



DOI: <https://doi.org/10.38035/gijes.v4i1>,
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Design and Fabrication of a Smart Waste Bin Using Arduino for Improved Hygiene and Waste Management

Tina Ishioma Francis-Akilaki¹, Raymond Alex Ekemube²

¹University of Benin, Benin City, Nigeria, tina.odibi@uniben.edu

²University of Benin, Benin City, Nigeria, raymond.ekemube@uniben.edu

Corresponding Author: tina.odibi@uniben.edu¹

Abstract: Predominantly in emerging nations, the inevitability for sanitary and efficient waste disposal systems has increased because of rate of waste generation development and urbanization. The aim of this study is to use an Arduino microcontroller and ultrasonic sensor technology to design, fabricate, and assess a low-cost smart waste bin. A HC-SR04 ultrasonic sensor is utilized in the designed and fabricated smart waste bin system to sense user proximity. A servo motor is then automatically stimulated to open and close the bin lid without necessitating physical contact. In order to certify reproducibility in settings with limited resources, hardware, embedded programming, and construction were all completed using simply accessible and reasonably priced components. The operational dependability, response time, and detection accuracy were used for performance evaluation. The experimental outcomes showed constant system performance, less false activation, and reliable lid actuation within the sensing range calibrated. The smart waste bin's design and fabrication greatly advances waste handling proficiency, user convenience, and hygiene. The study establishes that low-cost embedded automation can enhance sanitation infrastructure and offers a scalable foundation for future smart waste management systems.

Keyword: Arduino, Embedded Systems, Smart Waste Bin, Ultrasonic Sensor, Touchless Sanitation, Waste Management.

INTRODUCTION

Waste management remains the most important environmental and public health concern in rapidly urbanizing societies. The increase in population growth and consumption patterns continue to raise municipal solid waste generation, thereby applying pressure on sanitation infrastructure (Yusuf et al., 2019; Voukkali et al., 2024). Conventional waste bins commonly used in homes, offices, hospitals, and public facilities need manual lid operation, which disclosures users to contaminated surfaces and increases the likelihood of disease communication (Bello et al., 2023; Alabi et al., 2023). Also, reported by Alabi et al. (2023), and WHO (2020) that conventional waste bins require physical contact during operation, thus increasing the risk of microbial transmission and environmental contamination. Studies by

Kumar et al. (2018); and Akinwumi and Sanni (2023) reported that the growing complexity of municipal waste streams has further necessitated the adoption of intelligent waste handling systems capable of improving operational efficiency and environmental sustainability

The COVID-19 pandemic additionally emphasized the risks accompanying with frequent contact with shared surfaces and highlighted the importance of touchless sanitation technologies (WHO, 2014; WHO, 2020). Additionally, hygiene concerns, manual waste bins frequently suffer from poor user compliance, as lids are often left open, leading to odour emission, pest infestation, and environmental pollution. These lacks impair general sanitation expertise and have a harmful impact on contemporary places' visual appeal.

The low-cost microcontrollers and improvements in embedded systems have created novel avenues for the development of automated sanitation devices. Definitely, Arduino platforms provides adaptable and open-source settings for integrating sensors and actuators into useful automation systems (Patel et al., 2020; 2023; Mohankumar et al., 2024). According to Patil and Kale, (2016); Kumar and Singh (2017) reported that Arduino-based automation platforms have been widely validated for low-cost embedded control applications due to their modularity, open-source ecosystem, and ease of rapid prototyping.

Owing to their excellent accuracy, affordability, and resistance to interference from ambient light, ultrasonic sensors have become one of the most widely utilized sensing technologies for closeness detection (Reaño et al., 2021). Previous studies have demonstrated that ultrasonic proximity sensing provides superior stability in short-range detection compared with infrared-based alternatives, particularly in environments with varying lighting conditions (Abdulkader et al., 2020; Panchal et al., 2023).

In spite of these technical advancements, many of the smart waste bin solutions presently on the market place a strong emphasis on cloud-based monitoring structures, artificial intelligence, or Internet of Things (IoT) connectivity (Singh et al., 2022). In spite of their efficacy, these systems regularly raise design complexity, energy consumption, and overall cost, which confines their applicability in developing nations where simplicity and affordability are decisive.

Hence, there is still an understandable need for an easy-to-use, reasonably priced smart waste bin that enhances cleanliness and user convenience without demanding a lot of technology. By designing and constructing an Arduino-based smart waste bin that uses ultrasonic closeness sensing to open and close automatically, this study fills the aforementioned gap. The system highlights affordability, ease of replication, and dependable performance and is exactly modeled for home and semi-public settings. This study is to design and construct an affordable smart trash can with a touchless lid that operates automatically.

METHOD

Systems Design Overview

Figure 1 illustrates the designed and constructed smart waste bin. It was developed as an embedded mechatronic system with three main subsystems including the actuation unit, the control unit, and the sensing unit (Figure 2). The Arduino controller processes the signals, the servo motor actuates the lid, and the ultrasonic sensor senses the user's hand. This design conforms with recommended hygienic waste-handling procedures and ensures totally touchless operation (WHO, 2020).

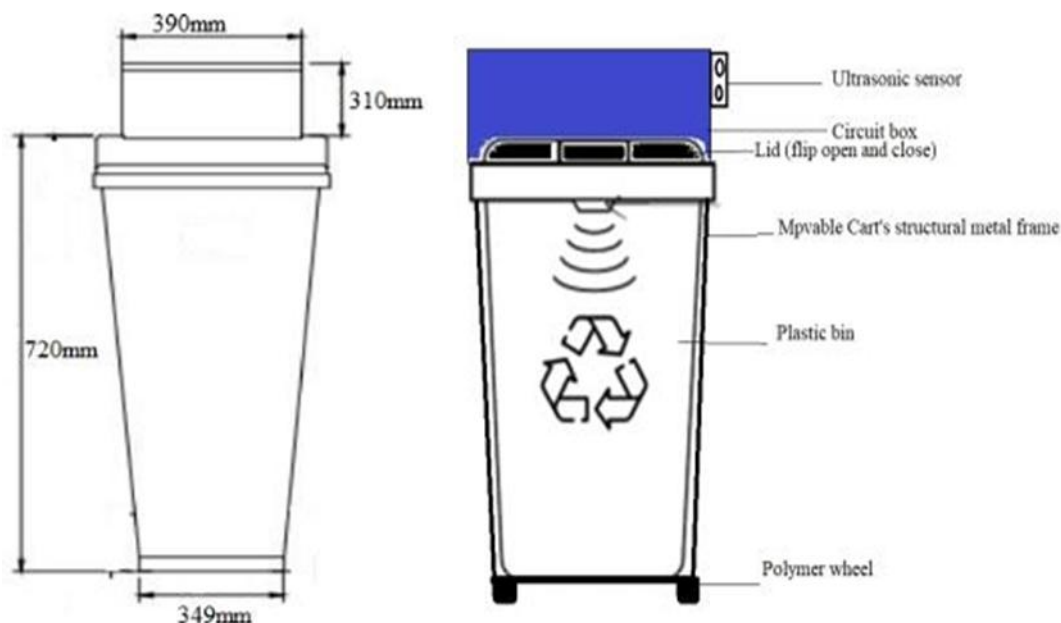


Figure 1. Schematic of Smart Waste Bin

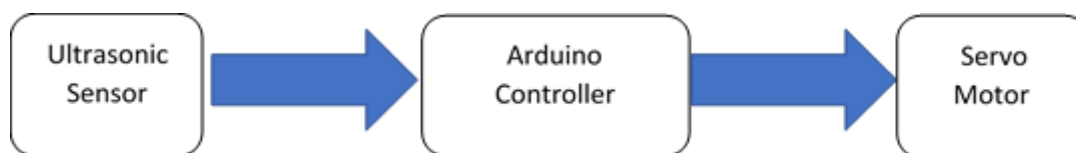


Figure 2. Smart Waste Bin System Block Diagram

Materials Used

In Table 1, the important elements of the smart waste bin system are shown. For the reason of their availability, cost, and proven effectiveness in embedded automation applications, the HC-SR04 ultrasonic sensor and Arduino platform were selected. This is consistent with similar research conducted by Mohankumar et al. (2024) and Patel et al. (2020, 2023). Similar component selection strategies have been reported in recent smart bin prototypes targeting low-cost deployment in developing regions (Lawal, 2023; Sivapriya et al., 2024).

Table 1. Important Components of the Smart Waste Bin

Component	Function
HC-SR04 ultrasonic sensor	Detects user proximity
Arduino Mega/Uno	Central control unit
SG90 servo motor	Lid actuation
Power supply unit	Provides regulated voltage
Breadboard and jumper wires	Circuit connections
Structural frame	Mechanical support
Plastic waste bin	Waste container

Hardware Implementation

1. Ultrasonic Sensor Module

As shown in Figure 3, the HC-SR04 ultrasonic sensor was utilized to determine the distance by sending high-frequency acoustic pulses and computing echo return time. For touchless interfaces, this pulse-echo technique offers reliable short-range detection (Reaño et al., 2021). This pulse-echo measurement principle has been extensively applied in embedded

distance-measurement systems due to its robustness and computational simplicity (Angadiameya, 2021; Kumar et al., 2018).

The sensor is appropriate for hand-gesture waste disposal applications since it performs very well within 2 to 400 cm with an accuracy of about ± 3 cm.



Figure 3. Ultrasonic Sensor Module

2. Microcontroller Unit

The ATmega2560 microcontroller, which is the basis for the Arduino Mega/Uno shown in Figure 4, was carefully chosen due to its various I/O capability, programming flexibility, and low power consumption. Researchers such as Patel et al. (2020) and Mohankumar et al. (2024) have extensively reported similar Arduino-based systems as active for solo automation tasks.



Figure 4. Arduino Mega (the MCU)

3. Actuation Mechanism

To make available exact angular motion, a hinge-lever system was utilized to mechanically attach a typical SG90 servo motor, as depicted in Figure 5, to the bin lid. Due to its positional accuracy and low power consumption, servo-based actuation is frequently utilized in smart bin designs (Bello et al., 2023). Servo-based lid mechanisms remain the preferred actuation approach in compact smart bin designs because of their precise angular control and low energy requirement (Rahul et al., 2024; Jain, 2017).



Figure 5. Servo Motor

4. Power Supply Design

The power unit comprises of step-down transformer (230 V AC \rightarrow 15 V AC), bridge rectifier, filter capacitor (1000 μ F) and the voltage regulators (7812 and 7805) which are shown in Figure 6, the controlled outputs supply has 12 V for the control circuitry (Relay Module), and Figure 7 displays 5 V for the sensor and servo used in the design.



Figure 6: Relay Module



Figure 7: IR Sensor

5. Control Algorithm

The embedded control logic starts from initializing the system, measure the distance, compare it to the threshold, open the lid, wait for the predetermined amount of time and finally close the lid if the distance is less than the set value.

Smart Waste Bin Fabrication

As shown in Figure 8, the smart waste bin was constructed with a servo linkage system, hinged lid mechanism, internal mounting frame, and a durable plastic housing.



Figure 8: Fabricated Proof of Concept of Smart Waste Bin

Performance Evaluation

Reliability, false-activating rate, detection accuracy, and response time were used to evaluate the smart waste bin system's performance. To verify real-time operation, numerous experimental tests were carried out at various hand-to-sensor distances.

RESULT AND DISCUSSION

Detection Performance

By means of measuring the percentage detection success and the associated response time at different user sensor distances, the performance detection of the developed smart waste bin was evaluated. The system attained 100% detection success at 5 cm and 10 cm, conferring to the results shown in Table 2 and Figure 9, indicating the great sensitivity of the HC-SR04 ultrasonic sensor in close proximity. The detection success declined somewhat from 98% to 95% when the distance was extended from 15 cm to 20 cm, reduced echo strength across greater distances, mostly in settings with little auditory interference.

This slight reduction can be ascribed to ultrasonic waves' inherent dispersion and attenuation with increasing propagation distance. This decrease is in keeping with the attenuation behavior of ultrasonic waves reported in earlier research (Reaño et al., 2021). At extended ranges, ultrasonic sensors usually display condensed echo strength, particularly in settings with low levels of acoustic interference.

Table 2. Detection Accuracy and Response Time

Distance (cm)	Detection Success (%)	Response Time (s)
5	100	0.45
10	100	0.48
15	98	0.52
20	95	0.58

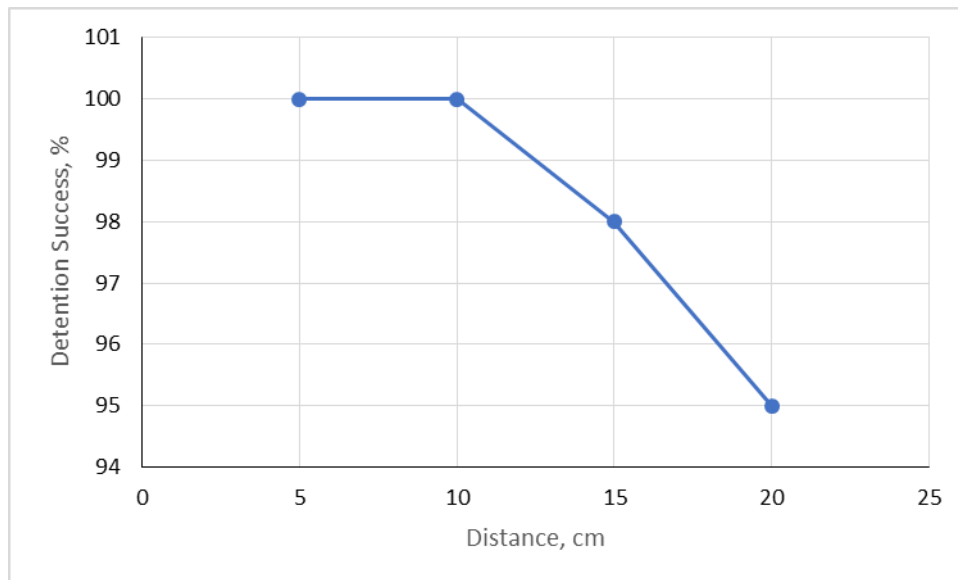


Figure 9: Detection Accuracy of Smart Waste Bin

Accordingly, 5 to 15 cm was acknowledged as the system's ideal operating window, within which the waste bin lid responded often and dependably. This calibrated range is suitable for conditions involving the disposal of waste by hand in both private and semi-public settings. Moreover, the measured reaction times (0.45 to 0.58 s) verified that the sensing-actuation loop functions efficiently with very little delay. The results authenticate that the embedded system architecture is proficient of real-time closeness detection without noticeable delay to the user. Generally, the detection subsystem meets the functional obligation for touchless sanitation devices and compares favourably with similar low-cost embedded sensing applications stated in the literature. These results are comparable to detection efficiencies reported in similar Arduino-ultrasonic waste bin systems (Shubham & Goyal, 2020; Yusof et al., 2018)

System Response Characteristics

Smart waste bin system responsiveness is a thoughtful serviceability parameter for automated sanitation devices. The designed and constructed smart waste bin system response characteristics are shown in Figure 10. The developed smart waste bin showed consistently fast response times less than 0.6 s transversely all tested distances. This rapid response can be attributed to several design factors such as efficient pulse-echo processing by the ultrasonic sensor, real-time signal handling by the Arduino microcontroller, low-inertia actuation of the SG90 servo motor, and improved the threshold in the embedded code.

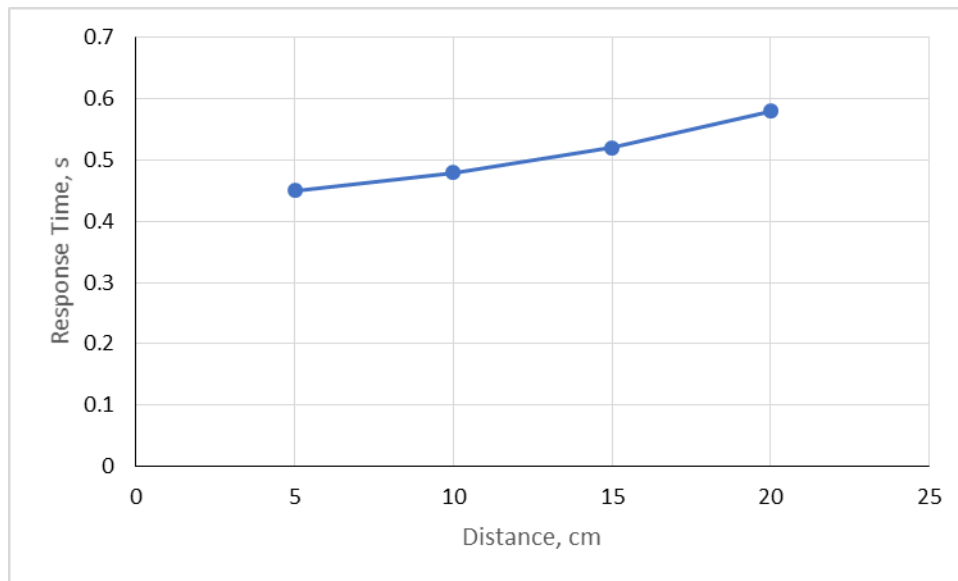


Figure 10: Response Time of the Smart Waste Bin

Observing the human-machine interaction perception, response times less than 1 second are generally assumed as instantaneous by users. Fast system responsiveness is a critical usability metric in human-machine interface design for smart sanitation devices (Han et al., 2012). The measurable values consequently stipulate excellent user experience performance. The outcomes approve the appropriateness of embedded ultrasonic control for touchless sanitation devices. This akin to the findings of Patel et al. (2020).

By comparison with manual waste bins, that needs physical lifting and repositioning of the lid, the automated system reduces user effort, curtails reluctance during waste disposal, and motivates proper bin usage compliance. Also, the slight upsurge in response time with distance is anticipated due to longer ultrasonic travel time directly affects the echo-processing duration. However, the variation remains small and does not deteriorate practical usability. The outcomes approve that the design and fabrication achieve the intended objective of fast and user-friendly touchless operation.

Reliability Assessment

The testing of the reliability of the designed and fabricated smart waste bin was carried out repetitively by open-close cycling of the smart waste bin under consistent operating conditions. All through the test time, the system kept consistent mechanical and electrical performance, indicating strong design resilience. Important outcomes were the absence of servo stalling or jitter, steady Arduino control signals, consistent sensor readings all over testing, and smooth, repeatable lid motion.

A vital sign of system dependability, the inappropriate activating rate was insignificant. Once compared to infrared-based proximity sensors, ultrasonic sensing is integrally less sensitive to variations in ambient lighting. This peculiarity made a substantial input into the steady performance seen in this investigation. Additional important factor in reliability was the hinge-lever mechanical coupling. Precise angular orientation of the lid was guaranteed, and mechanical backlash was reduced with suitable alignment. Moreover, voltage variations that may otherwise cause servo instability were prohibited by the regulated power supply. The outcomes are in line with earlier study that found ultrasonic-based proximity systems to be very consistent for short-range automation applications (Reaño et al., 2021). In overall, the system delivers sufficient operational reliability for light public use and household use. The observed system stability further corroborates earlier findings that short-range ultrasonic

automation systems exhibit high repeatability under controlled operating conditions (Welman & Ar-Rafif, 2021)

Hygiene and Practical Implications

This study's main motivation was to advance sanitation and lessen contact-based contamination linked with traditional trash cans. By means of effective elimination of the necessity for direct lid contact, the constructed smart waste container lowers the likelihood of germ transmission. This is consistent with the outcomes of Alabi et al. (2023) and with WHO guidelines emphasizing reduced contact with common surfaces to stop the spread of infection (WHO, 2020). From the perspective of public health, touchless waste disposal systems are specifically useful in settings where food is handled, such as households, workplaces, schools, hospitals, and clinics. Better user compliance, less odour contact, augmented accessibility for senior users, and appropriateness for resource-constrained locations are some perceptible advantages found. Due to the design of avoiding expensive IoT modules, it remains economically feasible for disposition in developing areas. Touchless waste interfaces have been shown to significantly reduce contact-mediated contamination risks in high-traffic environments (Utomo et al., 2018).

Comparison with Existing Systems

The designed and fabricated smart waste bin was compared with both conventional manual bins and more complex IoT-enabled smart bins as presented in Table 3. The comparison (Table 3) emphasis on the design philosophy of functional simplicity with cost proficiency. The comparison with conventional bins of the designed and fabricated waste bin system offers fully touchless process and enhanced hygiene. The comparison to IoT-enabled smart bins, the designed and fabricated system offers lower cost, abridged power consumption, simpler maintenance, and easier repetition. These findings backing earlier observations that Arduino-based standalone systems remain highly operative where connectivity is not the main requirement. This supports the findings by Patel et al. (2020). While IoT-enabled bins provide fleet-level analytics, several studies emphasize that standalone smart bins remain more practical for household-scale deployment in developing economies (Okubanjo et al., 2024).

Table 3. Comparison with Conventional Bins

Feature	Conventional Bin	Conventional Bin
Physical contact	Required	Required
Hygiene level	Low	Low
User convenience	Moderate	Moderate
Cost	Low	Low

CONCLUSION

The study effectively designed and fabricated a low-cost smart waste bin using an ultrasonic sensor and Arduino microcontroller. Based on the calibrated range, the developed system verified excellent detection accuracy, quick response time, and dependable touchless operation. The constructed smart waste bin conserves affordability and ease of use while positively addressing hygienic issues allied with traditional garbage bins. Conferring to this study, embedded automation technologies can greatly advance waste management procedures in semi-public and residential settings. They also make available a workable basis for future smart sanitation systems in locations with limited resources

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