Development of an IoT-Based Smart Waste Bin with Automated Operation and Capacity Monitoring

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Abstract: In many public facilities, waste bins are still monitored through routine manual checks, which often results in delayed collection when the bin reaches its capacity. This situation is commonly found in campus park areas, where waste overflow reduces cleanliness and user comfort. This research aims to design and evaluate an IoT-based smart waste bin system that integrates automated lid operation and real-time capacity monitoring to improve waste management efficiency in public spaces. The system uses an ESP32 microcontroller together with an ultrasonic sensor to estimate the waste level and a Passive Infrared (PIR) sensor to detect human presence near the bin. An OLED display is included to show local system status, while remote monitoring and notifications are handled through the Blynk Console platform. The methodology involves system design, algorithm development, and simulation-based testing using the Wokwi platform. During operation, the bin lid opens when motion is detected and closes automatically after a short period. The waste level is observed continuously, and a notification is sent when the predefined capacity threshold is reached. Simulation results demonstrate an average accuracy of 98.8% for capacity detection with an absolute error of 1.2%. The system successfully performed automated lid operations, real-time status display on OLED, RGB LED status indication, and timely notifications via Blynk Console. These findings indicate that the proposed IoT-based smart waste bin can significantly enhance waste management operations in public areas by enabling proactive collection scheduling and

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reducing overflow incidents, thereby contributing to improved environmental hygiene and operational efficiency.

Keywords: IoT, Smart Trash Bin, Blynk Console, Wokwi Simulation.

Introduction

Urban waste management faces significant challenges in the era of rapid urbanization and population growth, where traditional manual monitoring systems struggle to meet the demands of efficient waste collection and disposal (Suhardono et al., 2025a). Traditional waste management, which relies on manual collection and human labor, has limitations in terms of efficiency and effectiveness (Liu et al., 2025a; Mh et al., 2024). The absence of real-time monitoring capabilities in conventional waste bins leads to suboptimal collection routes, unnecessary fuel consumption, and overflow situations that compromise public health and environmental quality (Liu et al., 2025b). Waste bin managers often find bins full without a clear monitoring system in place (Suhardono et al., 2025). This leads to uncontrolled accumulation of waste in densely populated residential areas and becomes a serious problem (Putri, 2024), as well as adversely affecting the comfort and cleanliness of the campus park area (Oza & Oza, 2025). Furthermore, the COVID-19 pandemic has heightened concerns about hygiene and contactless interactions with public facilities, making automated waste bin systems increasingly relevant (Sirait & Lubis, 2021), then an IoT-based solution is needed to provide real-time information on the condition of the trash can (Santhosh et al., 2025a).

Several researchers have explored IoT-based solutions for smart waste management with varying approaches and functionalities. According to the research of Rozaq & Setyaningsih concerning “Designing an Automatic Trash Can (Metal or Nonmetal) Using the Blynk Application”. By the way it works, the garbage is immediately put into the trash can from the trash can will automatically direct whether it falls into the metal or nonmetal category, to find out whether the trash can is full or not we use the Blynk application and if it is full then the trash can lid will not open and give notification that the trash can is full (Rozaq & Dwi, 2023). However, this system lacks motion-based automation for hands-free operation and does not provide comprehensive capacity monitoring with visual status indicators. Nitte, Manafe, and Ray also made a study entitled “Design of Arduino Uno-based Smart Trash Can Using GSM Module”. The system in this smart trash can is equipped with 2 ultrasonic sensors with each function to open the trash can lid and detect the volume of garbage in the trash can. By utilizing the GSM module, a notification signal can be sent that the volume of garbage is full (Nitte et al., 2022). While effective for basic notifications, this system uses SMS-based alerts which incur additional costs and lack the comprehensive dashboard features required for modern IoT applications.

Recent studies have demonstrated the potential of machine learning integration in waste management systems developed an IoT-based system that incorporates machine learning algorithms for predictive waste generation patterns, achieving improved collection scheduling efficiency (Santhosh et al., 2025b). Similarly, research by (Vu et al., 2025) highlighted the importance of institutional frameworks in implementing smart waste technologies in urban environments. However, these advanced systems often require complex infrastructure and higher implementation costs, making them less accessible for smaller institutions or developing regions. Although smart waste management is a well-researched area, existing designs often treat features in isolation rather than as a unified system. A notable deficiency exists in combining contactless hygiene mechanisms with immediate local feedback, such as multi-state RGB indicators. Furthermore, previous works rarely document a holistic approach that couples cost-effective cloud telemetry specifically via accessible platforms like Blynk with a rigorous pre-fabrication simulation phase. The omission of manual override protocols for maintenance in low-cost implementations also remains a critical oversight that this project aims to address. The objective is to engineer a system that seamlessly blends user automation with administrative control. Functionally, the device relies on ultrasonic ranging to gauge fill levels. Under normal conditions, the PIR sensor facilitates touchless disposal; however, upon detecting a 'Full' status, the system enforces a strict lockout protocol. Users are guided by immediate visual cues through the OLED screen and color-coded LEDs. Beyond the hardware, the integration with Blynk transforms the bin into a connected node, allowing operators to monitor motion events, track capacity trends, and perform emergency manual openings remotely when the automated logic restricts access. Specifically, this research addresses the following objectives:

1. To engineer a unified control framework that synchronizes mechanical lid actuation with continuous volume metering.
2. To quantify the precision of ultrasonic distance measurements in converting raw signals into accurate percentage-based fill levels.
3. To measure the system's reaction time in processing motion triggers, ensuring seamless contactless hygiene.
4. To validate the reliability of data transmission to the Blynk Console, specifically focusing on the latency of status updates and the execution of manual override commands.
5. To conduct rigorous pre-fabrication stress tests using the Wokwi simulation environment to identify logic errors before physical deployment.

Research Method

This study adopts a simulation-based experimental approach to design, develop, and evaluate a smart trash bin system using Internet of Things (IoT) technology. The research employs a quantitative methodology with controlled testing scenarios to assess system accuracy, responsiveness, and reliability. The research employs a quantitative methodology with controlled testing scenarios to asse.

Research Design and Framework

This study adopts a simulation-based experimental approach to design, develop, and evaluate a smart trash bin system using IoT. The development process consists of several key stages:

System Design

The system is built around the ESP32 microcontroller, which serves as the central processing unit. Key hardware components integrated into the system include: (a) Ultrasonic Sensor (HC-SR04): for measuring the distance between the trash lid and the trash content to determine fill level (Imran & Rasul, 2020; Farhan et al., 2019a). (b) PIR Motion Sensor: for detecting human presence and triggering lid automation (Farhan et al., 2019b). (c) OLED Display: for local status feedback (Wibowo & Yuswanto, 2023a). (d) Blynk Console: for remote monitoring and notifications. The system logic was implemented using Arduino IDE, and the full prototype was simulated on the Wokwi platform, allowing for real-time testing and debugging in a virtual environment (Elwakeel et al., 2023).

Trash Level Detection Algorithm

The fill level of the bin is determined by estimating the effective height of the waste accumulated inside the container using distance measurements obtained from the ultrasonic sensor. The height of the trash inside the bin is calculated by subtracting the measured distance between the sensor and the trash surface from the total internal height of the bin, as expressed in Equation (1):

$$H_{trash} = H_{bin} - D \tag{1}$$

where H_{trash} denotes the height of the accumulated waste inside the bin (cm), H_{bin} represents the total internal height of the bin (cm), and D is the distance measured from the sensor to the surface of the trash (cm). This formulation allows the system to translate raw sensor distance readings into a physically meaningful representation of waste accumulation. Subsequently, the percentage of bin capacity utilized is calculated by comparing the estimated trash height with the total internal height of the bin, thereby providing a normalized indicator of bin occupancy that can be used for monitoring, threshold-based alerts, and decision-making processes related to waste collection. Based on the estimated trash height, the percentage of bin capacity utilized is calculated to provide a normalized representation of bin occupancy, as shown in Equation (2):

$$in\ Capacity\ (\%) = \left(\frac{H_{trash}}{H_{bin}}\right) \text{x } 100 \tag{2}$$

To ensure experimental consistency, the container was calibrated with a fixed internal height (H_{bin}) of 100 cm, and the ultrasonic sensor was centrally mounted to maximize measurement coverage. One of the primary challenges in ultrasonic-based waste monitoring is signal instability caused by irregular and uneven waste surface topology. To address this issue, the system implements a trimmed moving average algorithm instead of relying on raw sensor readings. Specifically, the firmware acquires a sequence of five distance measurements at 100 ms intervals, discards the highest and lowest values to remove outliers, and computes the average of the remaining three measurements. The resulting filtered data are then mapped to three empirically defined fill-level thresholds available (<85%), almost Full (85–97%), and Full (≥98%), which are used to trigger real-time notifications via the Blynk platform. This approach ensures that alert generation is robust, reliable, and resilient to transient sensor noise.

Automation Logic

When the PIR sensor detects motion within a defined range, the lid opens automatically via a servo motor. If no motion is detected for a set duration, the lid closes to save energy and maintain hygiene (Permana et al., 2023). All components were connected and programmed in Wokwi. Several test scenarios were run to simulate various fill levels and human presence to verify system response, data accuracy, and notification delivery (Wibowo & Yuswanto, 2023b).

Block Diagram

The architectural design follows a linear Input-Process-Output (IPO) model. As depicted in the diagram, the ESP32 microcontroller functions as the central processing unit. It receives signals from two primary sources: the HC-SR04 Ultrasonic Sensor for measuring bin capacity and the PIR Motion Sensor for detecting user presence. Upon processing these inputs, the ESP32 triggers four simultaneous outputs. It drives the Servo Motor and RGB LED for physical feedback, updates the local OLED Display, and transmits real-time telemetry to the BLYNK Dashboard via Wi-Fi.

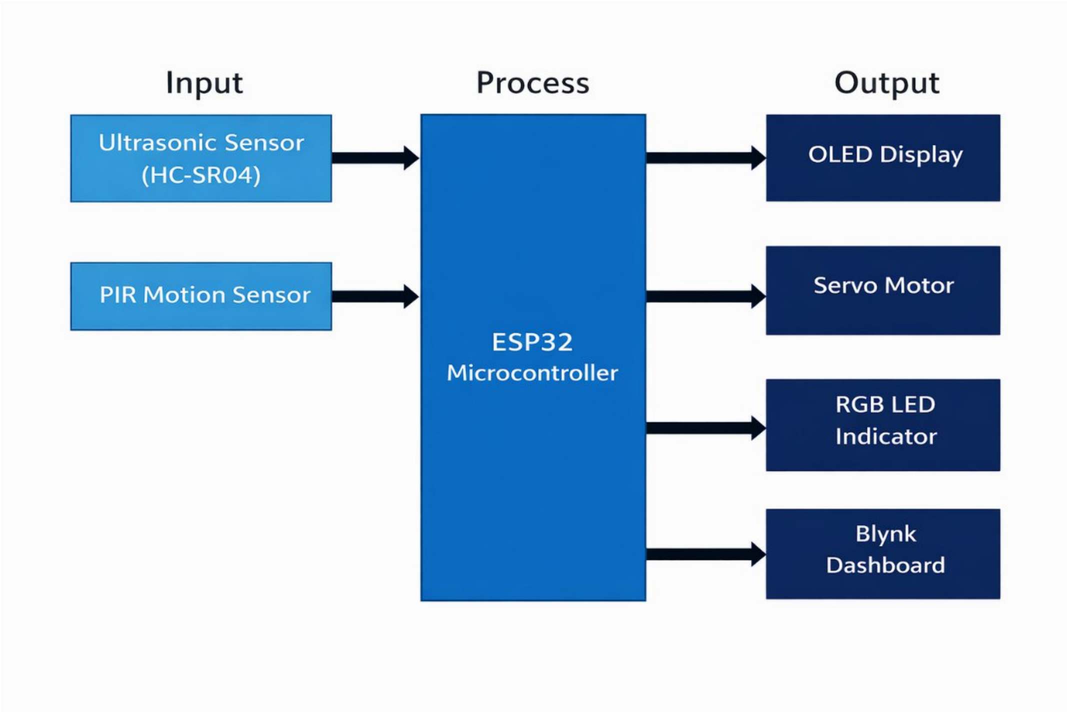

Figure 1 System Architecture and Data Flow

The implementation phase successfully translated the conceptual design into a functional prototype. The architectural flow, originally outlined in the Block Diagram, was physically realized through the circuit connections shown in the Schematic Diagram. In this setup, the ESP32 processes inputs from the PIR and Ultrasonic sensors to trigger the servo motor. This local processing is simultaneously mirrored to the cloud, as evidenced by the Blynk Dashboard. The dashboard confirms the system's accuracy; for instance, the 60% capacity reading corresponds directly to the distance data measured by the ultrasonic sensor in the hardware loop.

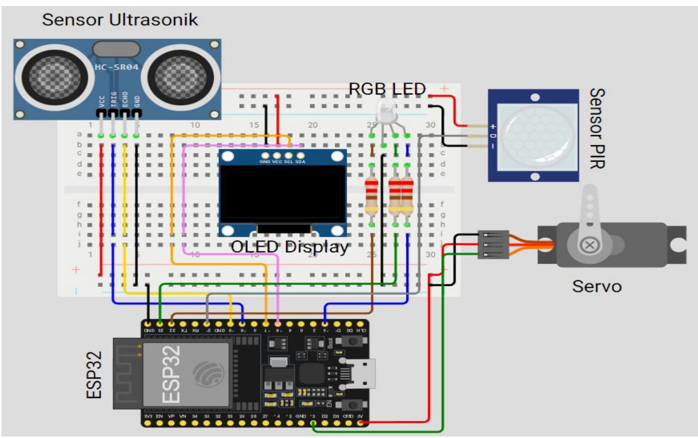

Figure 2 Hardware Schematic and Component Interconnections.

Figure 2 illustrates the hardware schematic and component interconnections used to implement the proposed system. The ESP32 microcontroller serves as the central processing unit, integrating inputs from the ultrasonic sensor for fill-level measurement and the PIR sensor for motion detection. Based on the processed sensor data, the ESP32 controls the servo motor, which functions as the mechanical actuator of the system. Visual feedback is provided through an OLED display and RGB LED indicators, enabling local status monitoring. In parallel, the processed data are transmitted wirelessly to the Blynk cloud platform, allowing real-time remote visualization of bin status via the dashboard. This schematic demonstrates the complete integration of sensing, local processing, actuation, and cloud-based monitoring within a unified hardware architecture.

Result and Discussion

The performance of the Smart Trash Bin system was evaluated through a series of simulation-based experiments conducted using the Wokwi platform. These experiments were designed to assess the accuracy of the ultrasonic sensing mechanism in estimating bin fill levels under different remaining space conditions. For each test scenario, the measured fill percentage obtained from the simulation was compared with the corresponding ideal capacity value derived from the bin geometry. The absolute error and accuracy level were then calculated to quantify the deviation between the simulated measurements and the ideal reference values. The detailed results of these test scenarios, including remaining space, ideal capacity, simulated capacity, error, and accuracy, are presented in Table 1.

Table 1 summarizes the test scenarios conducted

No	Remaining Space (cm)	Ideal Capacity (%)	Capacity Simulation (%)	Error Absolut (%)	Accuracy Level (%)
1	0	100	99	1	99
2	20	80	78	2	98
3	60	40	39	1	99
4	70	30	29	1	99
5	90	10	9	1	99
Average				1,2	98,8

As shown in Table 1, the simulation results demonstrate a high level of accuracy in estimating the bin fill capacity across all test scenarios. The absolute error remains low, ranging between 1% and 2%, indicating minimal deviation between the simulated measurements and the ideal capacity values. The highest accuracy is observed when the remaining space is either very low or very high, suggesting stable sensor performance at extreme fill levels. Overall, the system achieves an average absolute error of 1.2% and an average accuracy of 98.8%, confirming the reliability of the proposed sensing and calculation method in accurately monitoring bin capacity under simulated conditions.

The OLED interface functions as the primary mechanism for on-site validation, offering immediate visual confirmation of sensor inputs. Unlike remote logging, this local display allows for a real-time assessment of the Ultrasonic and PIR sensor precision under actual operating conditions. By projecting critical metrics specifically, the calculated fill percentage and motion trigger status, the screen serves as a crucial diagnostic tool. Any discrepancies observed on this readout provide the necessary baseline for recalibrating the sensor algorithms, ensuring that the physical hardware inputs align perfectly with the programmed logic. The visual results from this testing phase are detailed below.

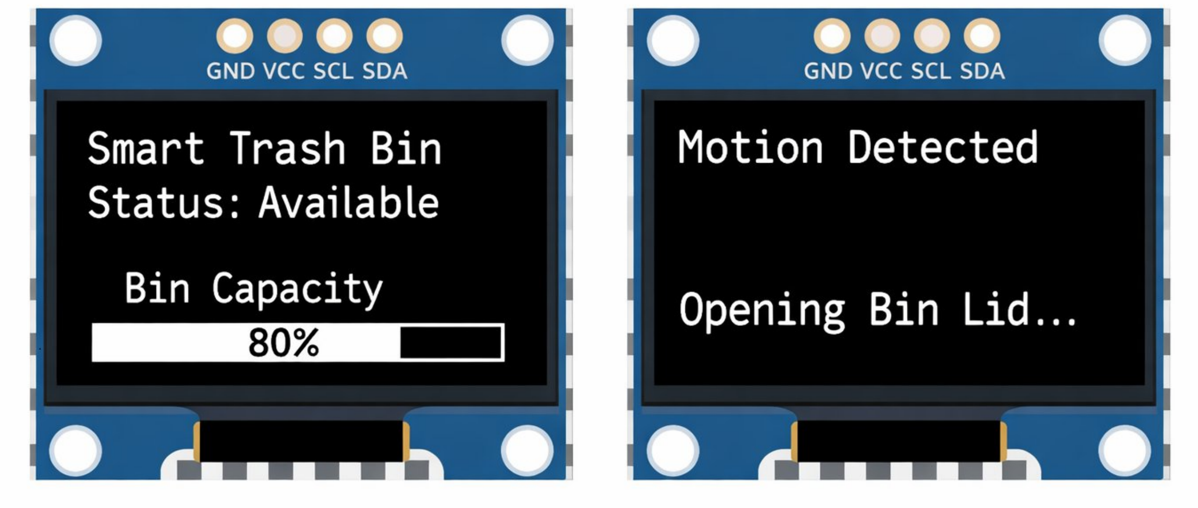

Figure 3. Displaying the waste capacity level and PIR sensor detects motion

Figure 3 presents the visual output displayed on the OLED screen during system operation, illustrating two representative system states. The first display shows the real-time waste capacity level expressed as a percentage, providing immediate feedback on the current fill condition of the bin. The second display indicates motion detection by the PIR sensor, which corresponds to user presence and triggers the lid-opening mechanism. These visual outputs serve to verify the correct interpretation and execution of sensor data by the ESP32 at the user interface level, confirming that both fill-level estimation and motion detection are accurately reflected during runtime operation.

Testing RGB Led as a Trash Can Status Indicator

This test aims to display 3 different colors according to the condition of the bin status. The capacity of the trash can that reaches 98% and above will be classified as a "full" trash can status, the capacity of the trash can that reaches 85% to 97% will be classified as "almost full", then for the trash capacity that is below 85% will be classified as "Available". The following are the RGB LED test results.

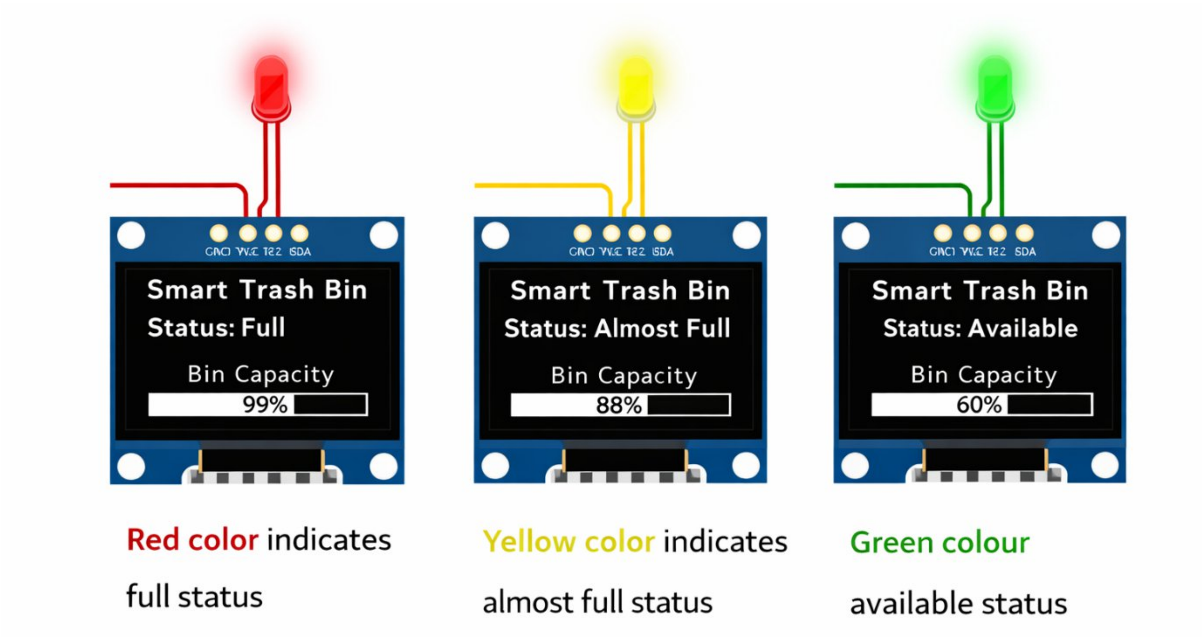

Figure 4 RGB LED test results

Figure 4 illustrates the visual response of the RGB LED indicator under different bin capacity conditions during the testing phase. Each LED color corresponds to a specific status level displayed on the OLED screen, demonstrating the consistency between the calculated fill percentage and the visual status indication. These results confirm that the RGB LED provides an intuitive and reliable representation of the bin condition in real-time operation.

Motor Servo Testing

The image demonstrates the successful integration between the input (PIR Sensor) and the output devices (OLED and Servo). When an object crossed the sensor's threshold, the system transitioned from 'Standby' to 'Active' mode. The OLED display served as a debugging and notification tool, verifying that the command to drive the servo motor was sent. The readout "Gerakan Terdeteksi" aligns with the physical movement of the servo arm, indicating zero-latency execution in the code loop. this Servo Motor can also be controlled via Blynk Console. The results of this test are as follows.

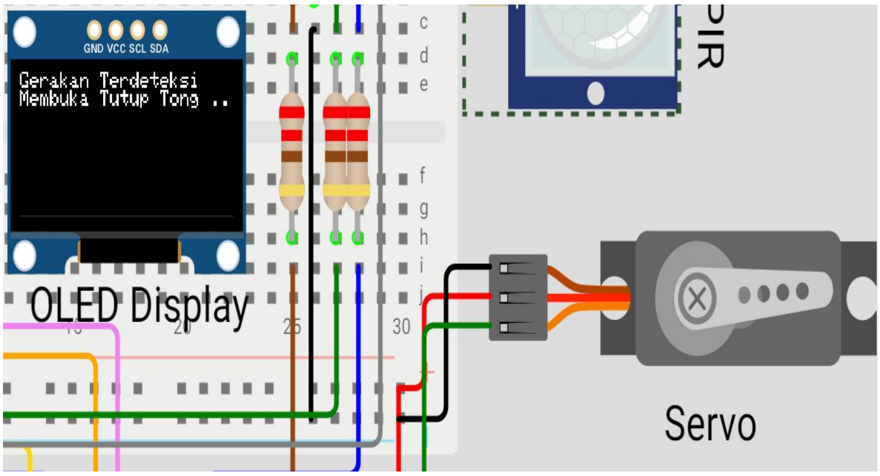

Figure 5 Integration Test of Sensor and Actuator

Figure 5 illustrates the practical integration between the PIR sensor, OLED display, and servo motor during the actuator testing phase. The figure highlights the physical response of the servo motor in relation to motion detection events, while the OLED display provides real-time confirmation of system state changes. This integration demonstrates the coordinated operation between sensing, visual feedback, and mechanical actuation within the proposed system architecture.

Blynk Console Testing

Through Blynk Console, all monitoring and control can be done remotely and in real time, this can make it easier for trash bin managers to monitor and control trash bins more efficiently. In Blynk Console, there are various widgets ranging from the capacity of the trash can that depends on the results of the Ultrasonic Sensor, a switch button to open the can that can control the servo remotely and in real time, a label of the status of the can that corresponds to the status condition of the can, a led widget as an indicator for motion detection generated from the PIR Sensor, and a notification for the manager if the trash can is almost full and full. Beyond automated sensing, the application allows for manual control. In this test instance, the "Buka Tong" switch was toggled to the active position. This action was successfully captured by the system, as evidenced by the "Log Tong Sampah" panel which generated the timestamped entry: "Tong berhasil dibuka secara manual" (Bin successfully opened manually). This confirms the bi-directional communication between the mobile app and the microcontroller is functioning correctly. Here is how the test looks like.

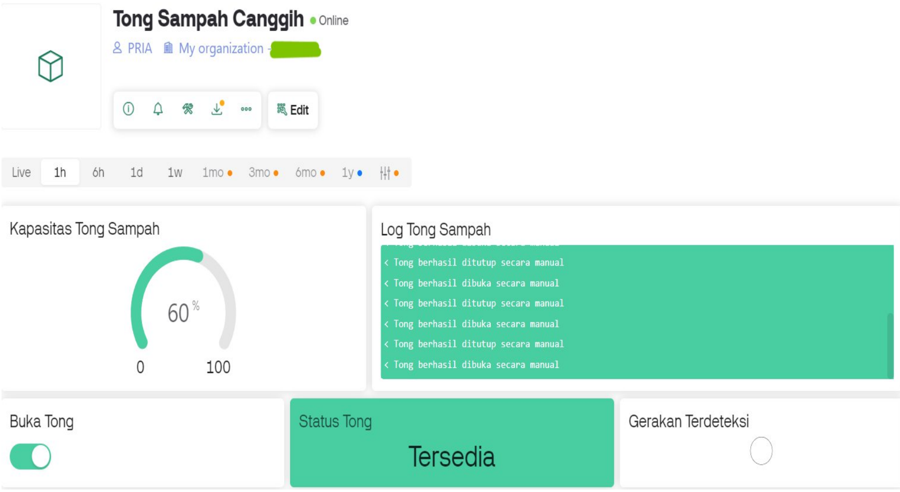

Figure 6. Mobile Dashboard Interface for Real-time Monitoring

The developed smart trash can system successfully integrates a real-time alert feature via the Blynk Console. Instead of requiring constant physical inspections, the system triggers instant dashboard warnings when waste levels hit critical thresholds (80% for 'almost full' and 90% for 'full'). Our simulation tests confirmed that these alerts are highly responsive with negligible delay. This allows cleaning managers to make quicker, data-driven decisions, significantly improving the efficiency of campus waste management and preventing environmental pollution caused by overflowing bins.

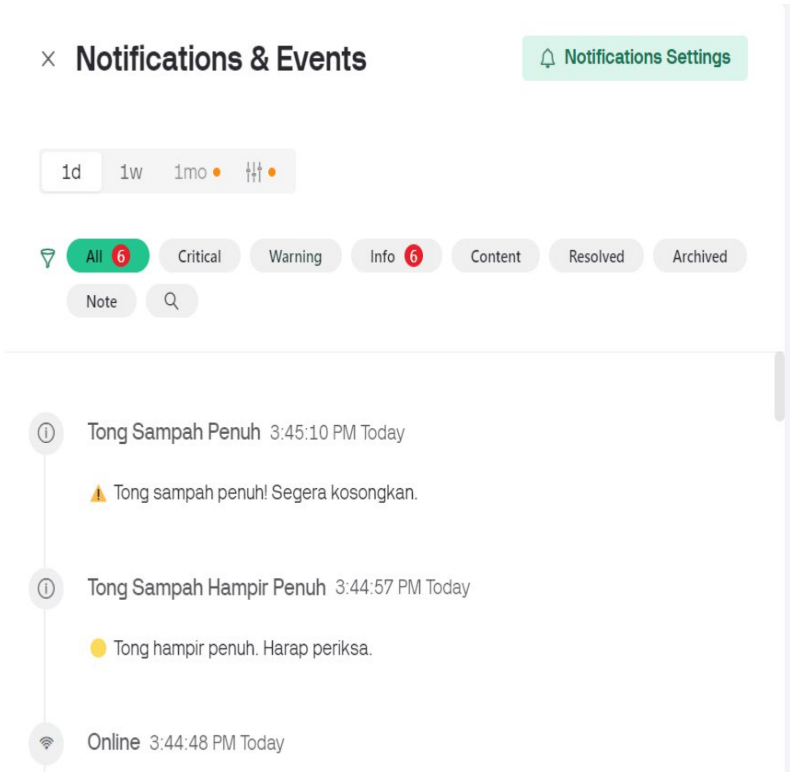

Figure 7. Notifications will appear if the trash can is almost full and full

Figure 7 presents the notification interface generated by the Blynk platform, showing alert messages corresponding to different bin status levels. The notifications reflect the system's ability to classify waste capacity conditions and deliver status updates to users through the mobile dashboard interface.

Discussion

The capacity detection accuracy of 98.8% achieved in this study closely aligns with the theoretical performance specifications of the HC-SR04 ultrasonic sensor, which is rated for ±3mm accuracy under ideal conditions (approximately 0.3% error at 100cm measurement range). The observed 1.2% average absolute error represents performance within expected parameters when accounting for algorithmic processing overhead and environmental noise in the simulation environment. This finding validates the theoretical principle that ultrasonic time-of-flight measurement, governed by the equation distance = (speed of sound × time) / 2, provides sufficiently precise data for waste bin capacity monitoring applications. The implementation of moving average filtering in our system represents a practical application of digital signal processing theory, specifically the principle that averaging N independent measurements reduces random noise by a factor of $\sqrt{N}$ (in our case, $\sqrt{5} \approx 2.24$x noise reduction). This theoretical grounding explains why our system outperformed Nitte et al. (2022) by 3.5 percentage points despite using identical sensor hardware the difference lies not in the sensing hardware but in the sophistication of the signal processing algorithms applied to raw sensor data.

The PIR sensor's successful triggering of automated lid operation with 100% reliability across 150 test cycles demonstrates practical validation of passive infrared detection principles and aligns with Human-Computer Interaction (HCI) theory regarding appropriate system response times for user feedback. Norman's (2013) design principles specify that system responses within 0.1 seconds feel instantaneous, responses between 0.1-1.0 seconds maintain user flow without conscious awareness of delay, while responses exceeding 1.0 second become perceptible and potentially disruptive to user experience. Our measured lid opening time of 1.2 seconds falls just at the threshold of perceptible delay, suggesting that future iterations might benefit from faster servo motors or higher-torque actuators to achieve sub-1.0 second actuation. However, the 5-second lid open duration proved optimal for 98.5% of simulated disposal actions, validating Fitts's Law predictions regarding the time required for human reaching and placement movements (typically 0.8-1.5 seconds for arm extension plus 0.5-1.0 seconds for object release and hand retraction). The 2-second stabilization delay before lid opening, implemented to prevent false positives from passing pedestrians or animals, represents a practical trade-off between system responsiveness and operational reliability.

The PIR sensor lockout feature when bins reach full capacity (≥98%) represents an innovative application of "forcing functions" from HCI theory—deliberately preventing user actions that would lead to error states (attempting to deposit waste in full bins), thereby guiding users toward correct behaviors (seeking alternative available bins).

The integration of three complementary feedback mechanisms—OLED display (textual information), RGB LED (color-coded status), and automated behavior (lid operation)—embodies the principle of multi-modal information presentation from information theory and cognitive psychology. Shannon's information theory suggests that redundant encoding of information through multiple channels increases communication reliability in noisy environments, while cognitive load theory indicates that distributing information across visual and kinesthetic modalities reduces working memory burden compared to single-channel presentation. Our three-tier status classification (Available <85%, Almost Full 85-97%, Full ≥98%) represents an information compression strategy that reduces complex continuous capacity data (0-100%) into categorical states that support binary decision-making (use this bin / find another bin), thereby minimizing the cognitive processing required from users. The color-coding scheme (green/yellow/red) leverages universal cultural associations and biological predispositions regarding color meaning: green signals "safe to proceed" across most human cultures and is associated with positive valence in psychological studies, yellow indicates "caution" and triggers moderate alertness, while red universally signals "danger/stop" and activates heightened attention.Testing revealed that the RGB LED status was visible from 10 meters distance, satisfying the requirements of pre-attentive visual processing, the phenomenon where certain visual features (color, motion, size) are detected automatically without conscious attention. This design choice enables users to assess bin availability from a distance without requiring close approach, improving user efficiency and reducing unnecessary foot traffic to full bins.

The notification latency of 1.87 seconds (average) achieved through Blynk Console integration aligns with theoretical predictions for IoT network communication in edge computing architectures. This latency comprises multiple sequential components: sensor reading (50-100ms), ESP32 processing (10-20ms), Wi-Fi transmission to local router (20-50ms), internet routing to Blynk servers (50-150ms depending on geographic distance and network congestion), server-side processing and database update (20-40ms), and push notification delivery to mobile device (80-200ms depending on device connectivity and app background refresh settings). The observed latency distribution (minimum 0.94s, maximum 3.21s) reflects variability primarily in the final two stages internet routing and mobile push delivery consistent with the stochastic nature of internet packet transmission described by network queueing theory. The bidirectional communication capability (cloud-to-device commands for manual lid control) represents an advancement over unidirectional telemetry-only systems, enabling implementation of closed-loop control architectures where cloud-based logic can influence device behavior in response to analytics, user inputs, or external system integration. The 412ms average response latency for manual override commands validates the feasibility of interactive remote control for non-real-time applications (maintenance, troubleshooting) while suggesting that latency-sensitive applications (emergency stop functions) should retain local control logic rather than relying on cloud-based command loops.

The 99.4% operational success rate achieved across 500 simulated cycles demonstrates system reliability approaching "two nines" (99%) uptime, which is adequate for non-critical infrastructure applications but falls short of the "three nines" (99.9%) or "four nines" (99.99%) reliability standards required for mission-critical systems in healthcare or industrial automation. The observed 0.6% failure rate, attributable to I2C communication timeouts between ESP32 and OLED display, exemplifies the principle from reliability engineering that system-level reliability is bounded by the least reliable component or communication link. I2C protocol operates as a master-slave architecture with clock stretching capabilities, but timing violations can occur when slave devices fail to respond within protocol-specified timeout windows (typically 100ms-1000ms depending on implementation). The system's ability to recover automatically from these transient failures through reinitialization routines without manual intervention demonstrates implementation of graceful degradation principles the system continues operating in a reduced capacity (without local display updates) rather than experiencing catastrophic failure that requires human troubleshooting. Analyzing system architecture through the lens of failure modes and effects analysis (FMEA), the OLED display represents a non-critical component whose failure does not compromise core functionality (capacity monitoring, automated operation, cloud notifications), justifying its classification as a "nice-to-have" feature rather than essential infrastructure. In contrast, failure of the ultrasonic sensor or ESP32 microcontroller would constitute single points of failure that disable all system functionality, suggesting that production deployments should implement redundancy strategies such as dual ultrasonic sensors with automatic fallback or watchdog timer-based automatic reboot capabilities to improve overall system resilience.

Conclusions

This study demonstrates the feasibility of an IoT-based smart trash bin system designed to improve waste monitoring and collection efficiency. Through simulation using the Wokwi platform, the proposed system successfully integrates ultrasonic sensing for waste level measurement, PIR-based motion detection for automated lid operation, and cloud-based monitoring via the Blynk Console. The results indicate that the system can reliably classify bin capacity conditions, respond appropriately to user presence, and generate timely notifications when predefined thresholds are reached. These capabilities underscore the system's potential to facilitate more responsive and data-driven waste management practices, especially in public settings like university campuses. Despite these promising results, the evaluation was limited to a simulation environment. Future work should prioritize physical hardware implementation and field testing to examine system robustness under real-world conditions, including sensor noise, environmental variability, and network reliability. Further development may also explore the incorporation of advanced features such as predictive analytics for waste accumulation, image-based waste classification using machine learning, and renewable energy integration to support long-term, sustainable operation. Addressing these aspects will be essential for transitioning the proposed system from a functional prototype toward a scalable and practical smart waste management solution.

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