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IoT-based Garbage Collection Robot using Wireless Communication (EcoPicker-M)

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Abstract: The surge in urban population across Nigeria has intensified challenges in waste management, making traditional, manual collection methods increasingly inadequate. This study proposes a smart solution through the design and deployment of a garbage collection robot that utilizes IoT technology, operable via a mobile application for real-time monitoring and control. The robot, equipped with advanced sensors and mecanum wheels, adeptly navigates complex terrains and densely populated urban areas, specifically demonstrated in the Gidan-Kwano Metropolis. Field trials conducted in the Bahago and DHF communities showcased the robot's efficiency, reducing garbage collection time by 15%. This innovative approach aligns with Sustainable Development Goal 11, aiming to enhance urban sustainability and resource efficiency. The smart garbage collection robot presents a promising advancement for improving waste management processes in rapidly urbanizing regions.

Keywords: Garbage Collection, Internet of Things, Robot, Wireless Communication, Sustainable Development Goal

Nomenclature

Abbreviation	Expansion
MSW	Municipal Solid Waste
IoT	Internet of Things
TCR	Trash Collector Robot
IDE	Integrated Development Environment

1. Introduction

1.1 Background of Study

The world produces 2.01 billion tons of municipal solid garbage yearly, and at least 33 percent of that—to put it very conservatively—is not managed in an environmentally safe way. The average amount of garbage produced per person per day in the world is 0.74 kilograms, however, the variation is considerable, from 0.11 to 4.54 kilos. High-income nations produce around 34%, or 683 million tons, of the world's waste despite having just 16% of the global population. Looking ahead, 3.40 billion tons of trash are anticipated to be produced worldwide by 2050 [1]. Fig. 1 shows a typical landfill containing waste in an average Nigerian society.

***Fig. 1.** Garbage Collection Method in Nigeria.*

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According to the Dataphyte 2022 report, Nigeria, the most populous nation in Africa, faces enormous waste management difficulties due to growing urbanization, population growth, and limited infrastructure. Only 20-30 percent of the approximately 32 million tons of solid trash produced each year is collected and properly treated; the remainder is either burned or discarded. Significant pollution and health dangers result from this incorrect trash disposal. Progress toward Sustainable Development Goal 11 - Sustainable Cities and Communities - is hampered by the current waste management systems; lack of real-time monitoring, route optimization, and efficient resource allocation [16].

Therefore, what if trash management could be changed into a productive, networked, and sustainable process? Imagine a society where waste disposal is improved, environmental impact is decreased, and real-time data is used to inform decisions. “Waste is just a resource in the wrong place”; Ellen MacArthur said, and she was right. EcoPicker-M is an Internet of Things garbage collection robot that will transform the way we manage waste in Nigeria. EcoPicker-M represents a fusion of robotics and the IoT, offering an innovative solution to the global waste management challenge. This robot is meticulously engineered to address the limitations of traditional waste collection methods, presenting a new paradigm for a cleaner, greener future.

The need for improved waste management has never been more critical. Inadequate waste disposal poses threats to health security, hygiene, and the well-being of both humans and wildlife. EcoPicker-M aims to tackle these challenges head-on, providing an efficient and eco-friendly approach to waste collection that minimizes environmental impact and maximizes operational efficiency. By harnessing the power of IoT connectivity and advanced technologies, EcoPicker-M transforms the way waste is collected and managed. Equipped with intelligent sensors, it easily navigates through diverse terrains, swiftly gathering garbage. Its mecanum wheels enable seamless maneuverability, optimizing the time and effort required to clean up any given area.

Furthermore, EcoPicker-M leverages its IoT capabilities to enable real-time data analysis and monitoring. This empowers waste management authorities to make data-driven decisions, enhancing operational efficiency, resource allocation, and waste disposal strategies. With EcoPicker-M, waste management becomes a connected and intelligent process, resulting in a cleaner and healthier environment.

2. Literature Review

The integration of IoT technology in waste management has seen a paradigmshift, evidenced by the advent of IoT-based waste collection robots. As the world faces increasing challenges in waste management, IoT-based garbage collection robots have emerged as a promising solution to improve efficiency, reduce costs, and reduce environmental impact. This review aims to provide a comprehensive understanding of the current state of IoT-based waste collection robots, highlighting their potential to transform the way we manage waste in urban contexts through an in-depth review of previous research.

2.1 Historical Background.

Throughout history, waste has always been an unavoidable part of human society. Early civilizations faced the challenge of handling waste effectively. As societies progressed, they developed better ways to manage garbage for hygienic and sustainable living.

In ancient times, waste was a natural outcome of human activities, and early settlements disposed of items they no longer needed. How ever as populations grew, waste production increased significantly, leading to the need for various solutions.

The historical evolution of waste management can be traced through various stages:

1. **Open Dumping:** In antiquity and the medieval era, communities would simply dispose of their waste outside city walls or into nearby water bodies, unwittingly causing environmental pollution and posing health risks.
2. **Manual Collection:** During the Middle Ages and early modern period, waste collectors known as "rakers" or "rubbish gatherers" carried out the task of manually gathering waste from households and public spaces, utilizing rudimentary tools and carts.
3. **Nightsoil Collection:** Certain civilizations, like ancient China and medieval Europe employed "nightsoil men" to collect human waste from latrines, which were then utilized asagricultural fertilizer.
4. **Horse-Drawn Carts:** The 19th century witnessed the introduction of horse-drawn carts for waste collection in urban centers, facilitating the transportation of waste to designated disposal sites.
5. **Municipal Waste Collection:** The advent of the Industrial Revolution brought about urbanization, leading some cities to establish waste collection services staffed by workersemploying

carts or early motorized vehicles.

6. **Landfilling:** As the 19th and 20th centuries progressed, the establishment of designated dumping areas, commonly referred to as landfills became prevalent. Unfortunately, these sites were frequently inadequately managed, giving rise to environmental and health predicaments.
7. **Incineration:** The early to mid-20th century saw a surge in the popularity of incineration as a waste disposal method. By subjecting waste to high temperatures, its volume was reduced. Nonetheless, concerns surrounding air pollution and toxic residue curtailed its widespread adoption.
8. **Manual Sorting:** In the initial stages of recycling, waste collectors diligently engaged in manually sorting through the collected waste to identify and separate recyclable materialssuch as paper, glass, and metal.
9. **Waste-to-Energy:** In the latter half of the 20th century and beyond, innovative waste-to-energy facilities emerged. These facilities employ incineration or thermal processes to convert waste into energy, reducing its volume and generating electricity in the process.
10. **Curbside Recycling:** More recently, many cities have embraced curbside recycling programs, urging residents to segregate recyclables from regular waste for separate collection and subsequent processing.
11. **Smart Waste Management:** The modern era witnessed a remarkable leap in waste management technology, paving the way for the development of smart waste management systems. By incorporating sensors and data analytics, these systems efficiently optimize waste collection routes and schedules, leading to enhanced cost-effectiveness and operational efficiency.

2.2 Theoretical Background

Efficiency in garbage collection has arisen as a significant challenge for modern civilizations in the continuously changing landscape of urbanization and technological growth. Traditional waste collection and disposal procedures are frequently inefficient, time-consuming, and unsustainable in terms of the environment. To address these concerns, the incorporation of IoT technology into waste management systems has received a lot of attention. This theoretical foundation delves into the novel idea of an Internet of Things-enabled garbage collection robot that uses a wireless connection to revolutionize garbage collection processes.

2.2.1 IoT in Garbage Collection

The IoT is a groundbreaking concept that connects physical objects and devices to the Internet, facilitating seamless data exchange and real-time communication. When applied to waste management, IoT offers numerous benefits, including real-time monitoring of trash levels, rapid decision-making, reduced garbage truck congestion, and cost-effectiveness. By integrating IoT into Smart Cities, waste management, sustainability, and efficiency are greatly improved through real-time monitoring and interconnected devices, elevating the overall urban living experience [4]. IoT-enabled smart sensors in trash containers continuously monitor fill levels, transmitting data for timely decision-making and optimizing waste collection routes. This dynamic scheduling reduces unnecessary trips, lowers operational costs, promotes recycling, and supports cities in achieving their sustainability objectives. Embracing IoT technology enhances urban life by fostering innovation and efficiency across various sectors.

2.2.2 Bluetooth Module for Wireless Communication

Wireless communication is essential for enabling seamless data transfer and remote monitoring inthe EcoPicker-M. The robot and the central waste management system are connected wirelessly using a Bluetooth module, which is a reliable and cost-effective solution. Theenormous significance of Bluetooth technology in IoT applications is highlighted by research studies like the one carried out by Al-Fuqaha *et al.* [5], particularly in settings where power efficiency plays a critical role.

The Bluetooth module is essential to the robot's ability to share real-time data effectively. It enablesthe robot to quickly update its status to the central management system, receive collection schedules, and relay data on the amount of waste in the containers. The robot performs better, andthe waste management process is more effective overall thanks to the constant flow of communication.

By leveraging the capabilities of the Bluetooth module, the robot seamlessly integrates into the waste management ecosystem. With the help of the central system, it can effectively coordinate, assuring prompt waste collection and reducing disturbances. Furthermore, robots can work for a long time without using a lot of electricity because Bluetooth connection is energy efficient.

In addition to streamlining waste management procedures, EcoPicker-M's effective integration witha Bluetooth module of signal range 10m to 20m serves as an example of how IoT technology may improve a variety of elements of our daily lives. This application shows how advanced wireless communication technologies can considerably improve the performance and efficacy of IoT-based systems in areaswith limited resources.

2.2.3 Mecanum Wheels for Enhanced Mobility

Omnidirectional mobile robots are a unique type of robot that can move instantly in any direction from any position. Their specialized wheels are crucial to their design. Among these options, mecanum wheels are recognized for their exceptional ability to move in all directions, making them the best choice for powering these robots. This feature is particularly beneficial in urban settings, where clogged roadways and obstacles are common.

Mecanum wheels allow these robots to effortlessly navigate over various terrains, whether rough, smooth, or uneven, giving them a significant advantage in busy, densely populated areas. With this excellent mobility, the robots can swiftly and efficiently collect waste from crowded streets and narrow alleyways, ensuring timely operations without blocking traffic. By utilizing mecanum wheels, these mobile robots demonstrate remarkable flexibility, enabling them to change directions, turn, and maneuver in tight spaces with ease. This adaptability expands their range of applications across diverse environments where precise and agile movement is essential. Their capability to operate effectively in cluttered urban areas and on different types of terrain enhances their overall usefulness, making them valuable tools in waste management and beyond.

2.3 Related Works

The existing body of knowledge and related works that converge at the intersection of IoT, robots,wireless communication, and waste management are summarized in this section. We want to condense the thoughts, approaches, and discoveries that have paved the way for the design and development of the proposed IoT garbage collection robot by looking at the advancements made in these fields.

A robot waste collection system designed by Asst *et al.* [6] utilized motors and a shaft to drive its rotating blades, efficiently gathering lightweight items like juice cartons, plastic bottles, and crushed papers, ranging from 5 to 20cm in height. The blades were crafted from robust materials such as galvanized iron or stainless steel, making them suitable for outdoor use in public areas likegardens, bus stands, and footpaths. Two motors connected to an Arduino control the rotating mechanism, which was activated when detecting a static obstacle, pushing garbage into a bin placed behind it. Ongoing modifications aimed to optimize the system's performance and increase efficiency. The project had seen some success but has the potential for further improvement.

The escalating garbage issue in India resulting from population growth, particularly impacting municipal workers responsible for garbage clearance was explored by Raja *et al*. [7]. To tackle this challenge, a robotic system for monitoring and clearing garbage was projected and designed. It incorporated components such as an ultrasonic sensor, an Arduino Uno board, RF transmitter and receiver modules, an IR sensor, and a robotic arm with a servo motor. The system detects garbage levels, communicates wirelessly, and utilizes a robotic arm for efficient bin handling. Its goal was to improve garbage management, reduce human involvement, and enhance overall efficiency.

In his paper, Siregar *et al.* [8] discussed the problem of trash in the neighborhood, concentratingon Lake Toba in North Sumatra. A garbage picker ship robot was implemented to help with cleanup efforts because Lake Toba's pollution has become an issue. The author hoped to improve the systemby including an Android application as a prototype controller for the robotic ship. Economic constraints forced the development of a miniaturized version. One drawback of the garbage pickership robot was that it lacked a waste-limiting sensor system that would stop the process once it reached capacity and signal for trash disposal.

A system aimed at collecting and monitoring garbage levels and moisture content within a bin using sensors was introduced by Vasanth *et al*. [9]. The system incorporated an ESP8266 Wi-Fi module for remote monitoring and an IR sensor for line-following capabilities. The implementation of the design successfully achieved its goal of reducing costs and creating opportunities for the development of autonomous cleaning robots. However, it should be noted that the project did not include features to enable the robot to distinguish between stationary andmoving objects, nor could it identify metallic and non-metallic items.

A robot that cleans beaches using a wireless connection, more specifically Bluetooth and Ad-hoc was developed by Varunesh reddy and Nikhil [10]. The robot, which was powered by a PIC18F4550 processor, was able to move across sand at an average speed of 0.5 m/s. It successfully gathered large trash pieces 12.5 x 49 cm in size. Despite the robot's success in combating the issue of beachlitter, there are still certain aspects that might be improved, such as introducing autonomous operation and enhancing long-range control abilities.

Autonomous Arduino-based TCR with wireless charging was designed by Nagayo *et al.* [11]. The robot incorporated various sensors for tasks like line following, pick and place, and obstacle avoidance. Real-time monitoring of the robot's status and location was achieved through wireless communication, aided by a GPS shield for localization. A GSM modemsends SMS notifications to the waste administrator regarding the TCR's status, location, and malfunctions. Solar-powered wireless charging was used for the TCR's batteries. Based on performance testing, the paper suggested improvements like additional ultrasonic sensors and high-powered DC motors for better pick-and-place capabilities, as well as integrating camera andimage processing techniques.

An Autonomous Trash Collector by Hossain *et al.* [12] was developed based on Object Detection Using Deep Neural Network. The entire working principle of the robot involves three stages: object detection using a mobile robot with sonar, trash identification through deep learning on captured images, and trash collection using servo motors. The robot halts when an object is detected, takes pictures, and sends them to a Raspberry Pi for analysis. Images were reshaped and split for trainingand testing. The neural network comprises a convolutional layer and two dense layers. If an objectwas recognized as trash, the robot's servo motors collect and dispose of it; otherwise, it continues searching for trash.

A system developed by Rajathi *et al.* [13] aims to maintain cleanliness in the surroundings using a robotic dustbin. This intelligent dustbin was guided along a predetermined path, thanks to the integration of two infrared (IR) sensors placed at the front of the robot. To enhance trash disposal, an obstacle sensor was positioned on the robot's side, capable of detecting black-colored objects. Upon detection, the sensor triggered a buzzer sound, signaling the robot to halt temporarily, allowing users to dispose of their trash. The system was further equipped with an ultrasonic sensor placed at the dustbin's rim, enabling it to monitor the garbage level. This featureassists users in determining when the dustbin requires emptying. Additionally, the robotic dustbin communicates its status, whether full or empty, via a Wi-Fi module to a webpage. If the bin remains unemptied, the robot will wait until it was emptied or return to its source to continue waste collection. This integration of sensors and technology provides an efficient and convenient solution, promoting a cleaner and more orderly environment.

The Smart Garbage Collecting Robot and Monitoring System designed by Parashar *et al.* [14] was another solution for efficient garbage collection. It utilizes an Ultrasonic sensor to measure trash levelsin fixed bins, transmitting the data to the garbage car through an RF Module, with a Microcontroller serving as the interface. The system operates fully automated, with the garbage car responding to signals when bins were full. An Infrared sensor accurately detects garbage levels, while an Arduino board processes data to guide the car along a predefined path for efficient emptying. The integration of IR sensors, RF communication, and microcontroller programming offers a technology-driven and effective approach to managing garbage collection, contributing to a cleaner environment.

In his proposal, Krithiga [15] Introduces Earthbot, a flexible four-legged robot with an arm created specifically for rubbish collection on a variety of surfaces, including riverbanks, streets, and beaches. In contrast to typical wheeled garbage collectors, Earthbot's legs construction gives it extraordinary mobility to traverse uneven terrain, cross ditches, and climb steep terrain. Users control the robot manually using a teach pendant. The paper examined the real-time robot's practical implementation while acknowledging the foundational work done by earlier studies. It implies that effective project implementation is possible given enough cash and resources. The report also highlights the difficulties in creating the robot's kinematics and dynamics as well as guaranteeing its balance.

3. Design and Implementation

3.1 Components/Materials Used

The elements or materials consist of the individual, self-contained building blocks utilized in the creation of a system or circuit. These building blocks can be divided into two main categories: hardware and software. The essential hardware components required for system implementation are as follows:

- Arduino Mega
- 4-wheel chassis kit with DC motors
- 2xL298N Motor Drivers
- NodeMCU
- HC-05 Bluetooth Module
- Mecanum wheels
- Vero Board
- Adhesive glue
- Glue gun
- Soldering iron and flux
- Jumper Wires
- Android device with the installed Bluetooth RC Control app.
- DIY-Robotic Arm

- 2xUltrasonic Sensors
- Carton

In contrast, "software components" or materials are intangible entities that lack a physical presence. They can manifest as programs, simulations, web pages, and similar digital forms. These software components encompass:

- Arduino IDE
- Proteus Simulation Environment
- C++ programming language
- Bluetooth RC Controller

3.2 Block Diagram of IoT-Based Garbage Collection Robot

In the block diagram, the central component is the Arduino Mega microcontroller which functions as the primary control unit for the entire robotic system. To power the motor driver, we connect three Lithium-Ion batteries in series, providing 11.1-13V when fully charged. The Arduino microcontroller receives its power from the 5V terminal of the L298N motor driver.

Additionally,the Node MCU plays a crucial role in enabling data transmission from the robot to cloud storage on the Thing Speak platform. A separate 5V power source activates the servo motors used in the construction of the robotic arm. Furthermore, a mobile application with Bluetooth functionality governs both the robotic arm and mecanum wheels. Fig. 2 gives a comprehensive visual representation of these various components.

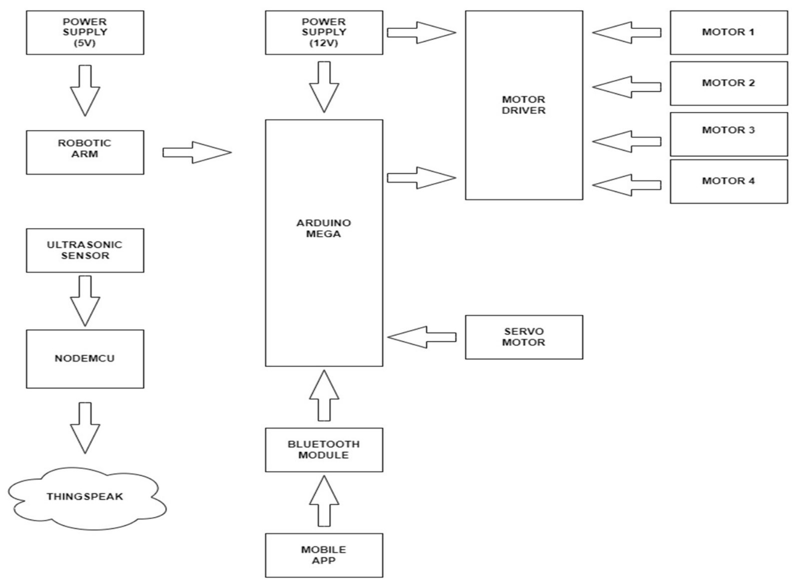

Fig. 2. *Block Diagram of IoT-Based Garbage Collection Robot.*

3.3 Flowchart of the IoT-based Garbage Collection Robot

The operational steps of the EcoPicker-M robot and their interconnected nature are illustrated in Fig. 3 through a flowchart. Upon activation, the robot adheres to commands from human operators transmitted through the mobile application, enabling omnidirectional movement. When the robot encounters an obstacle, it evaluates whether the obstacle constitutes a piece of waste. If the object is not wasted, the robot adjusts its course to bypass the obstacle and resumes its trajectory. In the case of identifying dry waste, the robot collects the material and continues its movement. This sequence of actions persists until the robot determines that the waste bin has reached full capacity. At this juncture, the robot halts its movement and is directed to the main dump site to empty the bin before resuming its operations.

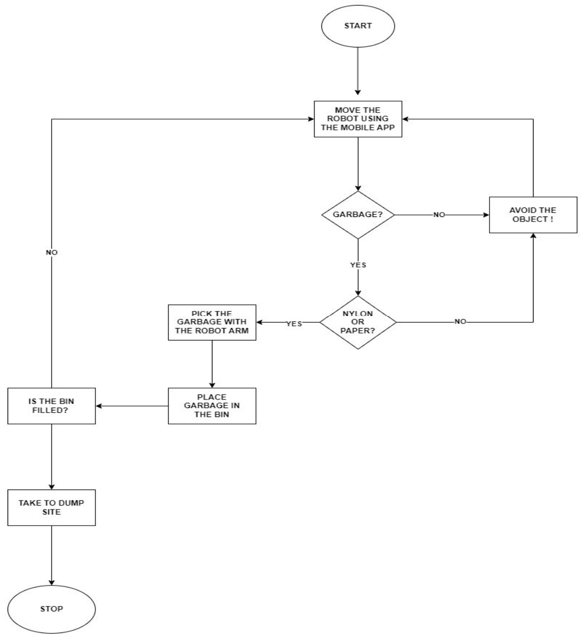

Fig. 3. *Flowchart of IoT-based Garbage Collection Robot*

3.4 Circuit Design

The circuit for EcoPicker-M was created through the utilization of Proteus software. This circuit design visually illustrates the complex web of connections and pathways, providing a systematic and clear overview of how these components interconnect and contribute to the functionality of the robotic system. This detailed design process plays a critical role in guaranteeing the smooth integration and operation of the garbage collection robot, "Eco Picker-M," which is based on IoT technology.

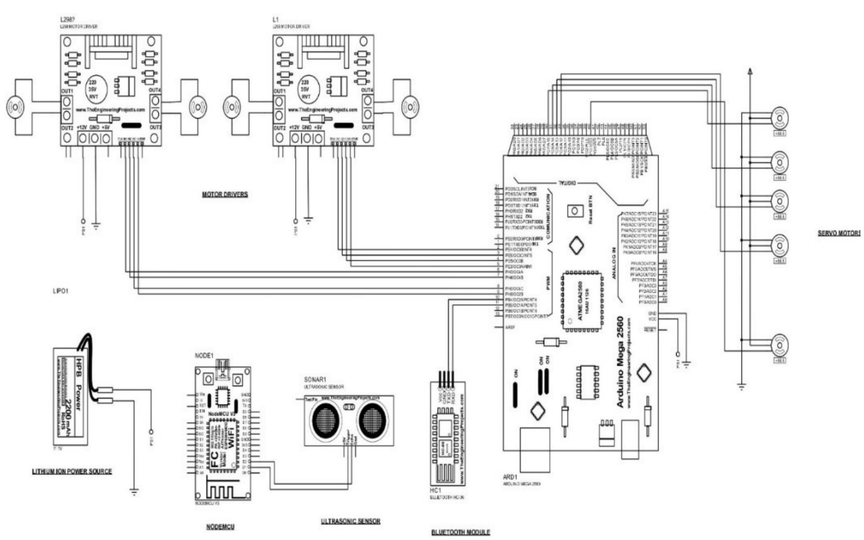

Fig. 4. *Circuit diagram of IOT-based Garbage Collection Robot*

3.5 Power Circuit Calculation

In our design, we utilized a series connection of three (3) Lithium-Ion batteries, each having a 3.7V rating. This arrangement yields a total voltage of 12V when the batteries are fully charged, as evidenced by the calculation:

4.2V x 3 = 12.6V (when fully charged). The 12V power output proves to be more than adequate to serve as the input power source for the motor driver. Additionally, it functions as the power input to the VIN (Voltage IN) pin of the Arduino Mega microcontroller, providing the necessary voltage for the microcontroller's operation. This configuration ensures that both the motor driver and the microcontroller are adequately powered, allowing for the seamless and efficient operation of the system.

For the power supply unit of the robotic arm, a 10,000mAh power bank was employed, capable of providing a stable 5 volts (V). This voltage proved sufficient to operate each servo motor, with each motor consuming approximately 550mAh. The total current for all five servo motors (I_{Total}) can be calculated as the product of the individual motor current and the total number of motors (550mAh * 5), yielding 2750mAh.

$$\mathbf{I}_{\mathbf{Total}} = 550mAhX5 = 2750mAh \tag{1}$$

The estimated operational time (T) can be determined by dividing P_{Total} by I_{Total}:

$$T\ (hours)\ =\ 10000mAh\ \div\ 2750mAh \tag{2}$$

$$T\ (hours)\ =\ 10000mAh\ \div\ 2750mAh = 3.64hrs \tag{3}$$

However, considering losses, the operational time could be estimated to be about 2 hours when the power bank is fully charged. This accounts for potential inefficiencies or energy losses in the system. This duration remains sufficient to ensure the robot's uptime is within an excellent range for effective trash collection.

3.6 Procedures

The following connections were made in the construction of the robot to ensure its smooth operation:

3.6.1 Power Supply Connection

- Connect the red wire from the battery holder to the "12V in" terminals on the First and Second motor drivers.
- Connect the black wire from the battery holder to the "GND" terminals on the first and second motor drivers.
- Take from the 12V terminal to the motor driver to the "Vin" of the Arduino Mega microcontroller to power it on.

3.6.2 Motor Driver A Connection

- Connect the wires from the front right motor's black wire to the first motor driver's "OUT1" terminal.
- Connect the red wire from the front right motor to the first motor driver's "OUT2" terminal.
- Connect the other red wire to the first motor driver's "OUT3" terminal.
- Connect the other black wire to the first motor driver's "OUT4" terminal.

3.6.3 Motor Driver B Connection

- Connect the wires from the front right motor's black wire to the second motor driver's "OUT1" terminal.
- Connect the red wire from the front right motor to the second motor driver's "OUT2" terminal.
- Connect the other red wire to the second motor driver's "OUT3" terminal.
- Connect the other black to the second motor driver's "OUT4" terminal.

3.6.4 Connection of Motor Driver A to Arduino Mega

- IN 1 to digital pin D2 on Arduino
- IN 2 to digital pin D3 on Arduino
- IN 3 to digital pin D4 on Arduino
- IN 4 to digital pin D5 on Arduino

3.6.5 Connection of Motor Driver B to Arduino Mega

- IN 1 to digital pin D6 on Arduino.
- IN 2 to digital pin D7 on Arduino.
- IN 3 to digital pin D8 on Arduino
- IN 4 to digital pin D9 on Arduino.

3.6.6 Connection of HC-06 Bluetooth Module to Arduino Mega

- Connect VCC to 5V on the Arduino.
- Connect GND to GND on the Arduino.
- Connect TXD to RX (pin 10) on the Arduino.
- Connect RXD to TX (pin 11) on the Arduino.

3.6.7 Robot Arm Connection

- Connect the output of the gripper servo to D30
- Connect the output of the elbow servo to D31
- Connect the output of the shoulder servo to D32

- Connect the output of the base servo to D33
- Solder the 5V terminal of the servos together and connect to the positive of the battery terminal.
- Solder the GND terminal of the servos together and connect to the negative of the battery terminal. Then, connect the negative terminal to the GND of the Arduino.

3.6.8 Waste Bin Connection

- Connect the 5V terminal of the servo to the 5V Arduino port
- Connect the GND terminal of the servo to the GND Arduino port
- Connect the output of the servo to D40
- Connect the VCC of the ultrasonic sensor to 3.3V of the NODEMCU
- Connect the GND of the ultrasonic sensor to the GND of the NODEMCU
- Connect the TRIG pin of the ultrasonic sensor to D1 of the NODEMCU
- Connect the ECHO pin of the ultrasonic sensor to D2 of the NODEMCU

4. Test, Result, and Discussion

Tests on the developed IoT-based garbage collection robot, focusing on study objectives were conducted. The robot's performance and how it navigates and collects garbage were conducted using systematic experiments. The findings serve as the foundation for a full assessment of its performance, addressing difficulties and providing remedies. The mobility, connectivity, and user experience were also evaluated to provide ideas for future enhancements.

4.1 Robot Test

Polarity and continuity tests and right connections were carried out on all components to guarantee that all components are in good working order and that the complete system operates accurately and flawlessly as seen in Fig. 5.

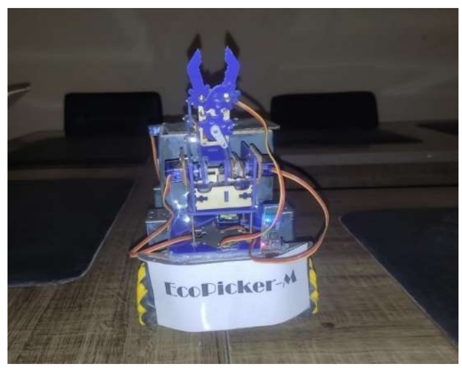

Fig. 5. *Pictorial Representation of Robot Test.*

4.2 Software Test

The implementation of Bluetooth remote control software having a range of 10m to 20m was essential for realizing the objectives of designing the robot. Fig. 5 visually represents the interface of the application within the proposed planned system. This software serves as a pivotal component, enabling seamless communication and control functionalities for the robot. The depicted interface reflects the user-friendly design incorporated into the application, emphasizing its role in facilitating effective interaction and operation of the robot. The utilization of this software contributes significantly to the overall functionality and performance of the robot, aligning with the strategic design objectives.

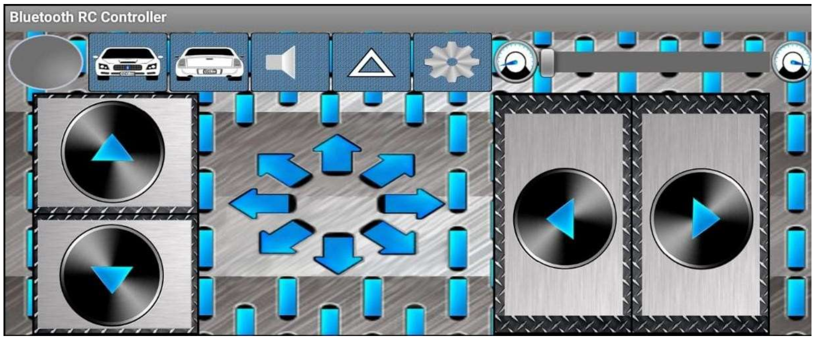

Fig. 6. *Mobile Application for the IoT Robot.*

4.3 Discussion of Result

An assessment was conducted in two different urban communities, Bahago and DHF communities in the Gidan-Kwano Metropolis respectively. The primary goal was to assess the robot's effectiveness in collecting dry waste and depositing it into the bin attached to the robot chassis, which measured approximately 11cm by 7cm by 7cm. Fig. 7a and 7b show graphs that depict the visual representation of data received by NodeMCU and transmitted to ThingSpeak. In the respective communities, the graphical representations depict the relationship between the height of the bin and the time required to fill it.

Fig. 7a. *Pictorial Representation of DHF and Bahago communities respectively.*

Fig. 7b. *Pictorial Representation of DHF and Bahago communities respectively.*

The experiment was conducted on separate days in un-swept conditions, revealing that Bahago had a higher volume of garbage compared to DHF. Consequently, more robots could be deployed to Bahago to expedite garbage collection. The robot, designed to collect waste every 12 seconds until its bin is full, demonstrated greater efficiency than traditional manual methods. Over one hour, the robot completed approximately 80 waste collection cycles, whereas manual collection methods typically achieved around 65 cycles. This difference represents a 15% productivity increase, attributed to the robot's continuous operation and real-time data management.

These findings highlight the importance of optimizing robot deployment according to the waste accumulation patterns of each community. In areas like Bahago, which generate more waste, deploying additional robots would lead to faster and more efficient collection compared to traditional methods that rely heavily on manual labor and are generally slower. The robot's ability to function continuously with minimal human intervention also makes it highly scalable, which is particularly beneficial in densely populated areas. In such regions, where waste accumulates quickly, deploying more robots would ensure a more efficient and responsive waste management system. In contrast, less densely populated areas would require fewer resources.

The garbage collection robot offers several distinct advantages over traditional methods. It is more productive, completing approximately 80 collections per hour, a 15% improvement over manual methods. This increased efficiency stems from the robot's continuous, uninterrupted operation. Furthermore, the robot is more cost-effective, reducing the need for human labor and requiring minimal supervision, thereby lowering operational expenses, particularly in high-density areas where manual collection would demand more workers and resources.

By adapting to the specific conditions of each location, the robot enhances waste collection efficiency and eliminates delays common in manual methods. Its ability to be deployed flexibly in areas with varying levels of waste allows for a more targeted allocation of resources based on community needs. Overall, the robot lightens the burden on human labor while offering a more efficient and responsive solution for waste management.

5. Conclusion

The robot, an IoT-enhanced garbage-collection robot, is a big step forward in tackling the problem of waste collection and management, especially in Nigeria compared to traditional garbage collection. Despite constraints such as the lack of machine vision and learning, which impedes independent garbage collection, the embedded system module and IoT functionality of the prototype demonstrate the viability of this method. Furthermore, the robot contributes to cleaner and more sustainable urban settings, which fits with Sustainable Development Goal 11 (SDG11) - Sustainable Cities and Communities.

5.1 Recommendations

To address the limitations of the current project and enhance the performance of the robot in the future, the following recommendations are proposed:

1. To augment the autonomy of the robot, it is suggested to integrate computer vision technology. This advancement would reduce the robot's reliance on human control and significantly elevate its overall efficiency.
2. The existing capabilities of the robot are limited to collecting dry waste like paper and polyethylene bags, neglecting other waste types such as metals and sewage. To address this, implementing a waste sorting system is highly advised. This system would enable the robot to effectively collect various types of waste and categorize them appropriately for recycling purposes.
3. Designing the robot to withstand diverse weather conditions is crucial, ensuring its operational suitability in various environments and seasons.
4. Consideration should be given to incorporating an enhanced disposal mechanism for the robot. This improvement aims to boost the robot's capacity to manage the collected waste efficiently and effectively.

Compliance With Ethical Standards

Conflicts of interest: Authors declared that they have no conflict of interest.

Human participants: The conducted research follows ethical standards and the authors ensuredthat they have not conducted any studies with human participants or animals.

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