



Development and Testing of an Automated Mobile Platform for Transporting Residential Garbage Bins to Collection Points.

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ABSTRACT– Waste disposal is a routine yet physically demanding household task. For residents of villas and townhouses, manually transporting garbage bins to roadside collection points presents significant challenges, particularly for elderly and mobility-impaired individuals. Missed scheduled pickups can result in waste overflow. To address this problem, this paper presents the design and evaluation of an autonomous mobile platform prototype capable of transporting a 35-liter trash bin to a collection point and returning within a residential driveway. The prototype utilizes an electric toy car as its base, incorporating an ESP-32 microcontroller, ultrasonic sensors for obstacle detection, infrared (IR) sensors for boundary navigation, and relay modules to actuate a garage door. The system was evaluated over 80 trials. During daytime testing, the final rotational maneuver achieved a 20% full-journey success rate, as intense ambient sunlight frequently overpowered the IR sensors. In contrast, nighttime trials yielded a 65% full-journey success rate, demonstrating improved performance when the sensors were not affected by daylight. These findings indicate that the IR sensors' sensitivity to daylight and the chassis' alignment issues during rotation limited the prototype's reliability, as the chassis struggled to realign with the boundary line after completing a U-turn. In summary, while the prototype demonstrates proof of concept and potential for automated waste transportation, further refinement of the navigational system and rotational maneuver is required for consistent and reliable operation.

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Introduction

The current waste disposal process is inefficient, particularly for residents of villas and townhouses. Unlike towers and high-rises, there is a glaring lack of adequate custodial support, which places a greater burden on residents, requiring manual labor and a tiresome, cumbersome process prone to human error and dependent on range/ease of mobility. The physical demands raise significant accessibility issues and do not take into consideration the elderly or differently abled individuals. For example, age-related loss of strength and balance makes it unsafe for older residents to move heavy waste containers to the street [1]. Pushing wheeled bins creates a real risk of falls and severe injuries, especially on slopes or uneven ground [2]. Because of these mobility issues, many are forced to either push past their physical limits or leave their garbage indoors [3]. Simply moving household waste to the street is a major physical challenge for these groups, underscoring a clear need for automated solutions [4].

Villas and townhouse residents do not benefit from building management or custodians who are responsible for moving garbage bins to collection points. Residents often struggle to dispose of their garbage properly on time because exceptional circumstances make it difficult to transport

garbage bins from one place to another. For example, if the person responsible is busy outside the house at the collection time or forgets the task, this results in a missed collection. Another example is when the sun's extreme heat makes it tedious and even dangerous to move the garbage outside. These issues highlight the need for a reliable, convenient method to move garbage bins to the collection point on time.

Currently, the most realistic solution is to have someone take out the trash, whether it is the head of the household, a family member, or hired help. These methods still fail to address physical disabilities, human error, or the simple desire to automate the process to eliminate reliance on others. Additionally, homeowners increasingly prefer to integrate smart home solutions for ease and comfort. Today, the primary reason people adopt smart home technologies is to increase convenience and reduce daily household chores [5].

While automated waste systems exist, they are usually designed for big public areas rather than private houses. For example, the DustCart project was built to collect garbage bags from users' homes and transport the waste to a dedicated area for disposal [6]. Similarly, recent commercial systems like Ursa Robotics use a fleet of smart bins that drive themselves to a communal neighborhood station for emptying [7]. While these are great for cities, they do not work for

individual villas or townhouses because they require expensive community infrastructure and cannot accommodate private home boundaries, such as a closed garage door.

To address this, two existing solutions have been developed to tackle waste transportation in residential households. These solutions sought to address the problem through automation and embedded electronic frameworks.



Figure 1. SmartCan by Rezzi

The first solution is a motorized trash bin called **SmartCan** (Figure 1), designed by the American company Rezzi, that can move independently to the collection point and return to its starting point [8]. The owner can link the trash bin to a companion app and create a schedule that specifies the day and time it needs to head out to the collection point and then return to the starting point. To set up the SmartCan, the owner must place a docking station where the trash bin is placed and place a second docking station at the collection point. This product is designed primarily to eliminate the recurring task of taking out the garbage [9].



Figure 2. Self-Driving Trash Bin

Another project that was made to automate trash disposal to the collection point outside the property was a DIY self-driving trash bin (Figure 2). To do so, the bin's wheel was replaced with a high-torque electric scooter hub motor powered by a 36V lithium-ion battery. To control the trash bin, a motor driver and a Raspberry Pi 3 B+ were used to set the speed and direction. A servo-controlled braking mechanism was installed to ensure the bin is exactly at the curb, preventing it from rolling away [10]. To protect the hardware components, a small plastic food container was used to house them and was placed inside the bin. For real-time obstacle detection, an NVIDIA Jetson Xavier NX single-board computer (SBC) was used. The board was connected to a webcam, positioned to look out the window and watch for garbage trucks. The board runs a machine learning model that can recognize garbage trucks as they approach [11]. Once the software detects a truck turning onto a street, it triggers a smart home assistant to open the garage door wirelessly.

These products automate a chore people often forget or find tedious; however, SmartCan is still in its prototype phase

and unavailable in markets, while the self-driving trash bin is a DIY project. The devices offer genuine accessibility benefits that will be helpful to the elderly and people with disabilities who struggle with physical tasks. Furthermore, these products share critical limitations. Both systems lack obstacle-detection sensors, making them susceptible to hitting people or objects in their path. Additionally, SmartCan will not be helpful if the house has a fence or gate, as it lacks a remote or sensor, while the DIY project cannot work with garage doors without Wi-Fi and cannot return to the starting point. These major limitations leave an obvious gap that a more innovative solution could fill.

Recognizing the limitations of these existing products inspired this study to facilitate a prototype to fill these technological gaps. The primary objective of this research is to design and evaluate an autonomous mobile platform capable of transporting a 35-liter residential trash bin across surfaces such as hexagonal interlocking pavements to a designated collection point. To achieve this, the proposed system fulfils several technical objectives, beginning with the development of a mobile robot platform programmed with an ESP-32 microcontroller. Unlike the Arduino Uno, which has no built-in Wi-Fi or Bluetooth, the ESP-32 is highly suitable for wireless connections to cloud platforms such as Blynk [12]. This directly facilitates integrating a mobile application dashboard to operate the robot via an activation switch. To maintain its path, the system relies on placing two white lines as boundary lines and installing two infrared sensors; if the robot crosses any line, the IR sensors signal the ESP-32 to push the robot in the opposite direction, ensuring the robot heads towards its goal while remaining steady.

Additionally, the design adds sensors and a buzzer to the robot for obstacle detection; if a sensor detects someone in its path, the robot will stop and sound a buzzer to alert the person to move out of the way. The prototype also features the ability to signal a real-life garage door to open and close as required. Finally, full autonomy is achieved by adding a sensor to the trash bin that detects when the garbage is removed. Once the robot reaches the collection point, it waits to be collected, and when emptied, it performs a rotating maneuver to return to the starting point.

By meeting these objectives, this study proposes several specific contributions to the field of domestic automation. To overcome physical access barriers, this prototype directly interacts with a standard relay module to control a garage door remote, successfully handling the physical closed-gate barriers that stop previous models like the SmartCan, and improving upon existing DIY projects that rely strictly on Wi-Fi-based smart doors. Furthermore, it resolves existing safety and navigation gaps through the integration of active obstacle-detection sensors (ultrasonic and buzzer alerts) to fix the safety issues found in previous models, while the automated return protocol ensures the robot makes the full return trip back to the start, which the prior DIY prototype lacked. Ultimately, this research increases user independence by eliminating repetitive labor and human dependency. The system requires minimal intervention; all the user has to do is

place a garbage bag in the attached bin and use the mobile application to switch the robot on.

Methods

To perform the autonomous operations described above, the system was built by modifying an existing mechanical platform rather than building a robot from scratch. The main approach was to build a central circuit, driven by an ESP-32 DevKit V1 microcontroller, that reads sensor data and directly controls the standard RC vehicle's remote control. By doing this, the ESP-32 can manage autonomous navigation, connect to the Blynk mobile app, and operate the garage door, all while relying on the toy car's existing strong motors to move the platform.



Figure 3. Electric Toy Car

For the robot chassis, the platform required four strong motors capable of moving on uneven surfaces and navigating slopes while supporting a minimum payload of 5kg. In addition, it needed customizable space for adding electronic components and mounting a medium-sized 35-liter trash bin. With these considerations in mind, the platform chosen for this project was a ride-on electric toy car for children (Figure 3). It was selected for its high-torque motors, which can support heavy loads, traverse uneven terrain, and climb slopes.

To adapt it for this study, the outer shell was stripped to remove its toy-like appearance. Conveniently, the car featured its own internal circuit with a built-in rechargeable battery already wired to each motor. This simplified the goal of finding the appropriate battery and motors for this project. Furthermore, the stripped chassis provided ample space to securely attach the necessary electronic components, such as the microcontroller, sensors, breadboards, and a power supply.

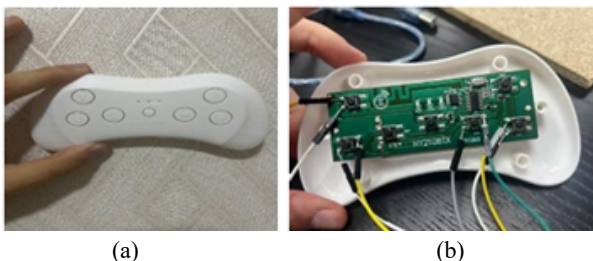


Figure 4. RC toy car remote control. (a). Standard external casing. (b). Internal printed circuit board with soldered relay wiring.

The toy car came with a remote that can control the vehicle's speed and movement (Figure 4). The remote has 4 buttons: forward, back, left, and right. This remote is the key to making the car autonomous; by connecting a microcontroller to it, the microcontroller can be programmed to press the remote's buttons, creating the illusion that the

robot can move on its own. This can be done by hijacking the remote with a relay module, with wires soldered to each button and connected back to the relay.

A. System Architecture

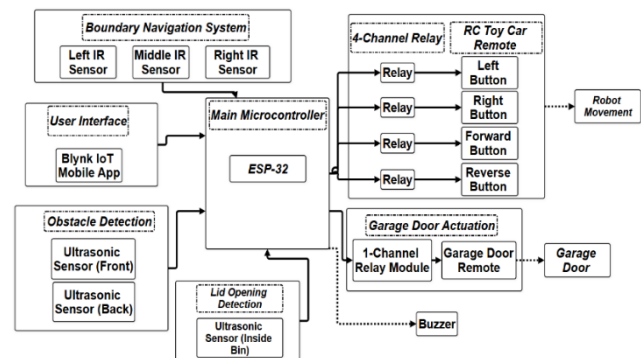


Figure 5. System Architecture Diagram

With the platform established, a circuit was built and mounted on the chassis to transform the electric toy car into an autonomous transport platform. As shown in the system architecture diagram (Figure 5), the ESP-32 is used as the main microcontroller. The system consists of 6 major subsystems: User Interface, Obstacle Detection, Lid Opening Detection, Boundary Navigation System, Robot Actuation, and Garage Door Actuation.

B. Main Microcontroller and Actuation System

The ESP-32 DevKit V1 was selected as the main microcontroller due to its Wi-Fi and Bluetooth capabilities, which are essential for mobile app integration. The ESP-32 came with a terminal adapter that made pin connections easier (Figure 6). The ESP-32 was programmed using Arduino IDE so it could function as intended.



Figure 6. ESP-32 with Terminal Adapter

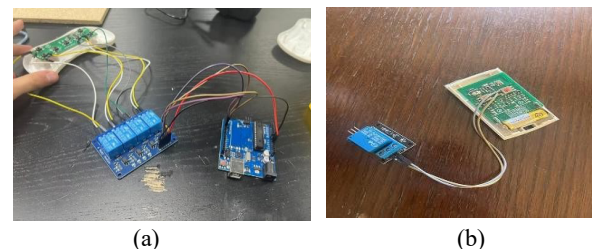


Figure 7. Relay Module. (a). 4-Channel Relay connected to both microcontroller and RC remote. (b). 1-Channel Relay connected to standard garage door remote.

Actuation of the vehicle and home infrastructure was achieved via a hardware relay-hijacking technique. A circuit was built to control the remote, which in turn controls the platform. Specifically, a 4-channel 5V relay module (Figure 7a) was wired in parallel to the directional buttons of the toy car's remote control to drive the chassis.

Similarly, a 1-channel relay (Figure 7b) was integrated into a standard Beninca garage door remote, allowing the ESP-32 to physically trigger the existing home garage door to open and close fully when the platform detects the garage threshold checkpoint during its transit.

C. Power Distribution and Isolation

To organize the circuit and enable easy prototyping, a standard breadboard was used, using its tie-point holes to insert and route the wiring securely (Figure 8). Because the ESP-32 cannot supply sufficient voltage to safely power multiple sensors and relay modules simultaneously, a breadboard power supply module was chosen. This device plugs directly onto the breadboard to provide a regulated 3.3V and 5V to the power rails. This greatly simplifies the wiring, allowing multiple components to connect and receive stable power directly from the rails easily.



Figure 8. Breadboard Power Mounted on a Breadboard



Figure 9. Power Bank

To drive this main logic system, a portable USB power bank serves as the project's primary power source (Figure 9). It supplies a steady input voltage to both the ESP-32 microcontroller and the breadboard power supply module, ensuring the sensors and Wi-Fi communications remain stable.



Figure 10. 6V Battery

However, a separate 6V battery (Figure 10) was installed specifically to power the 4-channel relay module. The reason is that the relays draw significant power when triggered, which can momentarily drain the main power supply. If the ESP-32 and the relays shared the same power line, this sudden voltage drop would frequently cause the ESP-32 logic board to freeze or reset, disrupting the entire system. Therefore, the relay module is powered independently by connecting the 6V battery directly to its alternate jumper pin. This isolated setup ensures that all components continue to operate smoothly without voltage issues during physical actuation.

D. Boundary Navigation System

To achieve autonomous navigation without relying on GPS or heavy computer vision, the robot uses infrared

sensors to detect physical guidelines (white tape) placed along the garage driveway (Figure 11).

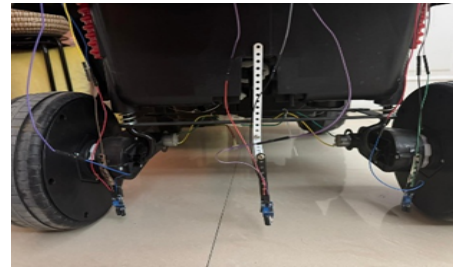


Figure 11. Three IR Sensors Attached on the Chassis' Lower Front Axis

The reason for using this sensor approach is that the RC toy car chassis could not maintain a straight, steady course on its own and often drifted from its intended path. To solve this issue, electrical white tape was used to mark two boundary lines from the starting point to the collection point. To monitor these lines and ensure the robot stays on a predefined path without straying, three infrared (IR) sensors were used.

Two IR sensors were placed in front of the vehicle to monitor the parallel boundary lines. If either front sensor detects the tape, the microcontroller interrupts forward momentum and counter-steers the platform. This continuous micro-correction ensures the vehicle remains centered. The third IR sensor was attached to the middle of the car. Thick horizontal tape lines were placed near the garage door and the collection point to serve as physical checkpoints. This center IR sensor acts as an event trigger, halting the platform when it crosses these designated horizontal checkpoints (e.g., the garage threshold and the curb).

E. Obstacle Detection System

For obstacle detection, two ultrasonic sensors were used (Figure 12). One sensor was attached to the front of the robot, and the other to the back. The purpose is to prevent the robot from hitting a person during the operation. If any of the sensors detect anything within 40cm, they would signal the ESP-32 to switch off the 4-channel relay connected to the remote, stopping the robot. A buzzer serves as an alarm in the obstacle detection system. If the robot stops when the ultrasonic sensor detects an object, the buzzer will emit a warning beep. If the pathway is clear, the buzzer will turn off, and the ESP-32 will turn the relay back on. The robot will continue right where it was left off.

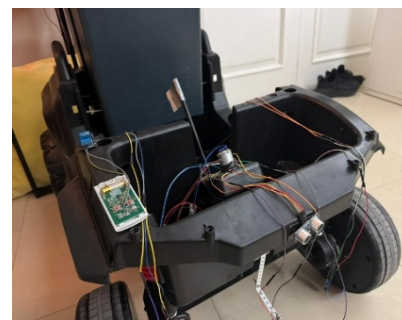


Figure 12. Ultrasonic Sensor Mounted on the platform

F. Lid Opening Detection System & Trash Bin Placement



Figure 13. 35-Liter Trash Bin Mounted on Top of the Platform

To simulate the robot carrying a garbage bin, a standard 35-liter home garbage bin was used in this project (Figure 13). It was mounted on top of the platform by using screws to bolt the trash bin into the chassis, keeping it locked in place.



Figure 14. Ultrasonic Sensor Taped Underneath the Lid of the Trash Bin

To notify the robot that the trash had been collected, a sensor was attached under the garbage bin lid (Figure 14). While the bin is closed, the sensor detects anything within its field of view for 40cm. If the lid opens, the sensor would be pulled away from the bin's interior, increasing the distance to the bin's interior. A sudden increase in the measured distance indicates the lid has been opened by waste collectors, which serves as the physical trigger for the robot to begin its return sequence.

G. Software & Control Interface

To establish a remote-control interface for the autonomous platform, the system uses the Blynk IoT platform to connect the microcontroller to a cloud server (Figure 15). The integration process began by creating a project template and defining a Datastream, which serves as a virtual pin that links a specific cloud variable directly to a physical hardware state on the ESP-32. By registering the physical robot as a device on the platform, unique authentication credentials (a Template ID and Authentication Token) were generated and

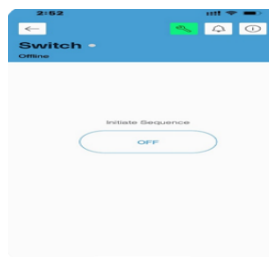


Figure 15. Blynk IoT App Switch

embedded into the Arduino IDE. This established a secure, low-latency Wi-Fi connection between the hardware and the cloud.

User interaction is facilitated through the companion Blynk mobile application, which serves as the primary control dashboard. A digital button widget was configured within the app and explicitly mapped to the previously established Datastream. This button serves as the master digital switch; upon user activation, it changes the virtual pin's state, signaling the ESP-32 to exit standby mode and autonomously initiate the waste transportation sequence.

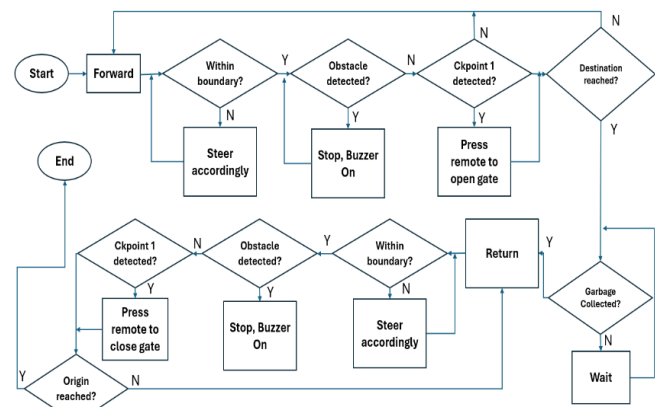


Figure 16. Software Logic Flowchart

Once the switch in the Blynk app is pressed, the ESP-32 initiates the waste-transportation sequence. The flowchart in Figure 16 shows the software logic used for this process. It explains the step-by-step sequence of how the microcontroller checks the sensors to move forward, steer within the boundary lines, stop for obstacles, and use the checkpoints to open the garage door, wait for collection, and return to the starting point.

H. Hardware Connections

A breadboard power module was mounted on the board (Figure 17), providing a stable voltage to the power rails to supply various components. One rail was set to 3.3V to power the IR sensors, while the other rail was set to 5V to power the other components. The breadboard was mounted in the center of the robot. Both negative rails were connected to the ESP-32's ground pin, allowing the circuit to establish a common ground with all the components.



Figure 17. Hardware Components Mounted within the Platform

To establish a connection with the robot, the ESP-32 was connected to the remote control to handle the movement and direction. This was done by opening the remote and soldering two wires to each directional button. Each set of wires was screwed to the corresponding output terminal relay on the 4-channel relay module, and each digital pin was wired to a different GPIO pin on the ESP-32. The alternate jumper pin was wired to the 6V battery, and the ground pins were connected to the negative rail on the breadboard. The garage door remote was hijacked just like the remote control, using a single-channel relay. Both the voltage and the ground pin were wired to the breadboard rails, and the relay was connected to one of the ESP-32's GPIO pins.

IR sensors were attached to the front of the robot: one to the left wheel, one to the right wheel, and one in the middle. Each sensor was positioned at a height of 3cm to detect the boundary line. The middle sensor was attached to detect the thick horizontal lines to stop the robot's movement, and each sensor was wired to the 3.3V power rail and different GPIO pins. Two ultrasonic sensors were wired to the breadboard rails; the Echo pin for each was connected to a different GPIO pin, while the Trig pin for each was connected to a single shared GPIO pin. Another ultrasonic sensor was taped underneath the trash bin lid and wired in the same way. Finally, a buzzer was mounted on the breadboard, with the positive pin wired to a GPIO pin and the negative pin to the breadboard's negative rail.



Figure 18. The Automated Trash Bin Carrier

I. Testing Environment & Pathway Setup

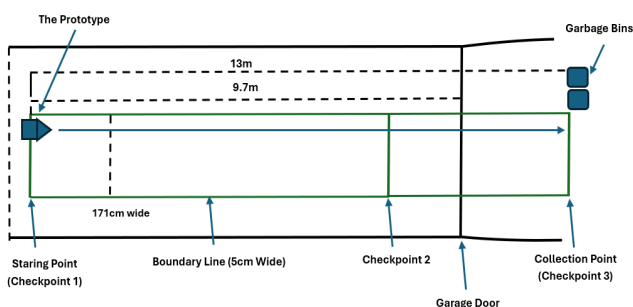


Figure 19. Garage Driveway Diagram

Once the robot was built, it was tested in a real outdoor residential garage driveway to simulate its ability to move an actual trash bin. The driveway is 9.8m long and 6.7m wide, featuring hexagonal stone pavers and a rooftop that covers the entire testing area. The space also features a large Beninca garage gate that opens sideways, which was used to test the robot's ability to trigger the gate remotes during its run.



Figure 20. Robot Pathway & Starting Point

For the setup, the platform was positioned near the property's entrance with the trash bin fully loaded. The robot remains on standby and begins its transit only after the Blynk app switch is pressed. Once triggered, the ESP-32 presses the remote's forward button electronically, making the robot move forward.



Figure 21. Robot Pathway & Garage Door

As shown in Figures 19 and 21, boundary lines were placed on the ground using white tape to serve as the robot's track during travel. Two parallel lines of 5cm-wide tape were placed 171 cm apart, creating a total path length of 13m for the robot to reach the collection point and return to the start. The two IR sensors installed on the left and right act as a corrective feedback loop; the moment either sensor detects the white boundary tape, the IR sensors signal the ESP-32 to interrupt the forward momentum and actuate the corresponding relay to counter-steer the platform. This continuous micro-correction ensures the vehicle remains centered within the designated corridor. In addition, the robot will halt at any point and sound the buzzer if the front ultrasonic sensor detects an obstacle within range, continuing its journey only when the path is clear.



Figure 22. Horizontal White Tapes. (a). Checkpoint 2 (Garage Door). (b). Checkpoint 3 (Collection Point).

In addition, three horizontal white tapes were placed at different locations to serve as checkpoints where the robot must halt (Figure 22). The robot detects these lines when its middle IR sensor passes over them. Checkpoint 1 is the starting and ending point of the journey. Checkpoint 2 is the middle point where the robot stops to open and close the garage door. Finally, Checkpoint 3 is the collection point where the robot stops and waits for the trash to be collected before heading back. Upon detecting checkpoint 1, the system triggers a localized halt, transmits a 1-channel relay

pulse to open the garage gate, and executes a mandatory 10-second wait state to allow the mechanical door to fully open before resuming transit. Similarly, upon detecting checkpoint 2 at the curbside collection point, the robot immediately halts. The system then shifts from a navigation state to a payload-monitoring state, waiting for the bin to be emptied.

Once the internal ultrasonic sensor confirms the waste bin has been opened and emptied, the platform automatically returns to the starting base. As the robot reaches the garage door checkpoint on the return trip, the middle IR sensor halts it again, prompting the ESP-32 to pulse the relay and send a close signal. The system waits 10 seconds to ensure the door fully closes before continuing. Upon returning to the base, the middle IR sensor detects the final line, stopping all motors, activating a success buzzer, and entering standby mode for the next trigger.

J. Number of Trials & Testing Conditions

When the robot was first placed for testing, the power bank was activated, which turned on the circuit and its components, making the Blynk app ready to be pressed. It was noticed that the IR sensors were not properly calibrated for outdoor use, and the potentiometer needed to be adjusted to ensure it detected the line. Initial testing (5 times) showed that the robot had trouble detecting the line and that it could not reach the garage door. Each time, the potentiometer was adjusted, but to no avail. Eventually, when it finally reached and opened the garage door, the IR sensors would work inside because it had a roof. However, when it passed it and went outside near the collection point, it had trouble detecting the lines again because the sun was stronger. This indicated that the sun posed significant difficulties for testing, leading to the decision to conduct comparative trials at night, where the sensors were observed to work much better.



Figure 23. Three IR Sensors Attached to the Back of the Platform

Based on these initial observations, it was decided to compare the robot's performance under two different test conditions. The first test case is the original setup, where the front IR sensors were not covered. For the return journey from the collection point, this setup relies on a reverse function that uses three additional IR sensors mounted on the back of the platform. Specifically, there are two sensors attached near the wheels and one in the center to detect both

the boundary lines and the checkpoints while reversing. They function just like the IR sensors on the front.

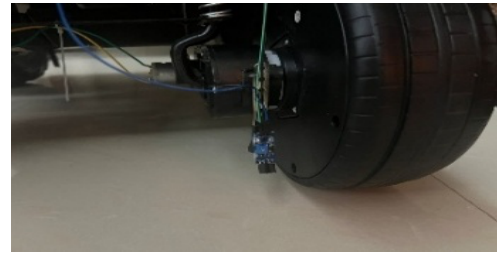


Figure 24. IR Sensor Covered Using Black Heat Shrink Tube

The second test case is the modified setup. As a measure to protect the sensors from sunlight interference, black heat-shrink tubing for cables was used to cover all the sensors (Figure 24). A tube was cut down to cover both LED lights on each sensor, and these covers were kept on during the night testing as well.

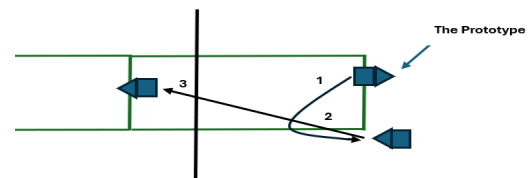


Figure 25. Rotational Maneuver Diagram

Additionally, the reverse function was scrapped, and a rotational maneuver (U-turn) was implemented for the return trip (Figure 25). To prevent the front IR sensors from falsely triggering boundary corrections while the chassis sweeps across the white lines during the turn, the microcontroller executes a blind delay. This function suspends IR sensor polling, allowing the platform to rotate 180 degrees uninterrupted. Once the rotation timer expires, the sensors are reactivated, and the robot reacquires the boundary lines for its inbound transit.

Each case was tested 20 times during the day and 20 times at night to compare the findings. The criteria for these 80 total trials are outlined in Table 1 below.

Table 1. Testing Condition Table

Test Configuration	IR Sensor Status	Return Function	Test Trials
Test Case 1	Not Covered	Reverser Function (3 IR Sensors)	Day (20 Trials)
			Night (20 Trials)
Test Case 2	Covered	Rotating Maneuver	Day (20 Trials)
			Night (20 Trials)

Results and Discussion

The data gathered during the trials for Case 1, where the IR sensors were left uncovered and the system relied on the reverse function for the return journey, and for Case 2, where the sensors were covered and the system employed a

rotational maneuver, are summarized in the subsequent tables. To accurately track the system's point of failure, the data records the robot's performance against specific criteria: garage door opened, collection point reached, and starting point reached, as well as its obstacle detection and average success rate.

A. Test Case 1 Results

Table 2 summarizes the performance of the system during 20 daytime and 20 nighttime trials. The evaluation covered obstacle detection, garage-door actuation, arrival at the collection point, return navigation, and full-cycle mission completion.

Table 2. Test Case 1 Result

Time	Obstacle Detection (Per Trial)	Garage Door Actuation (Per Trial)	Collection Point Reached (Per Trial)	Return Navigation (Per Trial)	Pass	Fail	Full-Cycle Success
Day	20/20	11/20	3/20	0/20	0/20	20/20	0%
Night	20/20	18/20	17/20	0/20	0/20	20/20	0%

During the daytime trials, the system achieved an overall mission success rate of 0%. While the obstacle detection system performed flawlessly (20/20), the navigation system had significant trouble maintaining its path outdoors due to the sun. It successfully opened the garage door 11 times but reached the collection point only 3 times out of 20. In all 20 trials, it never returned inside. The specific problem with the intense heat and sunlight is that it prevents the IR sensors from detecting the white boundary lines, causing the robot to drive off course once it passes the garage roof threshold. Furthermore, even when adjusting the potentiometer to compensate for the outdoor light, it sometimes causes the IR sensors to flicker. This flickering makes the microcontroller trigger false positives, causing the robot to counter-steer erratically even when it is properly detecting the line. Additionally, the reverse method proved completely unviable during the daytime. Not only did the chassis suffer from the same mechanical alignment and steering problems while moving backward, but the strong sunlight also prevented the rear IR sensors from working altogether, ensuring the robot could never complete the return journey.

During the night trials, the robot navigation system performed much better because there was no interference from sunlight. However, the overall journey success rate remained at 0%. While the sensors detected the lines much more easily due to the lack of sun interference, the middle sensor failed to detect checkpoints on several occasions. It happened twice at the garage checkpoint and once at the checkpoint near the collection point, and it required proper adjustment of its potentiometer. Aside from these instances, the robot reached the collection point 17 out of 20 times and opened the garage door 18 out of 20 times, with no failures in detecting obstacles in its path. However, despite the excellent outbound tracking, the reverse function caused a critical failure during the return trip. The main problem with the

reverse function is that the chassis moves much faster in reverse and does not turn very well when detecting the boundary line. Because the rear wheels could not rotate to execute proper steering adjustments, it was incredibly difficult for the platform to adjust its position when a sensor triggered. This caused the wheels to drive off course every single time, resulting in 0 successful return journeys. Because of this, while the robot was very successful going forward, opening the garage door, and stopping for obstacles at night, the reverse function proved to be a failure.

B. Test Case 2 Results

Table 3 summarizes the performance of the modified system during 20 daytime and 20 nighttime trials.

Table 3. Test Case 2 Result

Time	Obstacle Detection (Per Trial)	Garage Door Actuation (Per Trial)	Collection Point Reached (Per Trial)	Return Navigation (Per Trial)	Pass	Fail	Full-Cycle Success
Day	20/20	15/20	6/20	4/20	4/20	16/20	20%
Night	20/20	20/20	20/20	13/20	13/20	7/20	65%

During the daytime trials, the system achieved an overall journey success rate of 20%. In this test, all IR sensor LED lights were covered with black tube casings, and their potentiometers were adjusted properly. While the navigation was slightly better than in the first test, most trials still failed due to sun interference. Although the robot detected the lines in some trials (successfully opening the garage door 15 times and reaching the collection point 6 times), the intense sunlight still caused major problems. It caused the IR sensors to trigger false readings even without seeing the line, or to fail to activate at all when detecting the line, causing the robot to drive off course. Ultimately, the black tubes were not sufficient, as they do not guarantee complete protection from the sun. As for the return journey, the rotating maneuver introduced a new mechanical challenge. When rotating back, the robot rotates based on the number of seconds the relay presses the right and reverse buttons. In most cases, the robot's angle would be off after completing the turn, causing it to move off track. The system was adjusted to change the number of seconds required to turn, but it still failed. Furthermore, even when the robot managed a perfect turn, the intense sunlight still blinded the IR sensors, preventing them from tracking the boundary lines on the way back. Due to both alignment errors and sun interference, the robot completed the full journey only 4 times during the day.

During the night trials, the modified setup performed much better, achieving a 65% overall success rate. With the solar interference eliminated, the robot successfully navigated to the garage door and the collection point and detected obstacles in all 20 trials. Swapping the reverse function for the rotating maneuver proved to be a massive improvement over the first test. However, there were still 7 failures during the return trip. Just like in the daytime, because the rotation relies on the relay timing the button

presses, the robot's angle would sometimes be slightly off after turning, causing it to move off track. Despite this occasional alignment issue, the robot completed the full return journey to the starting point 13 times. This proved that using the rotating maneuver with covered sensors is a vastly superior and more viable method than the original reverse tracking method.

Demonstration video of the robot operation is available online on this URL:

<https://youtu.be/okFOusJ3L4g?si=y4JaVEV9BKcAZGRA>

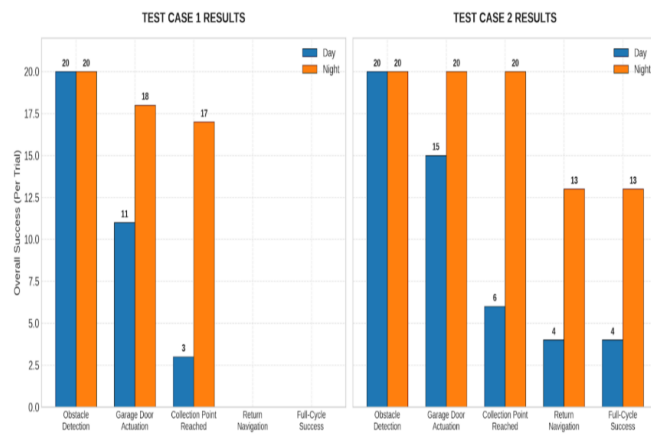


Figure 26. Test Case 1 & Test Case 2 Results

The comparison between the two test scenarios showed that covering the IR sensors and using the rotational maneuver yielded the best overall performance for the automated trash bin carrier. Therefore, Test Case 2 is considered the final working version of the prototype. With this setup, the robot successfully achieved its main objectives: transporting a medium-sized trash bin to the collection point for disposal and returning to its starting position. However, the results were not completely flawless due to lingering issues with the navigation system and the rotational maneuver.

Both testing scenarios proved that sunlight interference is a major problem for the navigation system. Because sunlight contains high levels of natural infrared light, it overpowers the sensors' receivers and triggers false readings. This intense sun interference makes it difficult for the IR sensors to detect the white boundary lines, causing the robot to drive off course during the day. Even though the sensors were covered in the second test phase, the black tubes were not sufficiently protective to completely shield the IR receivers from ambient sunlight. Therefore, an alternative method should be considered in the future to shield the sensors better. Conversely, the lack of sun interference is the exact reason the robot performed significantly better during the night trials; without the sun blinding the sensors, the navigation system could read the lines clearly and perform reliably.

Additionally, the reverse function used in Case 1 failed due to mechanical chassis limitations. The chassis was geared to move much faster in reverse, and because the rear wheels could not pivot, the robot could not execute accurate counter-steering when a sensor triggered. The rotational maneuver

was implemented as an alternative in Case 2. While it did provide much better results for the return sequence and allowed the robot to complete its journey, it still faced mobility issues. Because the rotation maneuver relies on a blind relay timer rather than sensor feedback to complete the U-turn, any slight wheel slip or uneven terrain would disrupt the chassis' mobility. This meant the robot's angle was often slightly misaligned after rotating, which caused occasional tracking failures on the return trip.

On the other hand, in both test scenarios, the autonomous trash bin carrier successfully performed all its other core functionalities exactly as intended, regardless of the time of day. The Blynk mobile app reliably signaled the ESP-32 every time the app switch was pressed. Upon reaching Checkpoint 2, the robot successfully opened and closed the garage door using the relay connected to the standard remote. Additionally, it seamlessly initiated the return sequence after the internal sensor confirmed that the trash had been removed from the bin. The active safety systems also performed flawlessly; the ultrasonic sensors successfully detected obstacles every time, immediately stopping the robot and sounding the buzzer. This proves that while the robot successfully executed these automated objectives without issue, its biggest drawbacks remain the IR navigation system and its return mobility, both of which require further evaluation and hardware improvements.

C. Challenges and Solution

- **Pathway Navigation Method:** Before implementing boundary lines, two other methods were considered: the homing beacon and the line following module. The line-following module was quickly discarded because, even though the robot could detect the line, it still drifted, making it difficult to time the robot's turn back to the line precisely. The Homing Beacon was tested by using an IR transmitter and receiver. However, the beacon only signals the robot to move forward; it still drifts as it moves. Given these issues, the boundary-line method was used instead. This formed the foundational navigation system evaluated in both test cases in the result section.
- **Black Tape:** Before using white tape, black tape was initially used instead. The robot detected black tape in the driveway; however, it was unable to pass through the garage door. This is because the middle IR sensor identified the metal railing from the garage door as a black line, causing the robot to stop midway. To solve this problem, white tape was used instead, and the IR sensors' logic was inverted in the microcontroller code to detect it. This adjustment was critical to achieving the successful "Garage Door Opened" metrics recorded in the final test trials.
- **Reverse Method:** Before implementing the rotating maneuver, the original idea was to have the robot reverse back when returning to the starting point. The method for reversing was just like the method for going toward the collection, using IR sensors and white tape. Three IR sensors were attached to the back of the platform, and each sensor functioned just like the sensors in the front.

Upon testing, there were two major issues: the robot's speed increased while reversing, and the rear wheels were unable to turn due to the chassis design, making it difficult to turn and properly straighten the robot's position. After some testing, the method was scrapped, and the rotating maneuver was used as an alternative. As demonstrated by the 0% return success rate in Test Case 1, these mechanical limitations caused critical failures. Therefore, the reverse method was scrapped, and the rotational maneuver was implemented as the primary alternative evaluated in Test Case 2.

D. Limitations

Although the prototype was able to perform its objectives and functionalities, several limitations were observed during implementation that directly impacted the system's overall success rates in the final testing phase. The limitations are:

- Originally, the Blynk IoT app was supposed to include a feature that allowed users to schedule a time for the robot to perform operations. Most users demanded this. The feature could not be implemented due to coding complexity, and thus, the switch option was added instead. Consequently, the system cannot operate fully autonomously on a schedule; all 80 test trials had to be manually initiated by the user.
- The RC toy car was a suitable pick to serve as a mobile platform due to its high-torque wheels; however, the chassis design itself came with mobility issues, such as being unable to keep a steady movement due to drifting and unable to turn more than 20 degrees, which made testing the rotating maneuver more difficult than it should have been. This directly caused the 7 tracking failures observed during the nighttime return trips in Test Case 2.
- The robot has two separate power sources: the toy car battery and the power bank that powers the main circuit controlling the digital remote. Both power sources must be turned on together to start the robot. This means that the robot cannot act on its own.
- The IR sensors can detect white tape in the driveway; however, sunlight can cause them to behave erratically, often leading the robot to either turn unexpectedly or fail to react at all. Each sensor was covered with a black tube to protect it from sunlight; however, this does not guarantee safety, as the IR sensors are prone to failing to respond properly. Therefore, for better results, the experiment was conducted between the afternoon and nighttime. This limitation is clearly reflected in the data, with the daytime success rate capped at 20% compared with 65% at night.
- The robot was only tested on the specific garage driveway detailed in Section 2.10. Additionally, the actuation system was specifically integrated and tested with a Beninca garage door. Therefore, the results recorded during testing, such as the 65% success rate at night, represent the prototype's performance strictly within this defined testing environment and hardware setup.

E. Comparison with Existing Solutions

As discussed in the literature review, two existing solutions, the Smartcan by Rezzi and the Self-Driving Trash Can, were previously developed to handle the task of residential waste transportation. The Automated Trash Bin Carrier was specifically designed to address the limitations and functional gaps found in these two projects. Therefore, the comparison table below was created to assess each system based on key functionalities, highlighting exactly what this prototype accomplished compared to the existing alternatives.

Table 4. Comparison Table

Feature/ Capabilities	Smartcan by Rezzi	DIY Self-Driving Trashcan	Automated Trash Bin Carrier
Two-Way Transport (Outbound & Return)	Yes	Partial (Outbound)	Yes
Garage Door Actuation	No	Partial (WiFi-enabled doors only)	Yes
Machine Learning/ AI Integration	Yes	Yes	No
Active Obstacle Detection Sensors	No	No	Yes
Mobile Application Control	Yes	No	Yes
Autonomous Scheduled Arrival	Yes	Yes	No (Manual Trigger Required)

As shown in Table 4, the automated trash bin carrier distinguished itself from the other solutions. Even though both the SmartCan and the Self-driving trash can possess more advanced features and maintain higher accuracy and reliability, the automated trash bin carrier achieved certain functionalities that the other two projects lacked, such as obstacle detection and garage door handling.

F. Future Work and Improvements

- A simpler, more immediate improvement would be to design better shielding for the IR sensors to block ambient sunlight during the day completely. Additionally, to address alignment issues during the rotating maneuver, improved turning control can be achieved by adding wheel encoders or an IMU (Inertial Measurement Unit). This would provide the system with real-time feedback on its angle and position, rather than relying on a blind delay timer.
- Implementing AI algorithms into the project can allow room for improvement, like knowing when or how to turn or position appropriately on its own. Furthermore, just like the self-driving trash can, a machine learning algorithm could be added to detect garbage trucks, so the robot knows exactly when to move.
- Some users requested that the project include a surveillance camera for visual feedback. This could be easily implemented in the future for security reasons and to allow the user to monitor the robot's journey.
- Instead of using IR sensors with white tape, a LiDAR sensor could be fitted for more advanced navigation.

This would create 3D maps of the surrounding area and collect precise data to make informed, split-second decisions about moving and turning along the entire path.

- Implementing the automatic scheduling feature through the Blynk mobile application, which was originally planned but scrapped due to coding complexity. This would allow users to set specific days and times for the robot to operate without needing to press the start switch manually.
- Currently, the robot relies on two separate power sources. Future designs should integrate the power supply so that the main circuit and chassis are powered by a single, unified battery, allowing the robot to operate completely on its own.

Conclusion

In conclusion, this study demonstrated the feasibility of using a low-cost ESP-32-based platform to transport a garbage bin to the collection point without human intervention. This project was conducted to propose an alternate solution to help residents, particularly the elderly and people with disabilities, transport their garbage without physical struggle. The prototype successfully demonstrated its core functionality, including structural stability, mobile application control, sloped terrain traversal in a real-life driveway, opening and closing an existing garage door, and detecting obstacles in its path. However, further improvements are needed to increase reliability, especially during daytime operation. The two main flaws are the navigation system and the rotating maneuver. Using IR sensors to detect boundary lines in broad daylight proved unreliable, and the platform's ability to turn around is prone to errors and failures. Additionally, the system was not tested in extreme weather conditions. Further development or testing is required to address environmental resilience before full deployment. These drawbacks show that the prototype requires further evaluation and improvement. Therefore, the prototype serves as a successful proof-of-concept rather than a fully reliable product.

Author Contributions

O.A.H.: Conceptualization, Methodology, Data Collection, Visualization, Writing Original Draft. J.P.: Supervision, Review and Editing.

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Competing Interest

The authors(s) declare no competing interest.

Declaration of Generative AI Technologies Use

During the preparation of this manuscript, the author(s) used Google Gemini for text drafting, editing, and structural assistance. The author(s) have reviewed, edited, and verified all AI-assisted outputs and take full responsibility for the content of the manuscript.

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