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# KANJIBIN: AN ARDUINO-BASED SOLAR-POWERED AUTOMATIC WASTE COMPACTOR AND SEGREGATOR

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***Abstract:*** Solid waste management mainly refers to the complete process of collecting, treating, and disposing of solid waste. Considering the increasing amounts of waste produced, solid waste management is a crucial concern for the world. Chemical exposures from waste create a significant risk to workers in handling garbage; technological innovations may be utilized to assist solid waste management safely. Therefore, this paper constructed an Arduino-based solar-powered Automatic Waste Compactor and Segregator made of new materials and designed to reduce the researchers combined the compactor and segregator with two power sources, battery, and solar power, and programmed the robot with their original code. The Arduino Uno ATmega320P was used as a microcontroller. Further, the methodology was divided into three parts, i.e., the mechanical schematics, hardware description, and the programming design. All parts were assembled, and experiments were performed to determine the robot's functionality. The study outcomes revealed that the robot is functional in terms of Mechanical Design, Electrical Design, Solar Harvesting, Charging Efficiency, Wireless Operation, Waste Compactor Capability, Waste Segregator Ability, and Durability. However, it was observed that the compaction force of the robot was insufficient, and the robot was limited to handling only one bin at a time. Therefore, it is recommended that future researchers consider incorporating an additional linear actuator to enhance the compaction force and integrate a module to compact and segregate multiple waste bins simultaneously for improved efficiency.

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## INTRODUCTION

Solid waste management is a significant global challenge intensified by expanding urban populations and rising trash production. The issue transcends simple waste collection; it necessitates thorough operations that include waste reduction, recycling, and safe disposal. Conventional trash management techniques frequently depend on human sorting, which is labor-intensive and susceptible to inaccuracies. Current studies on solid waste management emphasize several strategies, including source reduction, source segregation, and recycling programs. Research indicates that source segregation enhances waste processing and disposal, while sustainable techniques such as composting and waste-to-energy technologies contribute to reducing environmental effects. Nevertheless, although these methods diminish garbage production and alleviate landfill pressure, they frequently lack automation, constraining their scalability (Malav et al., 2020).

Moreover, technological improvements, especially in robotics and automation, have presented intriguing techniques for waste management. Robotic systems for garbage sorting and recycling have exhibited enhanced sorting precision, reduced health hazards for employees, and augmented operational efficiency. Robotics can enhance waste management via effective sorting and compaction, with the creation of robotic compactors and segregators demonstrating significant advantages in reducing waste volume and enabling safe disposal (Kaur, Gambhir, & Kumar, 2016).

With these pressing technological advancements, the researchers in this study developed a product, named KanjiBin, which represents an innovative step in waste management practices, specifically designed for educational institutions like Colon National High School. By integrating automated sorting and compaction, KanjiBin maximizes storage efficiency and enables effective waste disposal, promoting environmental responsibility within the school. This prototype serves as a foundation for future STEM students to expand upon, offering an effective and sustainable waste management solution that could be adopted in similar institutional settings.

Also, this study addresses the engineering challenge of inefficient solid waste management, particularly prevalent in school environments where improper disposal is common. The project aimed to develop a sustainable and efficient solution in the form of an Arduino-based, solar-powered automatic waste compactor and segregator system equipped with HC-SR04 sensing modules. By automating the sorting and compaction processes, the device enhances waste management by ensuring accurate segregation and minimizing the need for storage. Designed to serve as a model for educational institutions seeking eco-friendly waste disposal practices, this project builds on previous innovations by integrating Arduino technology and solar power to boost sustainability and operational efficiency. Ultimately, this autonomous system reduces reliance on manual labor while fostering responsible waste management practices.

**Objectives of the Study**

This study built an autonomous, Arduino-based, solar-powered waste compactor and segregator system designed to enhance solid waste management in school environments.

In completing this study, the researchers performed these subsequent tasks:

1.) Build an autonomous, Arduino-based, solar-powered waste compactor and segregator system robot.

2.) Test the built autonomous, Arduino-based solar-powered waste compactor and segregator system robot in terms of its:

2.1 Mechanical Design;
2.2 Electrical Design;
2.3 Solar Harvesting;
2.4 Charging Efficiency;
2.5 Wireless Operation;
2.6 Waste Compactor Capability;
2.7 Waste Segregator Ability and
2.8 KanjiBin's Durability.

**Research Questions**

Directed by the objectives of the study, the researchers sought answers to these questions:

1.) How can an autonomous, Arduino-based, solar-powered waste compactor and segregator system robot be built?

2.) What are the results of the tests performed in the built Autonomous, Arduino-based, solar-powered waste compactorn and segregator system robot in terms of its:

2.1 Mechanical Design;
2.2 Electrical Design;
2.3 Solar Harvesting;
2.4 Charging Efficiency;
2.5 Wireless Operation;
2.6 Waste Compactor Capability;
2.7 Waste Segregator Ability and
2.8 KanjiBin's Durability?

**Significance of the Study**

This study is hoped to be beneficial to the following:

To the Robotics. The experts recognized the existence of robotics. They understood that this would not only offer improvements to the world but would also be advantageous for the discipline of solid waste management. The researchers chose to create a prototype robot that compacts and separates solid waste because, in addition to its importance to society, it advances the subject of robotics, which several students are interested in. This built prototype solar-powered Arduino-based automatic waste compactor and segregator will attract more students and researchers to robotics. In turn, it may result in exploring breakthroughs that may enhance people's lives by making them more convenient, secure, and improved. Furthermore, the limitations and deficiencies in this study present an opportunity for students and other researchers to conduct further investigations to enhance the prototype Arduino-based automatic waste compactor and segregator.

To the Environment. The researchers remained dedicated to encouraging environmental protection by creating a prototype Solar-powered Arduino-based automatic waste compactor and segregator with new materials. In addition, the researchers were knowledgeable about unjust behaviors and other environmental concerns. If humans persist in utilizing items that have been improperly discarded without assuming full accountability, the natural environment will be thrown into utter disarray. This creation mitigates the adverse impacts of waste disposal on the environment. Automating waste segregation and compacting could decrease the amount of waste sent to landfills and mitigate environmental degradation. To fully advocate for a clean and sustainable environment, the researchers examined the potential consequences of persisting in activities that harm the environment.

To the Community. This study may help the community. The implementation of such a system may result in cleaner and improved living conditions in a community. Reducing the volume of garbage generated and enhancing waste segregation may improve the general health of a community. Waste management in the community may become more effective using the KanjiBin. Automating the trash-sorting procedure and using linear mechanism compaction lessens the physical effort necessary for these jobs. Cleaner neighborhoods and a lower risk of health problems related to garbage treatment may also be outcomes of this efficiency. Further, this automatic waste segregator and compactor is the most important and influential of these recent technological advancements. Indeed, the current researchers' creation of an Arduino-based solar-powered automatic waste compactor and segregator benefits the community in Maasim because it gives the municipality's waste collectors access to a robot that is both an automatic waste compactor and a waste segregator. The robot intends to condense and separate waste in these functions to decrease improper disposal.

To the School Academe. This study may benefit the school stakeholders, students, and all individuals involved in the academe. It may assist them in improving students' learning progress and determining their ability to conduct robotics-related courses of study. This STEM solar-powered Arduino-based automatic waste compactor and segregator provides the school academe with a foundation for improving STEM curriculum by establishing enhanced robotics teaching and learning and by creating a conducive environment for students that facilitates effective STEM learning and facilities that support STEM students' robotics learning. As an outcome, the school academe may seek assistance from prospective external stakeholders to provide sufficient finances for the STEM Department to strengthen robotics teaching and learning.

To Colon National High School Students. This research may have an immense impact on them, especially now that robotics studies at Colon National High School have increasingly developed in the field of research. This research may persuade students to pursue robotics-related studies. This research may benefit them since people have been introduced to the world of consumed technological advances, in which they depend on the existence of valuable products they use daily. The study of robotics may drive students to do their best to develop things that benefit them and the school, especially since this is a new milestone for the educational institution.

To the STEM Students. This study assists them in being progressive students because they exhibited their work in ways that corresponded to their fields of interest, reflecting their growth as STEM students. It also assists students in retaining information and the ability to be resilient and dynamic when an unprecedented occurrence occurs in their community, contributing to a significant aspect that can enhance optimism and satisfaction. STEM students are allowed to do a Capstone project as part of their educational experience, employing their expertise in the field of research while keeping to its ethics to prevent further unfavorable consequences.

They were able to explore new things and develop personal changes by being exposed to a new world beyond their comfort zone, where they exploited their various skills, such as problem-solving, linguistic proficiency, critical thinking, public speaking, media literacy, teamwork, planning, self-sufficiency, and goal setting, to prepare them for their next endeavors, i.e., in college, organized careers, and mature life, through this project. The current study of STEM student researchers on constructing a prototype Arduino-based automatic waste compactor and segregator allowed them to apply their scientific and research knowledge, which is advantageous to their collective intellectual development.

To the Future Researchers. This study may benefit them by considering the gaps and limits of the present research and the reasons for them, which have previously been stated. In this way, future researchers may be able to pursue regions that current researchers may have not yet investigated for plausible reasons. Future researchers may improve the construction of the solar-powered Arduino-based automatic waste compactor and segregator by filling in the gaps and overcoming the constraints of this study. As a result, another landmark in robotics technology and the solar-powered Arduino-based automatic waste compactor and segregator may occur, considerably contributing to the range of robotics outputs and developments.

**Scope and Delimitation of the Study**

This study focused on the development and evaluation of a Solar-Powered Arduino-based automatic Compactor and waste segregator with an HC-SR04 sensing module. It examined the system's effectiveness, accuracy, and efficiency in sorting and compacting waste materials while exploring the integration of automation and renewable energy in solid waste management. The study was conducted within the context of smart waste management and environmental sustainability, evaluating how robotics may improve waste segregation and disposal methods to enhance operational efficiency.

Furthermore, adopting a quantitative research approach, this study collected both experimental and observational data through system performance tests, efficiency evaluations, and accuracy assessments of the HC-SR04 sensor. The primary data collection methods involved functionality tests in terms of its mechanical and electrical design, charging efficiency, wireless operation, ability to separate and sense waste, ability to compact, and durability., real-time monitoring, and systematic documentation of results, with additional surveys and expert evaluations to validate the prototype's effectiveness. The research was conducted at Colon National High School, where the prototype was deployed for testing and evaluation under controlled conditions. The school was selected due to its accessibility and its relevance to the study's objective of promoting sustainable waste management in educational institutions. Also, this study took place over six months, from November 2023 to May 2024, covering the design, development, testing, and evaluation phases.

**Limitations of the Study**

Despite its scope, this study did not address more general concerns with waste collection logistics, bulk waste disposal administration, or treatment of industrial wastes. The study only concerned local, small-scale segregation and compacting of trash, namely the recyclable and non-recyclable school and household wastes. As resources were limited, the study did not cover duration tests of durability or environmental endurance tests under adverse conditions on the prototype. The collection of data was confined to a controlled environment and not to a large city waste disposal plant. Additionally, qualitative comments from general consumers were minimal because the study focused on technical precision and performance data.

Moreover, participants without related knowledge of waste management, automation, or engineering were excluded from the study. Other than that, there was no information on public perception of automated waste management as a waste segregation habit since this research was concerned with technical efficiency and not behavior analysis. Although an attempt was made to generate standard test conditions, environmental factors like variability in solar power availability and variable waste materials could have introduced variations in the outcome. The controlled test setting and small sample size also restricted the external validity of the results to full-scale waste management systems. The system was not tested for other geographic sites or in varying operating conditions, and the budget affected how many different materials were tested for segregation and compaction.

With the above limitations, the research was tried out to provide a preliminary evaluation of an automated waste segregation and compaction system, which may be followed by more advanced research and development of sustainable waste management systems.

**RESEARCH METHODOLOGY**

In this study, the researchers employed an original protocol for building the KanjiBin, an automatic waste compactor and segregator using Arduino Uno and other materials. This addresses the deficiencies of the prior research by Endaya, Mabitasan, and Gonzales (2020) by enhancing and incorporating elements, hence creating an original protocol, as their study lacked a protocol related to programming and structural development. Also, the researchers utilized the quantitative method, particularly true experimental design, to test the mechanical design, electrical design, solar harvest, charging efficiency, wireless operation, waste compactor capability, waste segregator ability, and Kanjibin's durability.

The main objective of this study was to build an autonomous, Arduino-based, solar-powered waste compactor and segregator system designed to enhance solid waste management in school environments. The system aimed to automate the sorting and compaction of waste, thereby improving accuracy in waste segregation, minimizing storage requirements, reducing manual labor dependency, and promoting sustainable waste disposal practices within educational institutions. According to Pubrica-Academy (2022), experimental research involves manipulating one or more independent variables to observe their impact on dependent variables. By observing the effects and recording data, researchers can conclude the relationships between variables. Experimental research, often associated with laboratory test procedures, involves quantitative data collection and statistical analysis throughout the study process.

**Materials Used**

The KanjiBin was built using a variety of parts to enhance the efficiency of garbage segregation and compaction. The most important part is the controlling board, the Arduino Uno (ATmega328P), which is regarded as the brain of the device, interprets the input of sensors and controls the activation of motors and actuators. In so doing, the waste segregation robot can differentiate between several types of waste using an ultrasonic sensor (HC-SR04), an inductive sensor (LJ 30A3 15 Z AX), and a capacitive sensor. The solar panel system uses the Light Dependent Resistor (LDR) to detect light. Different Linear actuators compress waste mechanically, such as 200 mm stroke and 100 mm stroke. The L298N motor drivers control movement and the direction in which force is applied.

In addition, the unit uses a 20A 12V battery for its power requirements and an e-Bike battery charger to allow for longer working hours. Also, to charge in an eco-friendly way, there is a 200W solar panel with a 30A charge Controller and a car battery charger for additional charging. The Towerpro MG996R servo motors perform specific movements on different parts of the KanjiBin. Visual feedback and interaction are enhanced by a V380 fisheye IP camera, which makes it easier to interact with and monitor the waste disposal of people, as well as a built-in 16x2 LCD module, which provides information regarding the operation of the device.

Additionally, the skeleton that supports the entire robot and protects its internal components is made from various structural materials from junk, such as angle bars, steel compacting blades, PVC, and acrylic sheets. Rubber wheels and bearings offer mobility, allowing the robot to maneuver within its environment. Finally, wiring accessories like jumper wires, cable ties, and USB cables ensure connectivity and secure attachment of electrical components and LED lights for signaling

**Tools Used**

The screwdriver is a device that is typically used by hand and is used to turn screws with slotted heads. It was used to loosen or tighten the screws on the motor. On the other hand, the Arduino USB cable is popularly used to gather, transfer, and store data from one device to another. The USB cable is the passage through which the codes transfer from the desktop to the Arduino Uno. The cutter pliers were used to cut unnecessary wires. A tape measure, often known as a measuring tape, is a hand tool commonly used to measure distance or size. In addition, Cutter was used to cut materials of different kinds of products such as wires, cables (electrical, coax, multi-strand), wire ropes, fencing, bolts, rods, prestressed concrete wires, and strapping.

**Equipment Used**

A voltmeter-amperemeter-resistor meter (VOM), also known as a multimeter or a multi-tester, was used to determine the current and voltage measurement and the resistance measurement of the robot. With a soldering iron, the LED was fixed, and its wire ends were completed. A welding machine created the KanjiBin that holds metal elements together. Most robots contain more than one piece of metal that must be watertight in other forms for the robot to function well. That is why welding is applied more often. It allows for clean, strong joints between the metal parts, thus ensuring the robot's efficiency and its working mechanisms. A speed control device is a device that adjusts the various characteristics of an electric motor to control the speed of the motor. This device allows one to specify, for example, the rotation velocity of an electric motor. It is present in appliances, including fans and drills.

However, a hot glue gun is a lightweight and compact tool that operates by heating solid cylindrical glue sticks and then releasing them to glue surfaces together while performing light construction or craft work. Additionally, a grinder is a power tool with a disc fitted with abrasive surfaces that spins at high speed. This power tool is meant for cutting, grinding, and polishing soft materials such as metal, stone, or wood; hence, it is widely used in working on metals, construction, and woodwork.

**Paraphernalia Used**

The researchers used the following paraphernalia for their KanjiBin: The electrically insulated rubber gloves protected users from electrical shocks and burns, and the electrical goggles protected the researchers' eyes while conducting the experiments. Moreover, a welding helmet is an essential type of protective headgear that prevents harmful UV and IR rays, sparks, and too much light from reaching the welder's face and eyes during welding activities. It helps protect the user's eyesight yet allows him to see clearly through the tinted glass.

**PROCEDURE**

**A. Construction of KanjiBin: An Arduino-Based Solar-Powered Automatic Waste Compactor and Segregator**

To set up Arduino Uno (Master Arduino) with Motor Driver 1, connect ENA on the motor driver to Pin 9 on the Arduino, IN1 to Pin 10, and IN2 to Pin 11. Connect OUT1 to the positive terminal of Actuator 1 and OUT2 to the negative terminal of Actuator 1. Then, connect the GND on the motor driver to the breadboard's negative rail and the power supply's negative terminal. Finally, 12V from the power supply is connected to the motor driver's positive terminal, and 5V from the Arduino is connected to the positive rail of the breadboard.

For the ultrasonic sensor, connect VCC to the breadboard's positive rail, TRIG to Pin 3, ECHO to Pin 2, and GND to the negative rail. For the inductive sensor, connect the brown wire to the breadboard's positive rail, the black wire to the negative rail, and the blue wire to A0 on the Arduino Uno. For the capacitive sensor, connect the brown wire to the positive rail, the black wire to A1, and the blue wire to the negative rail of the breadboard. Connect the buzzer's red wire to Pin 7 and the black wire to the negative rail. For the LCD, connect GND to the breadboard's negative rail, VCC to the positive rail, SDA to A4, and SCL to A5. For Servo Motor 1 (Open Gate Servo), connect the red wire to the breadboard's positive rail, the brown wire to the negative rail, and the orange wire to Pin 6.

For Servo Motor 2 (Segregation Servo), connect the red wire to the positive rail, the brown wire to the negative rail, and the orange wire to Pin 5. Finally, for Arduino Uno, connect GND to the breadboard's negative rail, 5V to the positive rail, GND to Arduino Uno 2 GND, TX1 to Arduino Uno 2 RX0, and RX0 to Arduino Uno 2 TX1. Arduino Uno (Slave Arduino) connection to Motor Driver 2, ENA to pin 9, IN1 to pin 10, IN2 to Pin 11, positive 5V to positive rail of breadboard, GND to negative power supply, positive 12V to positive power supply, OUT 1 to positive Actuator 2 (Macro Linear Actuator), OUT 2 to negative Actuator 2.

Arduino Uno 2 (For the Solar tracker) LDR 1, Black Wire to the negative rail of the Breadboard, Green Wire to A0, White Wire to the positive rail of the Breadboard. For LDR 2, Black Wire to the negative rail of the Breadboard, Green wire to A1, and White wire to the positive rail of the Breadboard. For the Servo Motor, Red wire to the positive rail of the Breadboard, brown wire to the negative rail of the Breadboard, orange wire to PIN 12, Arduino Uno 5V to the positive rail breadboard, and GND to the negative rail of the Breadboard.

For the Automatic Bin Alarm, connect Ultrasonic Sensor 1: VCC to the positive rail of the Breadboard, GND to the negative rail, TRIG to PIN 2, and ECHO to PIN 3. For Ultrasonic Sensor 2: VCC to the positive rail, GND to the negative rail, TRIG to PIN 4, and ECHO to PIN 5. For Ultrasonic Sensor 3: VCC to the positive rail, GND to the negative rail, TRIG to PIN 6, and ECHO to PIN 7. Moreover, for 3 LED lights, LED 1, VCC to PIN 8, GND to negative rail Breadboard, for LED 2 VCC to PIN 9, GND to negative rail Breadboard, and for LED 3 VCC to PIN 10, GND to negative rail Breadboard. Moreover, the last is for the Buzzer Red wire to Pin 11 and the black wire to the negative rail breadboard.

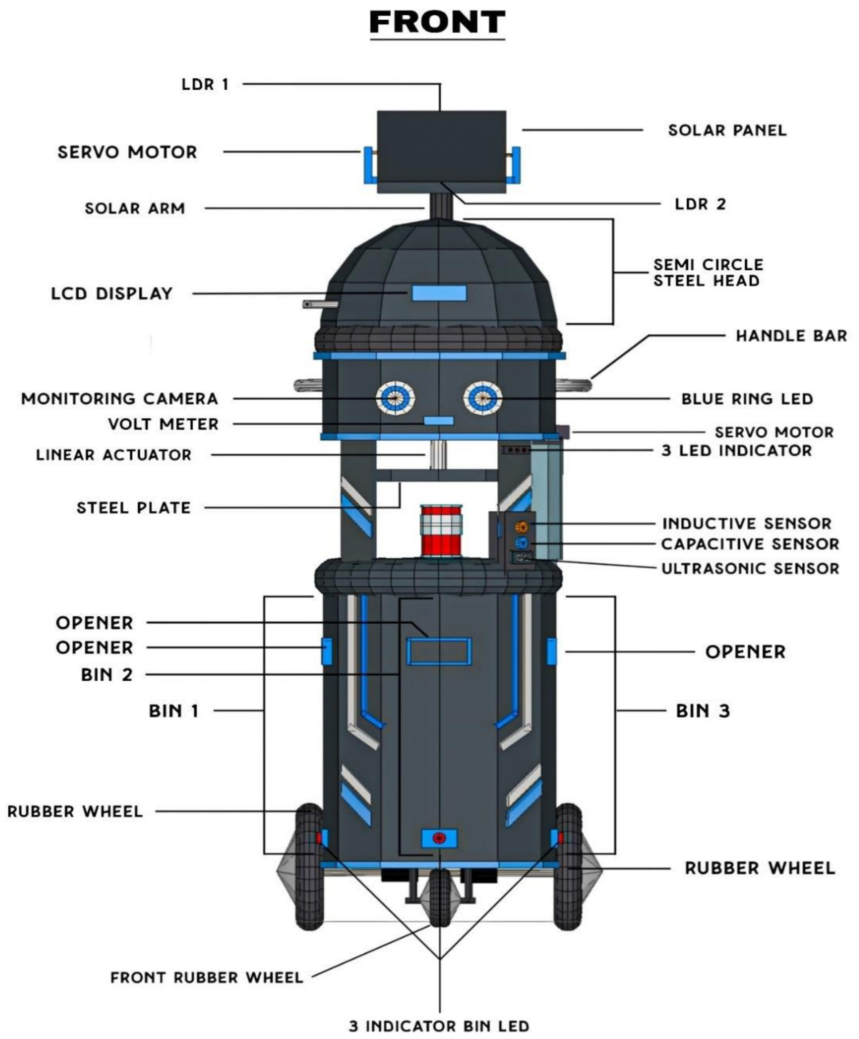


Figure 1. Blueprint of the KanjiBin (Front)

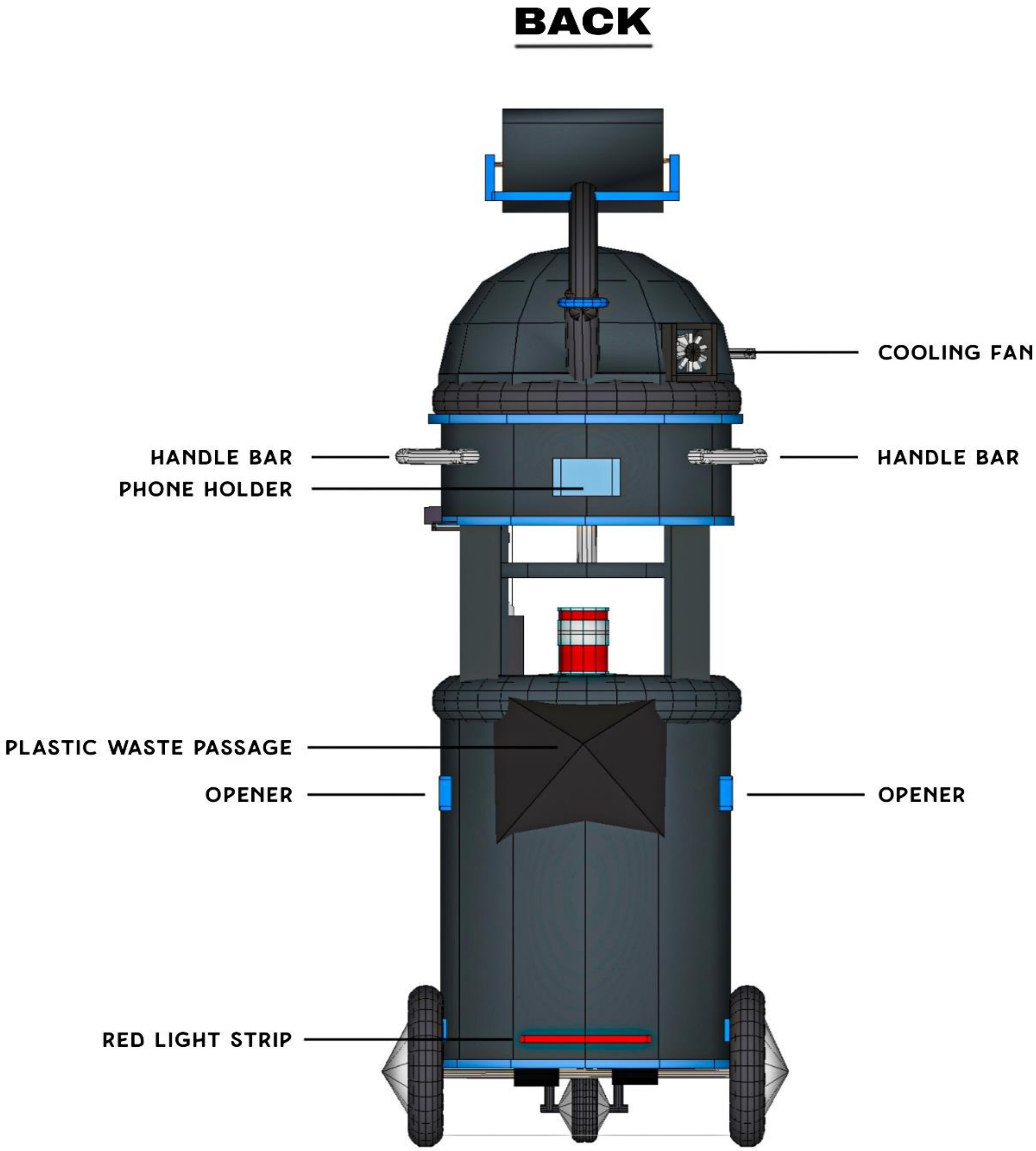


Figure 2. Blueprint of the KanjiBin (Back)

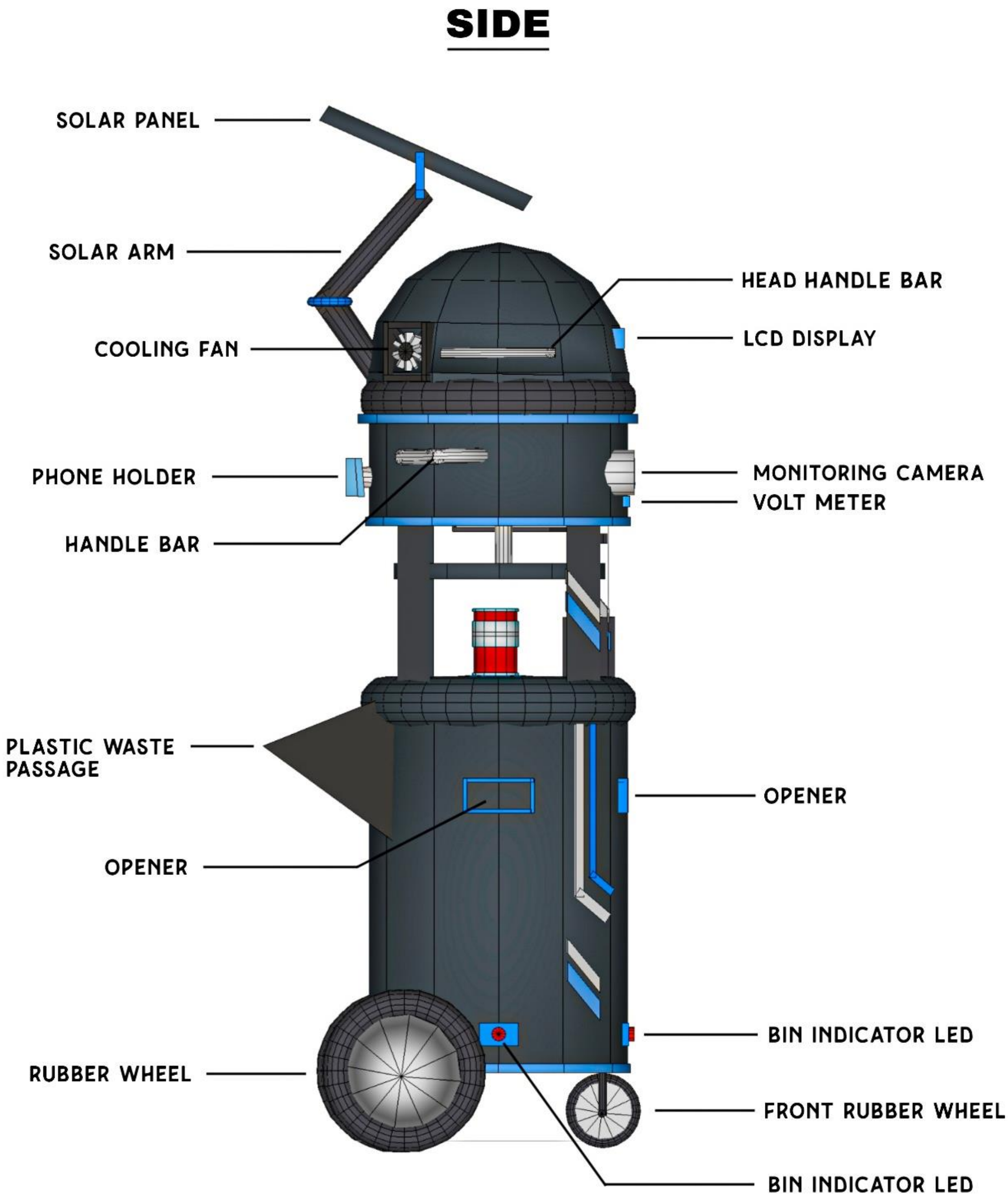




Figure 3. Blueprint of the KanjiBin (Side)

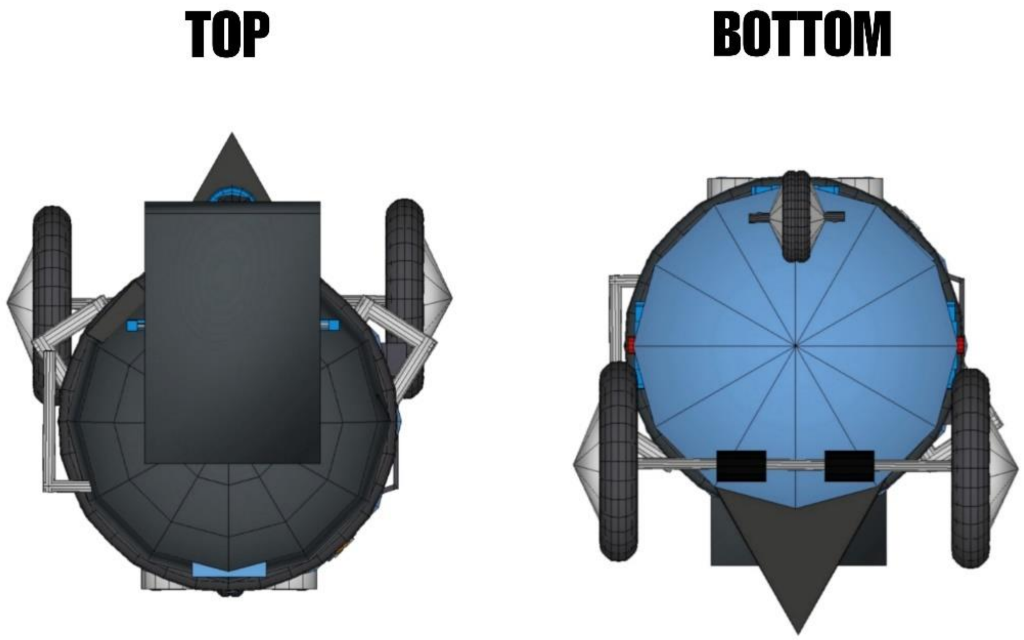


Figure 4. Blueprint of the KanjiBin (Top & Bottom)

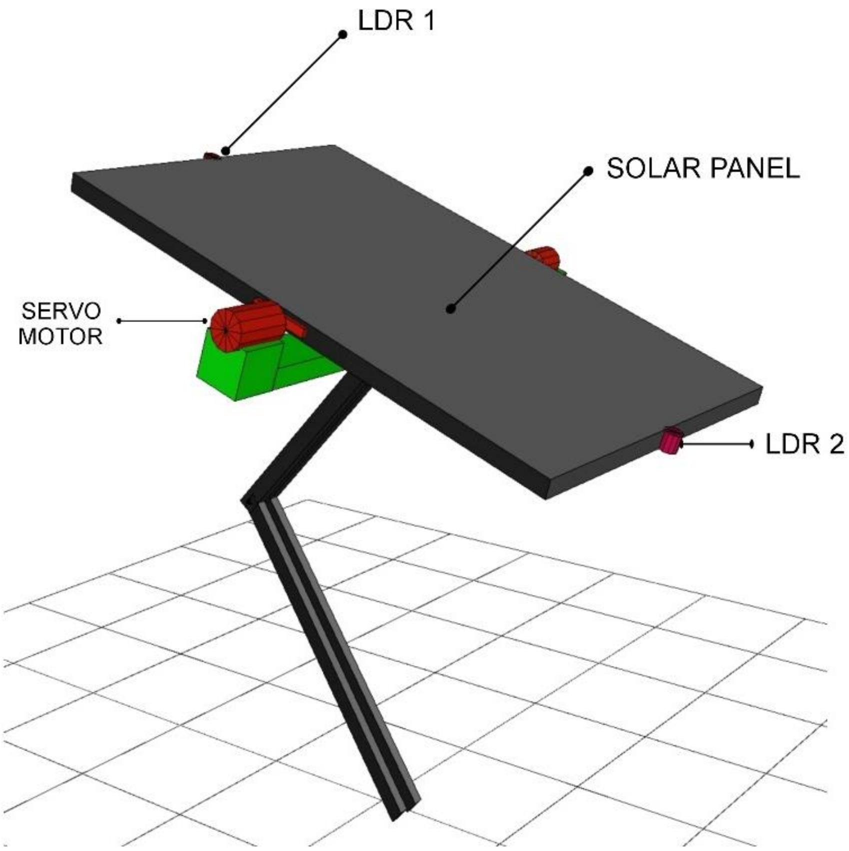


Figure 5. Blueprint of the KanjiBin (Solar Panel)

**B. Hardware Implementation**

The waste-sorting machine is only a prototype. With modifications and improvements, a similar concept of the waste sorting machine may be implemented in the household, offices, and industrial applications. Sorting wastes of different sizes and shapes is possible, but the performance is better with objects of cylindrical shape or cubic shape with limitations of the size (in terms of height) of Coca-Cola Cans (waste should be limited to a maximum of 1kg).

As a microcontroller board, the researchers will use the Arduino Uno, which is based on the ATmega328P. The digital input/output pins of the Arduino Uno are 14, with 6 of these pins providing PWM outputs. The Arduino Uno has a flash memory of 32 KB and 2 KB of SRAM, respectively, along with 6 analog inputs, 1 UART (hardware serial port), a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button.

1. Inductive Sensor: Inductive proximity sensors were used to detect metal objects. The researchers used a larger sensor, based on the requirement of having a larger sensing range
2. Capacitive Sensor: Capacitive sensors can sense any object within their sensing range. When the target approaches the face of the sensor, the capacitance increases, resulting in an increase in the amplitude of the oscillator. Then the solid-state output switch detects the increase in amplitude and based on that it is turned on or off. This sensor was used to detect paper waste.
3. Servo Motors: The researchers used servo motors for both gate and pipe, specifically, they used the TowerPro MG996R servo motors.
4. Ultrasonic Sensor: The presence of objects is detected without any physical contact using an ultrasonic sensor. This sensor operates by emitting ultrasonic sound waves and then measuring the time taken for these waves to reflect after hitting an object. Based on the time and speed of sound, the distance to the object is calculated. Ultrasonic sensors are often used to detect and measure distances to objects, regardless of their material, as the sound waves are not influenced by material type. The sensor can identify objects such as glass, plastic, and paper by calculating precise distances, ensuring reliable object detection and measurement in a variety of environments. Thus, the researchers used this for plastic waste detection.
5. Macro Linear Actuator: the macro linear actuator is rated at a speed of 30mm/s and is mainly used to tilt a metallic plate. This is to help in the placement of used and compacted waste into the two pipes of the servo motor for recycling. This motion is task-specific and facilitates the process, ensuring proper sorting once the material has been compressed.
6. 200MM Linear Actuator - The 200mm, 12V linear actuator, with a force capacity of 1500 N and a speed of 10mm/s, is explicitly designed for the compaction of waste materials. Because of its effective and precise linear motion, space is saved, and waste management operations are enhanced as it allows for effective and uniform compression. Its range of operation makes this actuator appropriate for applications where there is a need for accurate movement and applied load, such as in waste compaction systems.
7. LDR (Light Dependent Resistor) - An LDR is a sensor whose resistance decreases with increased light intensity. It is used in solar tracking systems to adjust solar panels based on sunlight, optimizing energy capture.

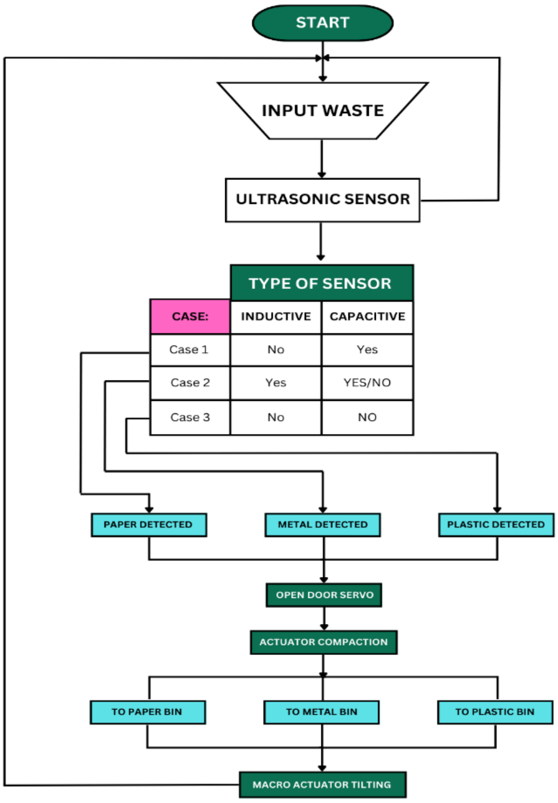


Figure 6. Flowchart of the Operation of the Constructed KanjiBin

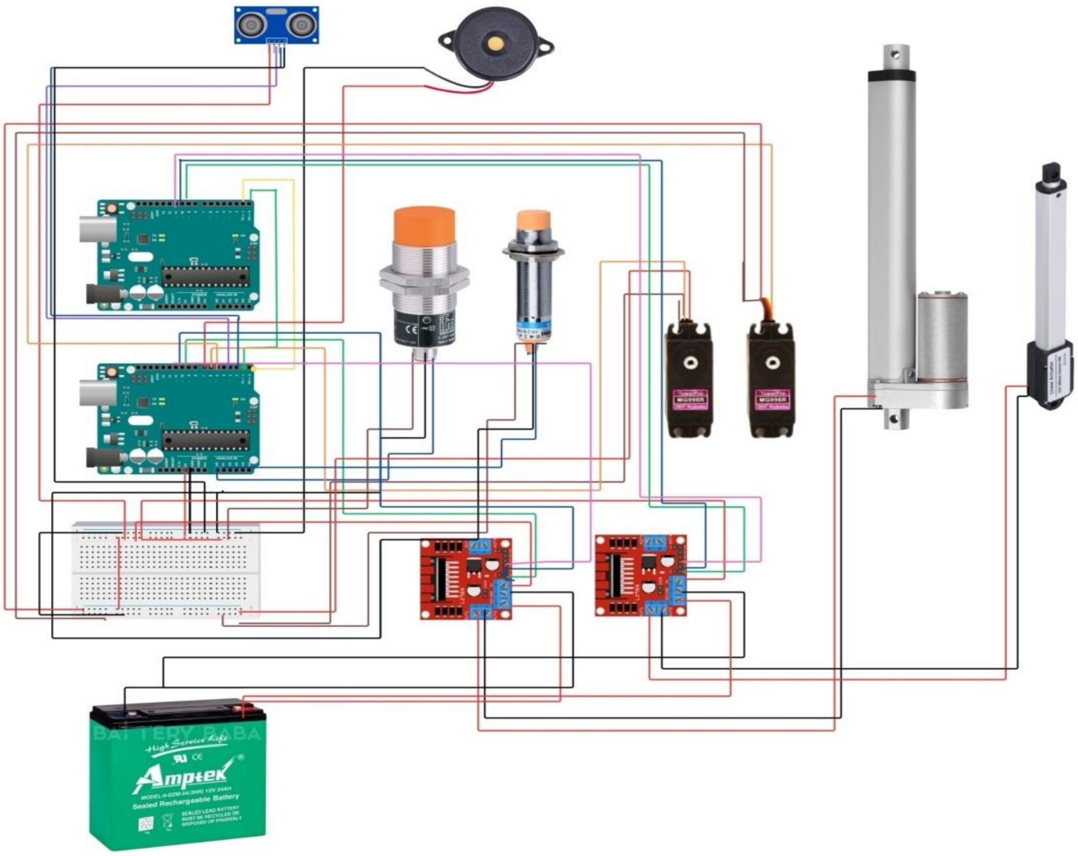

Figure 7. Wiring Diagram of the Waste Compactor and Segregator

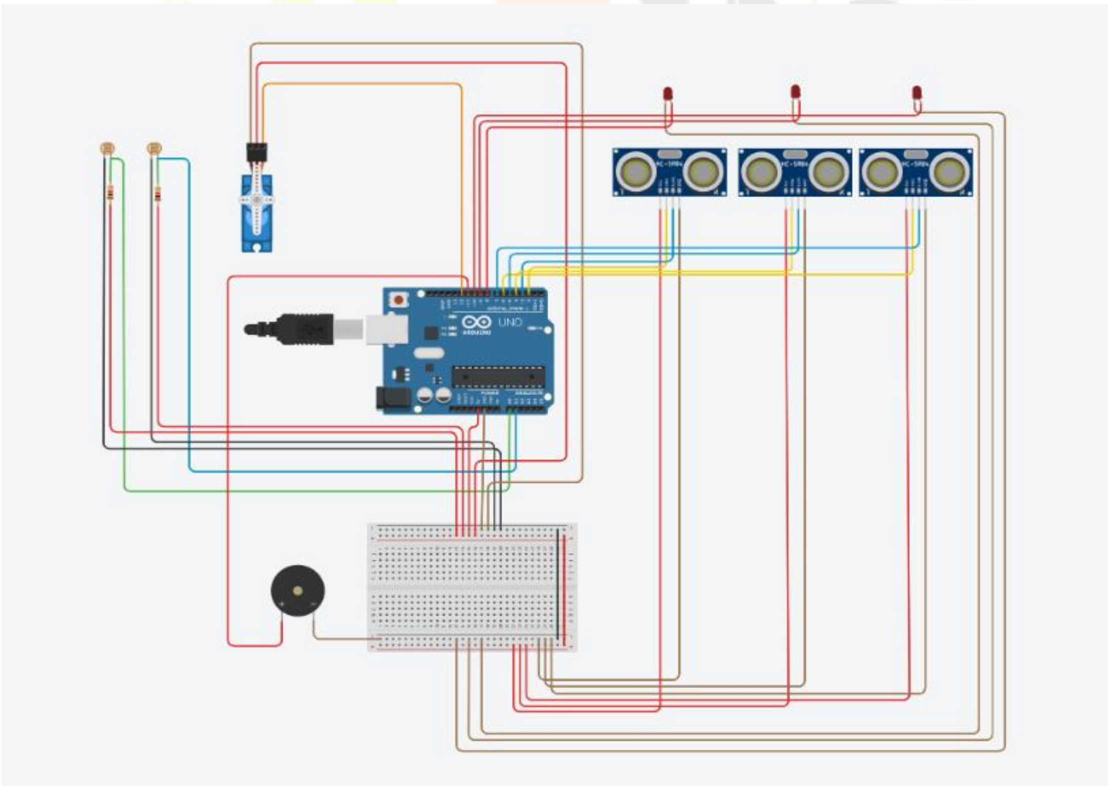

Figure 8. Wiring Diagram of the Alarm Buzzer and Solar Panel Tracker

**C. Testing the Functionality of the Robot in Terms of its Mechanical Design**

In testing the mechanical design, the researchers performed experiments on a survey checklist of mobility types to determine if the KanjiBin acquired its mobility. To assess its functionality, many trials were conducted for each mobility type, which was seen and evaluated by Grade 9 - Taborada STE (Science, Technology, and Engineering Program) respondents.

**D. Testing the Functionality of the Robot in Terms of its Electrical Design**

In testing the electrical design, the researchers subjected the KanjiBin to several trials using a survey checklist to determine the electronic materials' functionality.

**E. Testing the Functionality of the Robot in Terms of its Solar Harvesting**

In testing the solar harvesting, a comparative analysis was performed by assessing the voltage and current distributions within the charging station. This analysis involved 9 trials conducted with the automatic tilting mechanism.

**F. Testing the Functionality of the Robot in Terms of its Charging Efficiency**

In testing the charging efficiency, the researchers assessed the charging station's power consumption to determine its capacity for handling one device. Two mobile devices were utilized in the experiment.

**G. Testing the Functionality of the Robot in Terms of its Wireless Operation**

In testing the wireless operation, the researchers subjected the KanjiBIn to several trials using a survey checklist to assess the range and compatibility of different mobile phone versions.

**H. Testing the Functionality of the Robot in Terms of its Waste Compactor Capability**

In testing the KanjiBin's linear actuator mechanism waste compactor capability, the researchers tested its ability to exert the required force for effective waste automatic compression.

**I. Testing the Functionality of the Robot in Terms of its Waste Segregator Ability**

The initial phase in testing was to ensure that the sensor modules were accurate and reliable. As precise distance measurements are essential to waste segregation, this included testing the device's capacity to measure distances. During this stage, the robot's programmed logic was carefully examined to ensure it could classify and separate waste materials according to their characteristics and predetermined criteria.

**J. Testing the Functionality of the Robot in Terms of its Durability**

In testing the durability of the KanjiBin, the researchers subjected the robot to different checklists.

**Variables of the Study**

The independent variable of the study is the functional Arduino-based Solar-powered automatic waste compactor and segregator robot, while the dependent variables of the study are its electrical design, mechanical design, solar harvest, charging efficiency, wireless operation, waste compactor capability, waste segregator ability, KanjiBin's durability and accuracy of sensor detection (reliability of ultrasonic sensor, capacitive sensor and inductive sensor in identifying waste types).

## IV. RESULTS AND DISCUSSION

**Results of the Testing of the Constructed Project Arduino-Based Solar-Powered Automatic Waste Compactor and Segregator**

This study aimed to evaluate the functionality of the Arduino-based solar-powered automatic waste compactor and segregator robot across all domains. A systematic set of trials was conducted to ascertain the outcomes of these assessments, guided by a predefined checklist. Notably, the waste compactor's capability required a separate testing phase, involving precise measurements with the researchers and the adviser serving as witnesses. Detailed outcomes of these evaluations are presented in Tables *1-8*.

Table 1. *Mechanical Design Testing Results*

| **MECHANICAL DESIGN** | **Trial 1** | **Trial 2** | **Trial 3** | **Interpretation** | |
|---|---|---|---|---|---|
| | Percentage % | | | Yes | No |
| The gate opens after detection. | 97% | 97% | 95% | ✓ | |
| The compactor extends downward. | 100% | 100% | 100% | ✓ | |
| The compactor retracts back to its initial position. | 100% | 100% | 100% | ✓ | |
| The plate tilts downwards. | 100% | 100% | 100% | ✓ | |
| The elbow pipe rotates. | 100% | 100% | 100% | ✓ | |
| The solar panel tilts. | 90% | 93% | 91% | ✓ | |
| **Average** | **97.94%** | | | **Yes** | |

*Legend: Yes-75%-100%; No-0%-74%*

The mechanical design of the robot demonstrated a high average functionality score of *97.94*%, qualifying it for a "Yes" rating. Across three trials, all components—such as the gate, compactor, plate, elbow pipe, and solar panel—performed their intended functions with remarkable consistency. Components like the compactor, plate, and elbow pipe achieved perfect scores, while the solar panel tilt scored slightly lower but remained within the functional threshold. Overall, this strong performance highlights the mechanical system's precision and reliability, indicating its readiness for practical application and integration into the robot's overall operations. With *3* trials conducted, the robot's compactor successfully moved downwards with the speed yielded an average of *10* millimeters per second, extending an average of *200* mm; retraction yielded an average of *200* mm; and force yielded an average of *1,500*N.

Indeed, KanjiBin's mechanical design scored *97.94*%, meaning it works well, and its parts—like the gate, compactors, elbow pipe, and solar panel—are reliable and stable. This high score shows that KanjiBin is built to handle tasks where accuracy and repetition are essential. According to Wu, Yeong, Su, Holderbaum, and Yang (2023), having stable and consistent working parts is essential for robots that operate in challenging or changing environments, where even a small failure could lead to more significant problems or safety risks.

In KanjiBin's case, each part consistently did its job—whether opening, tilting, or rotating—which shows that the design is solid and ready for real-world tasks. This fits with the standards in robotics, which value getting the job done and ensuring the robot's parts last and stay reliable over time. Overall, these results suggest that KanjiBin is well-prepared for tasks that need precise, stable movements, meeting necessary standards for efficiency and durability (Wu et al., 2023). Additionally, its performance indicates potential for integration into automated waste management systems, enhancing operational effectiveness in various environments.

Table 2. *Electrical Design Testing Results*

| **ELECTRICAL DESIGN** | **Trial 1** | **Trial 2** | **Trial 3** | **Interpretation** | |
|---|---|---|---|---|---|
| | **Percentage %** | | | **Yes** | **No** |
| The servo motors are functional in terms of the command. | 90% | 94% | 94% | ✓ | |
| The actuators are functional according to the command. | 100% | 100% | 100% | ✓ | |
| The capacitive sensor is functional as it detects paper. | 92% | 93% | 95% | ✓ | |
| The inductive sensor is functional as it detects metal. | 95% | 94% | 95% | ✓ | |
| The ultrasonic sensor is functional as it detects plastic. | 85% | 90% | 91% | ✓ | |
| The buzzer is functional as it sounds when the bins are fully filled. | 75% | 75% | 76% | ✓ | |
| The LED lights are functional according to the command. | 68% | 75% | 86% | ✓ | |
| The LDR sensors are functional as they detect light. | 85% | 86% | 86% | ✓ | |
| The charger is functional as it provides power. | 100% | 100% | 100% | ✓ | |
| The three ultrasonic sensors below are functional as they detect fully filled bins. | 75% | 74% | 76% | ✓ | |
| The monitoring camera is functional as its purpose. | 96% | 95% | 96% | ✓ | |
| **AVERAGE** | **88.85%** | | | **Yes** | |

*Legend: Yes-75%-100%; No-0%-74%*

The electrical design of the robot achieved an average functionality score of *88.85*%, meeting the "Yes" threshold for operational reliability. Key components like the servo motors, actuators, sensors, buzzer, LED lights, LDR sensors, charger, ultrasonic sensors, and monitoring camera consistently demonstrated effectiveness in performing their designated functions. While most components, such as the actuators, inductive sensors, and charger, achieved near-perfect or perfect scores, a few areas, including the LED lights and buzzer, showed slightly lower but still acceptable performance. Overall, this high average confirms the electrical system's robust functionality and readiness for further integration.

The performance of the robot's electrical system was rated at *88.85*%, indicating an excellent level of Operating Reliability. In simple terms, nearly all the essential electrical components, including the servo motors, actuators, sensors, LED lights, and the charger, worked as expected without failure. Such parts facilitate locomotion, active energy supply, and even external environment control. Therefore, the efficiency of these components indicates that the robot can carry out the designated functions over prolonged periods without compromising the quality of the work done. Other devices got lower unique scores, whereas LED light bulbs and buzzers were specifically noted to have the lowest recorded score. This is due to the absence of more extended performance.

The electrical design of the robot achieved an average functionality score of *88.85*%, meeting the "Yes" threshold for operational reliability. Key components like the servo motors, actuators, sensors, buzzer, LED lights, LDR sensors, charger, ultrasonic sensors, and monitoring camera consistently demonstrated effectiveness in performing their designated functions. While most components, such as the actuators, inductive sensors, and charger, achieved near-perfect or perfect scores, a few areas,

including the LED lights and buzzer, showed slightly lower but still acceptable performance. Overall, this high average confirms the electrical system's robust functionality and readiness for further integration.

Nevertheless, such features do not influence the overall functionality of KanjiBin – the device can condense or separate collected refuse as the LEDs installed on the refuse bins merely show when the bins are filled. As far as workability is concerned, the electric circuit is the most critical aspect in the making of a robot since there is a need for all the active components, such as the sensors and actuators, to work as expected without failures to enhance the controlled functioning of the robot as a whole (Robotics in Power Systems: Enabling a More Reliable and Safer Grid, 2017).

Table 3. *Solar Harvest Testing Results*

| Trials | Time | Output Voltage (V) | |
|---|---|---|---|
| | | **Output Voltage (V)** | **Output Current (A)** |
| 1 | 8:00 AM | 14.40 | 2.9 |
| 2 | 9:00 AM | 14.80 | 2.1 |
| 3 | 10:00 AM | 15.20 | 3.7 |
| 4 | 11:00 AM | 15.70 | 4.5 |
| 5 | 12:00 PM | 14.80 | 3.5 |
| 6 | 1:00 PM | 15.60 | 3.8 |
| 7 | 2:00 PM | 15.30 | 3.5 |
| 8 | 3:00 PM | 15.30 | 3.2 |
| 9 | 4:00 PM | 15.40 | 2.3 |
| **AVERAGE** | | **15.17V** | **3.28A** |

Table *3* displays the results of the solar harvest testing conducted with the integration of an Arduino-based solar-powered automatic waste compactor and segregator. This system enables the solar panel to adjust its angle throughout the day to maintain optimal alignment with the sun's position, resulting in more consistent voltage and current outputs across different times. The data indicate that the highest output occurred between *11:00* AM and *12:00* PM, aligning with the sun's peak position, while the lowest readings were recorded during the final trial at *4:00* PM as the sun approached the horizon.

Nine trials were conducted to ensure consistency and reliability, with the average output voltage and current recorded as:

$V_{avg.t}$ = *15.17* Volts

$I_{avg.t}$ = *3.28* Amperes

This setup demonstrates the effectiveness of the solar tracker in maintaining a stable and enhanced solar harvest by continuously adjusting to the sun's path, resulting in optimal energy collection throughout the day. The implementation of this tracking mechanism notably enhances the solar harvesting potential, as seen in the consistent voltage and current outputs across trials.

Some of the key outcomes from the solar tracker experiments are shown in Table *4.3*. Nine trials with only minor variations in the recorded voltage and current provided a series of consistent data through this system for each trial, as illustrated by example one. Better use of the sun tracker is demonstrated by this consistent performance throughout the day. The core works by moving the solar panel to follow where the sunlight is for optimal energy acquisition. Key yields were between *11:00* AM to *12:00* PM at peak sun. This system performed the best in this period meaning that it extracts as much sunlight as possible to maximize its ability of catching sun rays from dawn till dusk. Most significantly, the trial results showed that in weather conditions where sun intensity may vary throughout one day, even increasing to a peak at noon and decreasing toward evening again (e.g., cloudiness/haze), the use of a solar tracker could stabilize energy production from PV panels.

The system produced an average of *15.17* volts, and the current was between a maximum of *3.28* amp; kindly show that it works well despite being installed to face one direction only across different times from morning till evening during operation hours. This is particularly important for solar-powered systems that need consistent fuel far from civilization. As a result, this device helps increase the efficiency of solar panels by changing their position according to sunlight availability around it, and hence, more light is captured easily. This was in agreement with the result of a study conducted by Mousazadeh, Keyhani, Javadi, Mobli, Abrinia, and Sharifi (2009) on how solar tracking systems can boost the power ever delivered from the panels as they are always looking directly to sky and received sunshine irradiance that leads in their efficiency improvements.

Table 4. *Charging Efficiency Testing Results*

| Quantity | Gadgets | Watts | Hours Use | Watt-hour |
|---|---|---|---|---|
| 2 | Smartphones | **30** | **1.5** | **90** |

The table above shows the experimental findings regarding charging efficiency even while the robot was working. It concludes that only one smartphone can be charged per *1.5* hours when the robot consumes electric current from solar energy. Since only one port is available, the charging station can be used again after one device is full. The total hours consumed by the two devices is *3* hours, and it is tested that there is no malfunction even though the robot uses energy from the solar harvest.

The findings from the charging efficiency testing (Table *4.4*) highlight the feasibility and reliability of using solar energy for auxiliary power functions, such as charging mobile devices, while the robot remains operational. This test demonstrates that, even with the robot drawing energy from its solar harvest, it can maintain sufficient power to charge a smartphone for over *1.5* hours without interruptions or system malfunctions. Such advances show how interconnected energy management can enhance the reliability and performance of solar-based systems in real-world applications (Villegas, Álvarez, & Martínez, 2024). As noted by Villegas et al., integrating solar-based energy solutions in robotics enhances operational longevity by reducing dependency on external power, allowing for more sustainable applications in remote or off-grid settings. Additionally, Yao, Da, Lu, and Wang (2024) that solar systems engineered with optimized energy allocation strategies improve both primary and auxiliary functionalities, supporting tasks like charging without compromising performance.

Table 5. *Wireless Operation Testing Results*

| WIRELESS OPERATION (Range) | Trial 1 | Trial 2 | Trial 3 | Average |
|---|---|---|---|---|
| 5 -10 meters | 100% | 100% | 100% | 100% |
| 10 – 15 meters | 100% | 100% | 100% | 100% |
| 15 – 20 meters | 100% | 100% | 99% | 99.67% |

*Legend:Connected-95%-100%, Connected yet disrupted-85%-94%*

The preceding table indicates that every aspect of the built robot's wireless operation is *99.89%* functional. When its connection range capacity was measured to test its wireless functioning, it was discovered that there were no errors with these systems in any of the three trials that were carried out.

The outcomes presented in Table *5* illustrate the stable operation of the wireless mechanism built within the robot, proving that it hardly experiences any functional challenges, regardless of the distance. The robot is also quite efficient from a wireless communication perspective, with a mean connection efficiency of *99.89%* within its range. It is critical in applications involving control and data transfer with real-time limits. The perfect success rates obtained at *5-10* meters and *10-15* meters ranges and lower but still commendable *99.67%* success performance at *15-20* meters range indicate that the gadget has been designed well for short and mid distances. This performance is critical, especially when communication may be out of reach for prolonged periods or may be affected by outside forces.

Such performance suggests that the design is efficient, and the signals are maintained at a high level for most of the robot's practical design applications, otherwise referred to as robotics, drone technology, and even internet-focused devices. Consequently, reliable communication systems can foster trust in robotic devices, making them more dependable in high-stakes or sophisticated situations, whether in industrial, medical, or service settings. This research underscores the necessity of advanced wireless communication frameworks to improve the overall efficiency and reliability of modern robotic systems (Zhang S., Wei, Zhang H., Zhang X. & Ma, 2017).

Table 6. *Waste Compactor Capability Testing Results*

| WASTE COMPACTOR CAPABILITY (SPACE REDUCED) | Trial 1 | Trial 2 | Trial 3 |
|---|---|---|---|
| SIZE BEFORE COMPACTION (INCHES) | SIZE AFTER COMPACTION (INCHES) | | |
| Plastic (Coke 8.5) | 5 – 6 | 4 - 5 | 4 - 5 |
| Paper (Cup 3.89) | 1 – 2 | 1 - 2 | 1 - 2 |
| Metal (Can 5.5) | 4 – 5 | 4 - 5 | 4 - 5 |

The Waste Compactor Capability (Space Reduced) table showcases the compactor's effectiveness in minimizing the size of various waste materials, with consistent results across three trials. For plastic (Coke bottles), initial sizes of *8.5* inches were reduced to between 5 and *6* inches, while paper (cups) of *3.9* inches were compressed to *1-2* inches. Metal cans, initially measuring *5.5* inches, were compacted down to *4-5* inches. This consistent performance across trials highlights the compactor's reliability and efficiency in reducing the volume of different materials, ensuring optimized space utilization.

The implications of these waste compactor test results suggest that the compactor could play a significant role in waste management efficiency, especially in urban or high-density areas where space for waste disposal is limited. By reducing the physical size of waste materials, the compactor minimizes the storage and transportation space required, potentially lowering costs and environmental impact. This also means that waste disposal sites, such as landfills, could accommodate more waste over time, potentially extending their operational life and delaying the need for new landfill sites.

The study found that compacting solid waste before transport reduces the number of trips needed for waste collection and the associated fuel consumption, ultimately cutting down on greenhouse gas emissions. This aligns with the compactor's effectiveness shown in the tests, as compacted waste requires less space, optimizing storage and potentially improving environmental outcomes (Ogwueleka, 2009).

Table 7. *Waste Segregator Ability Testing Results*

| WASTE SEGREGATOR ABILITY | Trial 1 | Trial 2 | Trial 3 | Interpretation | |
|---|---|---|---|---|---|
| | Percentage % | | | Yes | No |
| Paper bin segregation accuracy. | 92% | 93% | 95% | ✓ | |
| Metal bin segregation accuracy. | 95% | 94% | 95% | ✓ | |
| Plastic bin segregation accuracy. | 85% | 90% | 91% | ✓ | |
| **Average** | **92.22%** | | | **Yes** | |

*Legend: Yes-75%-100%; No-0%-74%*

The waste segregator Ability table demonstrates the accuracy of the robot's segregation mechanism across three trials. Paper bin segregation accuracy scored between *92%* and *95%*, while metal bin segregation achieved similar high accuracy, ranging from *94%* to *95%*. Plastic bin segregation, slightly lower but still effective, recorded accuracies from *85%* to *91%*. With an overall average of *92.22%*, the waste segregator's performance qualifies for a "Yes" rating, indicating a high level of precision and reliability in sorting materials into their designated bins.

The waste segregation robot consistently performed well in sorting different materials—paper, metal, and plastic—into the right bins, with an average accuracy of *92.22%* across three trials. This means that the robot is very reliable, correctly sorting over *9* out of *10* items on average. In simple terms, this level of accuracy suggests that the robot could be trusted in real-world settings where separating waste is essential, such as in recycling facilities or environmental clean-up projects.

Studies on similar technologies highlight how robots can help with waste management and reduce human error. Combining robotics with AI in sorting facilities not only improves sorting speed but also enables the handling of various materials, from plastics to metals, with greater precision than human-operated systems. These systems support sustainable waste management by promoting a circular economy through high-quality recycled materials, making them more attractive for reuse in new products (Jennings, 2024).

Moreover, advancements in sensor technology and machine learning algorithms allow these robotic systems to continuously improve their accuracy and efficiency over time. By adapting to different waste compositions and environmental conditions, they can optimize sorting strategies and reduce contamination rates in recycling streams. The automation of waste segregation also minimizes health risks for workers by reducing direct contact with hazardous materials. Additionally, integrating these systems with data analytics enables better monitoring of waste generation patterns, helping policymakers and industries implement more effective waste management strategies. As a result, the adoption of robotics in waste management represents a crucial step toward achieving more efficient and sustainable waste processing solutions.

Table 8. *KanjiBin's Durability Testing Results*

| KANJIBIN'S DURABILITY | Very Secured | Secured | Not Secured |
|---|---|---|---|
| Verify that all structural components are made from materials that can withstand expected forces and loads. | | ✓ | |
| Check for any visible cracks, deformations, or other signs of stress after testing. | | ✓ | |
| Ensure that parts designed to handle high friction have appropriate treatments or reinforcements, such as coatings or bearings. | | ✓ | |
| Ensure all wires are fastened firmly using cable ties, clips, or conduits to prevent movement and reduce wear over time. | ✓ | | |
| Insulations are installed to prevent potential degradation, especially near joints or connectors. | ✓ | | |

*Legend: Security Level; Very secured-90%-100%; Secured-80%-89%; Not Secured-0%-79%*

The durability test results indicate that most components of the robot's design, both mechanical and electrical, are securely in place. Structural components are made from durable materials capable of withstanding expected forces, ensuring the robot's frame and moving parts remain stable under stress. Additionally, friction points and wiring are reinforced or insulated appropriately, allowing these areas to handle wear over time without significant degradation. Wiring security checks confirm that cables are fastened securely and insulated well, which minimizes the likelihood of wear and tear. Overall, these findings demonstrate that the robot is robust and well-designed to operate in its intended environment, achieving a security level rating of "Very Secured" or "Secured" for most criteria.

The high ratings in durability tests suggest that KanjiBin may be used reliably in real-world conditions, where it would frequently encounter mechanical stress and electrical demands. For instance, proper insulation and secure fastening of wires mean that the robot would face fewer risks of wiring failures, reducing maintenance needs and improving operational safety. Likewise, the materials and friction handling ensure that moving parts won't wear down quickly, extending the robot's lifespan.

Research supports the importance of these durability aspects. Kampa (2018) discusses how component durability, operating conditions, and optimized design practices can reduce failure rates and extend robot lifespan. The study emphasizes the importance of monitoring and predictive maintenance in achieving high reliability in demanding industrial applications.

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