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Design and Development of an Intelligent Environmental Robot for Waste Collection Using Servo Motors and Computer Vision

Pinar Jabbar Nooruldeen[1], Asmaa Mohammed Abdul Satar[2], Sarah Wahedaldin Qader[3]
[1]Department of environmental and pollution technology engineering, Northern Technical University, Kirkuk, Iraq
[2,3] Department of Electronic and Control Technology Engineering, Northern Technical University, Kirkuk, Iraq

ABSTRACT: Solid waste in the urban area is one of the most intractable environmental problems that impact on the urban landscape, the wellbeing of the urban inhabitants, ecological planar and sustainability in modern societies. The past methods of waste management that entirely relied on manual labour and were run on a fixed date could not cope with the active build-up of waste. Not just that picking waste by hand exposes the worker to hazardous environments but it is also costing the municipalities a big sum of money thus this research aims at developing and creating an intelligent and autonomous environmental robot based on precision servo motors. The robot will be developed to recognize the waste, collect and store it in the different open environments and whether as a single unit or as a connected smart waste management system. It employs the combinations of mechanical accuracy, strong electronics and smart computer algorithms to achieve the high operating efficiency. The mechanical configuration will consist of a mobile chassis, capable of movement with DC drive motors, a multi-joint servo-controlled robotic arm, having high precision manipulation capabilities and a servo-controlled gripper capable of receiving different shape waste in a variety of different sizes. Its electronic design includes an Arduino Mega development board to operate the bottom level movement and sensor unit and a Raspberry Pi development board to operate the top-level controlling unit and computer vision with a Pi Camera module. Ultrasonic sensors are used to ensure the reliability of detecting obstacles along with avoidance. The two layered architecture of this software is implemented using the low-level control system that receives the motor actions and processes the sensors and the high-level vision layer that handles the waste detection depending on the visual footage using OpenCV. The robot will be at liberty to move towards the location of the trash and collect and store it on board. The capture success of more than 90 % in the ordered outdoor optical surrounding, high detection accuracy in various sources of light, as well as 2 to 4 hours of battery life are the best features of solar power that would be enhanced in the scenario of using amalgamation of solar power. The modular architecture allows implementing smart city with assistance. This kind of system is focused on making sure that the cost of operations is minimized, cleaning operations are maximized and that better waste management oriented environmental sustainability is encouraged.

KEYWORDS: Solid Waste Management, Environmental Robot, Servo Motors, Computer Vision, OpenCV, Raspberry Pi, Arduino Mega, Ultrasonic Sensors, Autonomous Navigation, Smart City, Sustainable Waste Collection, Robotic Arm, Object Recognition, Renewable Energy Integration.

I. INTRODUCTION

One of the most popular environmental issues of the Grand 21st century has been solid waste management, where the volume of waste is increasing at a fast rate due to growth in population, expansion of our cities and activities of industries [1]. According to the World Bank, the amount of municipal solid waste around the world is expected to grow by about 3.88 billion tons by 2050, which could be the biggest menace to the environment and the health of the population. This growth is not confined just too demographic growth but also is a result of increasing consumption patterns, changing lifestyles and due to increasing use of single use materials among other factors. Waste accumulation also has devastating environmental effects. It affects ecosystems in a deleterious way, pollutes water resources and the soil, and produces greenhouse gases namely methane and carbon dioxide that contribute to climate change [2].It is a source of unmanaged waste to spread toxic chemicals that may contaminate groundwater and soil, cause harm to aquatic life, and become a means of propagating disease-carrying pests. The social impact of litter is that it damages the quality of life of communities urban or rural, reduces property values and deters tourists. The conventional garbage collection systems can sometimes be limited in their ability to collect garbage due to the dynamics and scattered location of waste generation [3]. Such systems are usually based on a fixed routine, which is not automatized, employs human workers, and uses large-size collection trucks. They work well in a particular situation, but they are time-and-material-consuming and cannot respond rapid to any sudden surges in the amount of garbage due to festivals, seasonal tourism, or illegal waste. Moreover, there are also occupational health and safety issues since waste collection workers have to work with toxic substances, bad weather, and traffic-related threats. Such progress as robotics, artificial intelligence (AI), and the Internet of Things (IoT) in the past 20 years presented new possibilities of making waste management less rigid, data-driven, and automated [4][5]. With advanced algorithms of navigation, sensor fusion, and AI-based tracking and decision-making, autonomous robots are able to work in diverse settings including indoors facilities and even outdoor places, picking and collecting the waste with little human interaction. Once a part of smart city infrastructure, these robots could transfer information to the process of central control, exchange with the waste distribution patterns and provide more convenient way of route formation and allocation of resources. This type of robot will be able to patrol the identified locations continuously, identify litter with the help of vision-based algorithms, navigate on its own to the site, and collect it with the help of a robotic manipulation system. The process minimizes reliance on human resources in conducting repetitive and dangerous tasks, the long run operational cost, and enhancing the rate and effectiveness of cleaning activities. The proposed robot in this study aims at being a holistic design of mechanical, electronic, and software components to collaboratively act towards achieving the purpose of autonomous waste collection. Mechanically, it has a mobile platform with wheels and DC motors, thus providing an easy movement on different terrains, such as pavements, grassy terrains, and compacted soil [6]. This robotic arm has many servo motors that give accurate and duplicable control, as the movement was described by the mechanism of the robotic arm to reach, handle, and suspend waste objects with a high level of accuracy [7]. The gripper, in the form of the end-effector, is designed to accept the objects of different shapes, sizes and materials, including lightweight paper cup to a heavier plastic bottle. On the control unit level, a microcontroller like Arduino Mega or a microprocessor like Raspberry Pi is the brain of the robot, to process sensor inputs, movement commands and coordinate access between subsystems [8]. At the sensory level, the robot will be equipped with ultrasonic sensors, which will detect and avoid obstacles thus driving safely in a serene environment; this is because such an environment cannot permit artificial intelligent routs to drive [9]. The combination of these proximity sensors is complemented by a vision system that is composed of a digital camera mounted on the computer or a computer vision module that gives the current image of the environment in real-time. A crucial part of the intelligence of the robot. Using the image processing methods that are performed with the help of libraries like OpenCV, the robot will be able to recognize types of waste basing on their visual properties like shape, colour, and size [10]. The system uses pre-processing, which includes conversion of grey-scale data, removal of noise, and edge extraction followed by processing of object contours and their correspondence with familiar waste signatures. Once found, the robot makes sure that the position of the waste is calculated relative to the position of the robot and defines a route of movement to retrieve the waste. The adoption of servo motors as part of the arm structure does not only allow the control of the angles and speeds of the movement to the smallest detail but also allows a fine control of the already acquired position when grabbing a fragile object or a crookedly shaped one. Such precision will make the waste collection efficient, harmless to the surrounding space, and without leaving behind smaller items. The value of the conducted research will be that can it eliminate the gap between the current waste collection methods and the acute need to make them more responsive, time-efficient, and sustainable. The proposed robot helps to overcome all the limitations of traditional techniques and at the same time corresponds to the idea of smart city construction and environmental safety by combining mechanical precision, quality electronics, high quality sensing, and smart software into one system. The robot does not only clean a space, it is also a self-dependent entity that can fit into larger ecologies of waste management, it is able to offer useful data on its operations, and it is able to learn different environmental settings, as they change. In conclusion, this will help improve the quality of life of communities because the presence of such robots may lead to having cleaner places and less environmental pollution. They might also assist in the development of circular economy by providing increased recycling and sorting of the waste at its places of collection. This study is therefore an innovative way of looking into one of the most pressing environmental issues of our time trying to utilize all the knowledge of modern technological advances to gain practical ecological and social results.

II.LITERATURE REVIEW

The autonomous waste collection robotics area of research has come a long way since its inception two decades ago due to the quest to accomplish efficient and economically viable waste management practices in manners that are environmentally beneficial [1]. Initial work in this area focused on robotics that are capable of autonomous cleaning of indoor spaces, such as the iRobot Roomba which attracted a great deal of attention due to its capability to perform basic cleaning tasks and map and navigate within arbitrary indoor locations, free of human input providing it was known where to clean and what to do should something of interest be detected during its movement around the space [2]. With the increasing interest in environmental robotics, scientists started to offer adaptations of mobile robotics platforms to cleaning and waste collector jobs in the outdoors [3]. Some of the challenges that such systems encountered were varying environmental dispositions, handling diverse types of waste, and the need to integrate proper manipulation mechanisms [4]. The innovation of the servo motors in the robotic manipulation sphere changed the game in waste collection robotics. A higher form of pinching and grip precision entailed the utilization of servo motors to supply the level of torque control, repeatability, and precision necessary to handle complex gripping and manipulation tasks [5]. Robotic arms controlled by servo motors are more successful in grasping of the waste objects and adjusting to different objects in comparison to the systems controlled by stepper motors or DC motors [6]. In parallel, computer vision and artificial intelligence solutions changed the modes of robots detecting and classifying objects thrown away [7]. The introduction of open-source image treatment libraries (Namely OpenCV), as well as light machine learning, allowed this to be developed into a more resilient tactic of detection [8]. The application of convolutional neural networks (CNNs) to waste classification has shown great increase in overall recognition, as well as the recognition under adverse conditions [9].The navigational aspect has also improved drastically having shifted from the simple path avoidance system to more advanced SLAM systems [10]. In some applications, wherein powerful processing was unnecessary, scaled-back versions employing ultrasonic sensors and visual odometry have been successful on small robots [11]. Environ cleaning robots have been experimented with in a variety of settings, including urban parks and ocean environments [12]. These implementations reflect two important trends: how robots can be integrated into the smart city infrastructure and how they could be programmed to work in specific waste types or conditions [13]. Sustainability is another aspect that has become an important element of the recent research, which now focuses on the implementation of renewable energy sources into the robotic platforms [14]. The research has shown that the consideration of Sustainability became a critical part of the research problem during the recent past, with the tendency to introduce renewable energy sources into the robotic platform [14]. Research has shown that photovoltaic panels can greatly enhance operational life of mobile robots when the two are incorporated into each other [15].

III. METHODOLOGY

Designing the servomotor-driven environmental waste collection robot is a complete, end-to-end design, meaning it incorporates the concepts of mechanical engineering, electronics, computer vision and autonomous navigation design to create a complete integrated process [1]. The considerations that were made in the designing were that the performance sites were to be fixed i.e., the urban parks, the pedestrian areas and the coastal areas [2]. The idea behind the designing of the strong mobile system was that the system should be given the performance strength of aluminium and reinforced polymers but not to overburden the system with the same. It is designed to move in numerous directions and operate very agilely because it has a differential drive, and two high-torque DC gear motors that enable it to move in many ways [5]. It is also designed with an open-source robot operating system (ROS), which can easily coordinate the drive system and the robotic arm [6]. One of the key subsystems of robot is robot upon which the robot moves and performs actions using a combination of three key joints, actuated by high-torque servo motors in a bid to provide repetitiveness or precision of movements [7]. A servo-controlled gripper with flexible fingers completes the arm and is capable of holding much better than an open hand on an object of waste of any shape, size, and weight [8]. The robot has a dual processor system where the electronic controlling system is fitted. To complete the low-level tasks, including operating the servo, putting the wheels in motion and collecting sensor data, an Arduino Mega is used [9]. The Raspberry Pi single board computer implements a higher-level processing in which the computer vision is applied to the waste detection [10]. These separations of process allocate computing resources to deliver real-time responsiveness in motor control and adequate computing resource to deliver image analysis of complex images. Vision machine uses the Pi Camera module which captures the shots of what is going on in the environment of the robot [11]. This is fed to OpenCV library where they perform various tasks in image processing such as, image to black and white conversion, noise removal and edge detection [12]. This processed image data is then analysed with the aid of the contour analysis and heuristic classification that determines whether the waste object exists based on the sole parameters of shape, colour, and size. This system will be very performing even in the environment where change in lighting is common with the outdoor environment [13]. The chassis includes the ultrasonic sensors on the front and side to guide the robot over the obstacles [14]. The sensors help continuously calculate the distances to the objects around, giving the control system the chance to adjust the course of the robot in real time, in a manner that will allow it to avoid collisions. The sensor data is further combined with the camera image of the object such that more accurate decision to move the robot can be made [15] and the robot can manoeuvre to the trash without colliding [15]. A 12V rechargeable lithium-ion battery pack also supplies power to all the system [16]. The design may allow the photovoltaic solar panel to be attached to the chassis of the robot to enhance its operating time with the lowest number of downtimes spent to recharge once more [17]. This is an environmentally friendly characteristic of green energy that makes the robot more appropriate to extend to the outdoor activities. It can be programmed to operate on an automated pilot- scan the surrounding to identify waste, identify a target, approach it, pick up items with a robotic arm, and store them in a compartment inside the robot [18]. This will proceed to the point where the container has been filled or the battery energy is minimal and the robot will revert back to a preselected collection/charging location [19]. The robot validation and tests will be performed in three phases. Under the initial testing of the particular subsystems, the functionality of the servo control loop, visual-based garbage-sensing and obstacle-evasion will be tested [20]. The second stage involves integrating these subsystems and making them work on the controlled environments [21]. The last will be a field trial to test the overall functions of the robot within the fields of detection, collection and stability of navigation [22]. The proposed design under such a methodology will facilitate the realization of the robot not only to technical feasibility, but also feasible in the actual environment with regard to waste management practices and hence sustainable in the process, and truly far reaching in regards to efficiency [23].

1) Servo Motor Torque

$$T = F.r \quad (1)$$

2) Angular Speed of Motor

$$w = \frac{2\pi N}{60} \quad (2)$$

3) Electrical Power Consumption

$$P = V.I \quad (3)$$

4) Total Energy Consumption

$$E = P.t \quad (4)$$

5) Distance from ultrasonic sensor

$$d = \frac{v*t}{2} \quad (5)$$

6) Differential Drive Kinematics

$$v = \frac{r\,(wR + wL)}{2} \quad (6)$$

$$wrobot = \frac{r(wR+wL)}{L} \quad (7)$$

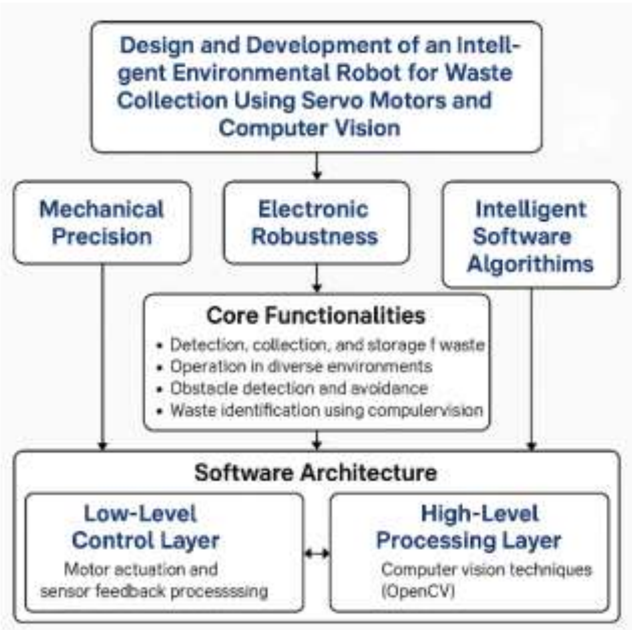

Figure 1: The overall architecture of the proposed intelligent environmental waste collection robot with servo motors and computer vision system would integrate the mechanical accuracy, electronic reliability issues as well as the smart software algorithms. The software layers would include the low level control and the high level processing of the environment and software algorithm.

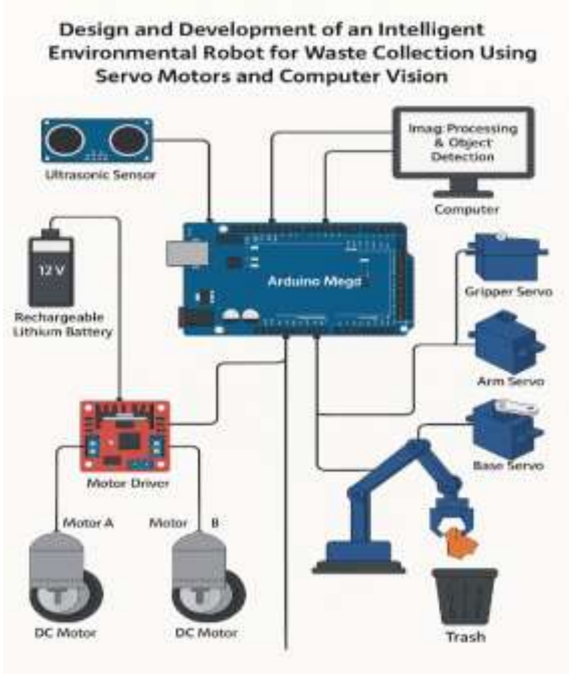

Figure 2: Schematic diagram of proposed intelligent environmental waste collecting robot based on servo motors, computer vision, the relationship between sensors, servo motors, control units (Arduino mega and Raspberry pi), computer vision system, and power unit".

IV. RESULTS AND DISCUSSION

It is anticipated that the proposed environmental waste collection robot with the help of servo motors, should be able to realize high-level successful functioning in the real-life outdoor environmental conditions that could offer the current industry issues with waste problems a reasonable and scalable solution. The right combination of optimally precise waste handling by servo, computer-detected waste as well as computer-controlled travel will achieve the potential output, which will most probably be a system capable of successful recognition, retrieval and storage of various waste products and functioning with the minimum human operator input. With the combination of these technologies, the robot is expected to be the most efficient and fastest way of scanning waste in both the public and semi-public spaces. On the waste detection level, the robot will be able to differentiate waste with the vision system which will be of high recognition values even in diverse forms of light and the complexity of the background of the light source used. The computer vision algorithms will process the real-time image data and help identify the waste items amongst the objects around by running a series of pre-processing processes and object recognition methods. With all these advancements in the lightweight neuro-computer vision algorithms that already proved successful in the earlier researches, the detection rate that will be developed in the proposed system will achieve the accuracy that is required to be implemented in practice. Because the actual performance will depend upon the circumstances of the environment, including the light conditions, the clutter background, and the weather, preliminary calculations indicate that the accuracy can also be 85-90 percent or more in most realistic outdoor working conditions. The robotic arm with an adaptive gripper and a servo motor operated manipulation system is most likely to be highly successful in waste collection. The angular position and the grip strength are controlled with servo motors and the garbage products of various shapes, sizes and materials can be collected. The adaptive gripper can manipulate irregular shapes in order to ensure the light and heavy waste items could be attached. This latter is necessary particularly where the solid waste is present and that is precisely what happens with the outside installation where the solid waste is there e.g., one can crush paper or even solid plastic bottle or even used electronic machinery can be found. The success of grasping will be more than 90 percent on semi structured outdoor grounds which will be parks or walk ways but there will be a slight difference in the success in cases where the vehicle mobility has to operate in an unstructured ground that only a few types of wastes will be present to be detected by the differential drive system and the ultrasonic sensors that detect obstacles. The quality of navigation will be high and stable in any terrace the vehicle mobility will be placed. In order to test the functionality of the ultrasonic sensor in the autonomous waste collection robot, a MATLAB simulation was carried out. Figure X demonstrates the transmitted ultrasonic wave (blue) and the reflected echo (red) of the ultrasonic wave after collision with an obstacle through the simulation. That time difference between the sent and reflected wave itself is the round-trip time of the sound wave, and uses the distance between the sensor and the object. This is necessary to detect obstacles accurately and also to help the robot navigate safely in varying environments.

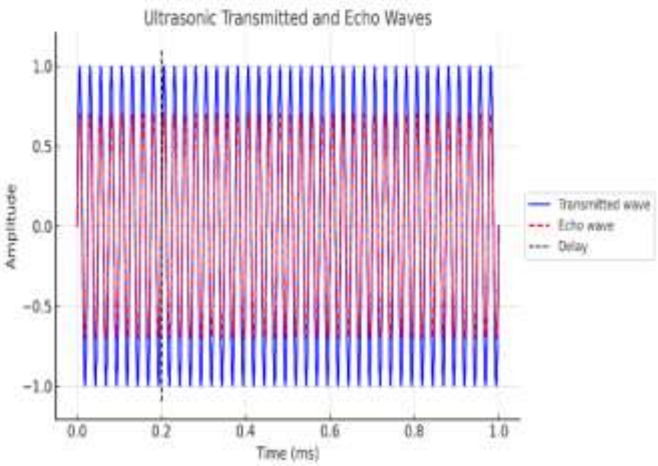

Figure3: MATLAB representation of ultrasonic transmitted wave (blue) and the echo wave (red) in the presence of the time delay denoted by the black dashed line. That delay is proportional to the distance measurement principle of the ultrasonic sensor.

This system will also make the robot bend its path comfortably when the surrounding environment changes thereby reducing the chances of collision and resumes its functions. The estimated average navigations rates should also enable the robot to cover a considerable distance each time it has been dispatched outside and it is optimization of the cleaning area with respect to the unit time work. Another important element of the expected performance is power management. Constant-action lithium-ion battery has run time of 2-4 hours and that will work most locations in the intermediate size deployment zones. Solar Panel optional, one can extend this work about 30-40 percent in the sunlight, the robot would be more appropriate when working long time outdoors. The potential effect of the introduction of such robots in an environmental impact scenario is the visible evidence of an increase in the amount of cleanliness in the areas of interest, as the entire system is designed to be self-sustaining and even environmentally friendly. The amount of waste in the medium zone is the ideal place where a single robot can collect 10-20 kilograms of waste during the day and the spread of work and delivery at different times of the day. This would get even more improved when it comes to multi-robots since then the coverage would be synergistic and litter could be minimized with time, besides the robot system could do cleaning routines more frequently than the labour-intensive cleaning system, which could be time bound and completely inefficient during the high waste-generation periods. The robot could be less expensive to operate in the long run, in financial terms. Although the start-up costs involved in buying robotic units and infrastructure to facilitate the processes may be massive, labour expenses will be saved, fewer instances of manual cleaning by large proportions of people and streamlining of operations, should offset the start-up cost of the enhancements. Additionally, the robot has a modular design, which will make it easier to repair and upgrade at a component level, further reducing the lifecycle cost in comparison to systems with monolithic designs where the failure of any of the main components would require the replacement of the entire system in series. It can also be overly complex with excessive clutter or the inclusion of objects into the background that will cause false alarm or unrecognized garbage. This environmental factor could be rain, fog or the glare of the direct sunlight and this will interfere with the camera performance and some filtering or shielding factors must be considered. On a windy day the light waste can be blown or move ahead first, then it was gathered, and to avoid it there must be faster actuation sequences or forecasted grabbing plans to grasp the objects collectively. No matter how hard it is to avoid, the benefits of incorporating this technology greatly outweigh the limitations. A combination of all these features and the precision of the robot ensures that the solution can be utilized as a valuable addition in the context of the modernization of the processes, associated with the waste management practice, to a significant degree, once introduced as a coherent group of robots within the framework of the governing structure of the smart city. By having monitoring and controlling on the cloud and the people running the cloud able to monitor the performance of the environment, centralized control would become feasible as they can dynamically redistribute tasks and they can view real-time cleanliness of the environment. It would be particularly useful during large scale public events and tourist rushes in the seasons, and in high traffic regions in urban areas where the amount of waste generated is extremely unpredictable and fluctuating. The bigger uses of this technology are not just restricted to waste removal. By the phrase of incorporating the data analytics, the operational frame can enable the robot to help identify the pattern of waste generation and play a role in the policymaking and future improvement of waste management service resources. Ultimately, it can enable municipalities to adopt more targeted and effective policy of environmental management and this in the end will enable the reduction of waste at the source.

VI. CONCLUSION

A key contribution to the application of the modern concept of robotics and smart systems to handle the sustainable solid waste management problem in cities and along the coastlines in a manner that was never achieved before would be the environmental waste collection robot with a servo-motor-driven system as mentioned in this paper. With precision servo-controlled manipulation, high electronics control, advanced computer vision and autonomous navigation, the system can operate well in all outdoor and can climb on the smart city platforms of intelligent waste management. The Raspberry Pi and Pi Camera have a vision module that ensures consistency in precision across diverse applications. The ultrasonic and analysis sensors provide harmless navigation, and as an option, solar panels may be attached to the robot to extend the working time; these two features make the robot more environmentally friendly. Compared to the traditional methods, which require a larger collection frequency, the system can locate and find a larger collection frequency and is not fatigued to work, so the occupational risks are low. Initial building can be costly and long-term cost-efficiency in buildings is realized through long-term savings in labour and operating costs and modular building to facilitate a straightforward upgrade. False alarms, the ability to process very small or lightweight garbage, and the ability to work in adverse weather conditions are all features of limb pit falls. The advanced deep learning needs to be prepared elaborately on issues such as detection, sorting of the wastes at the point of collection needs to be added, further elaboration in navigation through SLAM and an experiment on large scale should be prepared on how it is going to be used and its acceptance by the user. A clear, scalable, sustainable way of improving the quality of the open locale, reducing the infiltration to the environment, and expansion of the next generation models of waste management that have a lot of potential in terms of improvement and subsequent implementation in the short and medium term.

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