designed into three main blocks, input, processing, and output. As the main processing unit, an ESP32 DevKit V1 microcontroller is used which is mounted on an Expansion Board to facilitate power distribution. The input section uses two HC-SR04 ultrasonic sensor units, the first sensor is placed outside to detect the distance of the user's object, and the second sensor is inside the cover to read the distance of the trash pile. In the output section, a metal-mounted MG996R Servo Motor is used as a mechanical actuator to pull the automatic door lever. The percentage status of the trash capacity is displayed locally using a 16x2 LCD screen with an I2C module. The entire system is powered by a 5V 3A switching power supply to maintain voltage stability when there is a surge in current load from the movement of the servo motor. On the software side, the microcontroller logic is programmed using the C++-based Arduino IDE, while the cloud database management uses Firebase.

Data analysis and testing techniques System evaluation was conducted using two main approaches, namely functional testing and user testing. Hardware and software functionality were tested using the Black Box Testing method to validate the suitability between system input and output without the need to review the program code structure in detail [10]. Functional parameters tested included the accuracy of ultrasonic sensor distance readings, servo motor actuator response, and successful data transmission to Firebase. On the other hand, the level of usability and end-user acceptance were evaluated using the System Usability Scale (SUS) questionnaire instrument [11]. This questionnaire consists of 10 standard statements distributed to 10 evaluation respondents with answer choices using a Likert scale of 1 (strongly disagree) to 5 (strongly agree). The collected SUS scores were calculated mathematically using a constant of 2.5, then the average value was converted into a percentage, grade scale, and acceptability ranges to conclude the feasibility of the prototype that had been built.

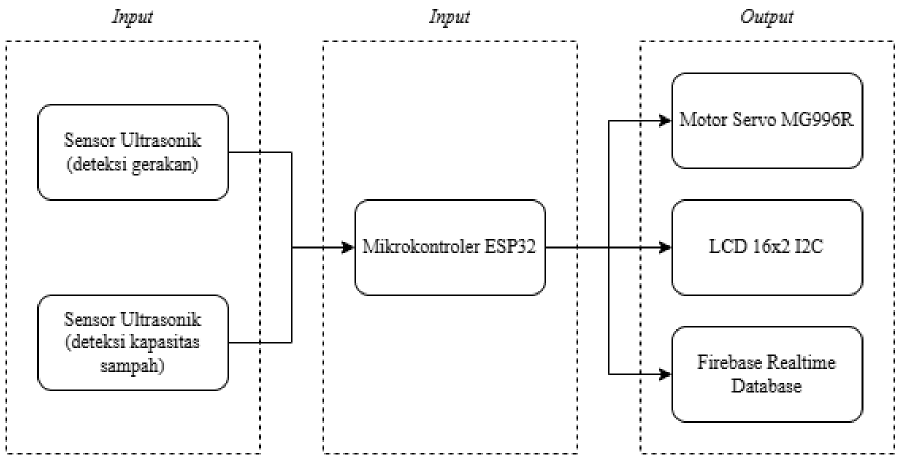

Figure 2. Block Diagram of the System

Results

The hardware implementation was successfully implemented by integrating an ESP32 microcontroller, two HC-SR04 ultrasonic sensors, an MG996R servo motor, and a 16x2 I2C LCD display. System functionality testing was performed using the Black Box Testing method to ensure each component responded properly.

Figure 3. Smart Waste Bin Testing

In user motion detection testing, the external ultrasonic sensor was able to consistently detect objects at a distance of less than 15 cm, which automatically triggered the servo motor to open the trash can lid.

Table 1. Ultrasonic Sensor and Servo Test Results

Number of Trial	Object Distance (cm)	Servo Motor Response	Status
1	5	Opened	Succeed
2	10	Opened	Succeed
3	14	Opened	Succeed
4	15	Opened	Succeed
5	20	Not Opened	Succeed

Next, the capacity measurement accuracy was tested on the internal ultrasonic sensor (the base distance of the empty trash can was configured at 30 cm). The comparison between manual height measurements and the percentage capacity readings by the microcontroller are shown in Table 2.

Table 2. Waste Capacity Accuracy Test Results

Number of Trial	Manual Measurement (cm)	Capacity Percentage (%)	LCD Status Display	Status
1	30	0%	Empty	Accurate
2	22	30%	Empty	Accurate
3	15	50%	Moderate	Accurate
4	10	70%	Moderate	Accurate
5	5	80%	Full	Accurate

In addition to local hardware, data delivery to the Firebase Realtime Database cloud service was also tested. This test evaluated whether the percentage and status displayed on the LCD screen were in sync with the updated data in the Firebase server interface. The test results showed a perfect delivery success rate, as shown in Table 3.

Table 3. Data Delivery Test Results

Number of Trial	Data on the LCD Screen	Data Shown in Firebase	Status
1	0%	Empty	Succeed
2	30%	Empty	Succeed
3	50%	Moderate	Succeed
4	70%	Moderate	Succeed
5	80%	Full	Succeed

In addition to technical functional testing, an end-user acceptance evaluation was also conducted using a System Usability Scale (SUS) questionnaire with 10 respondents, including students and cleaning staff. The questionnaire data, calculated on a Likert scale of 1 to 5, resulted in a total accumulated score of 785, with an average SUS score of 78.5.

Discussion

Based on the test results presented, this smart trash bin prototype has been proven to operate optimally in accordance with its design objectives. The HC-SR04 ultrasonic sensor demonstrated excellent and consistent accuracy in measuring the distance of the trash pile, converting it into a percentage. This performance aligns with the research findings of Priyansah et al. [4], who stated that ultrasonic sensors are highly responsive and precise for monitoring enclosed spaces provided there are no partial obstructions. The stability of the ESP32 microcontroller also proved excellent in executing two tasks simultaneously: controlling the physical movement of the servo motor and sending real-time capacity data updates to Firebase. Integration with the Firebase database was precise. This supports the research of Maulida et al. [12], which confirmed that Firebase's cloud storage structure has a very low latency level, allowing for instant synchronization of trash capacity data, ultimately resolving the inefficiency of manual checking.

Regarding user evaluation, the average SUS score of 78.5 indicates that the system built is in the Acceptable category with a Grade B or "Good" rating [11]. This result means that the physical interface of the device and the door opening automation mechanism are very intuitive, making it easier for users to dispose of waste hygienically, and can be well received by cleaning staff to assist in their routines. However, there are several notes regarding the stability of the mechanical and electronic components. The movement of the servo motor when pulling the trash lid requires a relatively large electric current supply [13]. Therefore, the use of a stable external power supply outside the ESP32 internal regulator is absolutely necessary to prevent the system from experiencing repeated restarts (brownouts). In addition, complete dependence on a local Wi-Fi network connection is also a major challenge when this prototype is widely implemented.

Conclusion

This research has successfully designed and implemented a prototype of an Internet of Things (IoT)-based smart trash bin system. The prototype has proven functional in executing touchless lid opening and closing automation to maintain hygiene, and is capable of accurately calculating the trash fullness level. The integration of a wireless communication network with the Firebase Realtime Database cloud service operates with a perfect success rate in instantly synchronizing capacity status. This system is highly recommended because it has been proven to support the efficiency of remote monitoring and real-time trash collection scheduling for cleaning staff, which is also validated by the high user acceptance evaluation score. For further development in the future, it is recommended to add alternative renewable energy sources such as solar panels so that the device can operate independently in outdoor public areas with minimal electricity access. In addition, improvements to the mechanical mechanism inside the container to level the pile of trash can be considered to optimize the reliability of the sensor's capacity percentage reading.

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