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Mobile Bottle-Recycling Robot with Automatic Identification and Compression

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Abstract: *The accumulative and poorly reversible nature of plastic pollution has wide-reaching impacts on our global environment. To counteract the problem and achieve sustainability, recycling efforts of plastic products need to be given greater attention. Instead of relying on people's initiative to recycle plastic bottles in non-mobile machines, this project aims to develop a mobile bottle-recycling robot with automatic identification and compression. The robot incorporates four main functions, an object detection program to identify plastic bottles, a chassis with four Mecanum wheels to move to the desired location, a conveyor belt unit to transport the bottle to the inside chamber, and an actuation unit to compress the bottle. The whole procedure can either operate automatically or be controlled manually. The developed robot frees manpower and human initiative from the process and decreases the cost of transportation through compression, providing both economic and environmental value. In the future, a larger database and improved functions of the robot will enhance the recycling results. This project brings an outlook on the future method of bottle recycling that is both economically efficient and environmentally friendly.*

Keywords: *Plastic bottle, robot, automatic identification, conveyor belt, sustainability*

1. Introduction and goal

Plastics have become a cornerstone of modern life. Unfortunately, behind its utility to society, the adverse effects of plastic on the environment are turning it into a hazardous product. Plastic products harm the environment in the form of air pollution, water pollution, land pollution, etc.

To combat plastic pollution, recycling plastic products like bottles is essential for reducing landfill use, conserving energy, and creating new products. China, the largest producer of plastic, consumes about 200 billion plastic beverage bottles annually, yet its recycling rate remains low at around 20%. Greater attention to plastic recycling is necessary for future sustainability.

Countries like Germany have implemented the Pfand system, a deposit-based recycling program that has reduced plastic waste by 25%. Japan's recycling policy, influenced by the Mottainai philosophy, encourages resource utilization, resulting in an impressive 85% recycling rate. These financial and cultural incentives significantly boost recycling initiatives.

In contrast, China lacks a comprehensive recycling system, which may take time to establish. Therefore, I propose a mobile bottle-recycling robot that automatically identifies and compresses plastic bottles, addressing the lack of voluntary recycling. This robot enhances recycling efforts, reduces transportation and storage costs, and allows for larger-scale recycling across various public sites in the community.

Current research on plastic bottle recycling primarily focuses on automatic classification using methods like color recognition and support vector machines. Hu proposes a computer perspective-based plastic bottle color recognition and classification system.[1] Another study applies the Support Vector Machine (SVM) method with Oriented Fast and Rotated Brief (ORB) feature extraction, achieving a classification accuracy of 74%.[2] Ramli, Mustafa, Hassain, and Wahb utilize a region-segmented technique for automatic detection of 'ROIs' and propose a histogram of pixel intensity algorithm to differentiate between PET and Non-PET bottles based on transparency and opacity, illustrated.[3] While these methods focus on classification, my robot aims to simulate a complete recycling process from identification to compression and storage. Mukhopadhyay and Tariq developed an autonomous robot that uses GPS and image-based techniques to collect plastic bottles from waste.[4] Another robot features a mechanical arm with six degrees of freedom and two cameras for locating bottles, illustrated.[5] Although similar, my robot includes compression and storage functions, enhancing its economic value and efficiency. Additionally, Varghese and Mohan discuss a beach-cleaning robot for plastic bottles that employs GPS navigation and a filtration unit.[6] A semi-autonomous system for collecting plastic debris in water bodies combines UAV and UUV technologies.[7] Unlike these environment-specific robots, my design targets plastic bottle recycling on various ground surfaces near human communities. Furthermore, Karin, Noor, and Zaman developed a Bottle Recycle Machine that rewards users for recycling bottles using an ultrasonic sensor for size recognition.[8] In China, a patented automatic bottle recycling machine incorporates multiple functions but lacks widespread usage due to reliance on user initiative My robot circumvents this issue by automatically identifying and collecting bottles without requiring user participation, significantly improving recycling efforts.

Hypothesis: I aim to develop a mobile bottle-recycling robot that can automatically identify and compress plastic bottles. My robot takes an innovative approach by incorporating more holistic functions of the bottle-recycling process, from identification and movement to transportation and compression. The entire recycling process can operate automatically at public sites, freeing manpower, enhancing practicality, and bringing a more complete and effective recycling result.

2. Methods

2.1 Theoretical Model

My robot will have four main mechanisms: an OpenMV camera that identifies bottles and detects their location, a chassis equipped with four Mecanum wheels that allow omnidirectional movement, a conveyor belt that transports the bottle to its cabin, and an electric actuator that compresses the bottle.

Omnidirectional movement means that a robot can move in any direction within a plane and rotate at the same time. To achieve omnidirectional movement, robots generally use two special wheels, the Omni Wheel or the Mecanum Wheel. Omni wheels and Mecanum wheels both consist of two main parts: the hub and the roller. The hub is the main support for the entire wheel, and the roller is a protruding unit mounted on the hub. The hubcap of an Omni wheel is perpendicular to the roller, while the hubcap of a Mecanum wheel is at an angle of 45° to the roller.

Illustrated in Figure 1, τ is the torque applied to the wheel, and r stands for the radius of the wheel. For the Omni wheel on the left, the magnitude of the reaction force of the floor on the roller along its axis is τ/r, and the magnitude of the force for the Mecanum wheel is $\tau\sqrt{2}/r$, assuming no roller bearing friction.

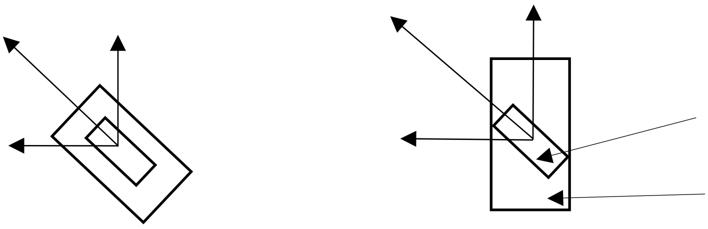
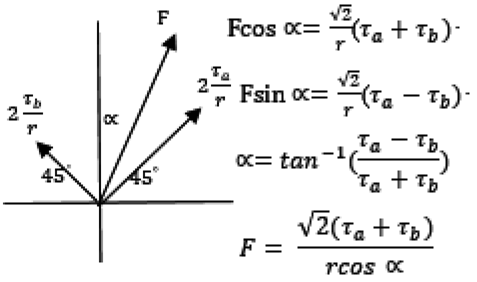


Figure 1: Reaction force of Omni Wheel and Mecanum Wheel along the roller's axis.

Illustrated in Figure 2 and Figure 3, τ_a is the torque applied to the left front and right rear wheels, and τ_b is the torque applied to the right front and left rear wheels. These vectors combine to give the force F acting at angle $\propto$.

By comparing the expression of F for Omni wheels and Mecanum wheels, it can be concluded that with the same wheel torque, Mecanum wheels have 41% more pushing force than Omni wheels. Since my robot incorporates many devices with a relatively heavy weight, the wheels need to have enough pushing force to withstand the weight of the robot. Due to this reason, I choose Mecanum wheels as the wheels of my robot.



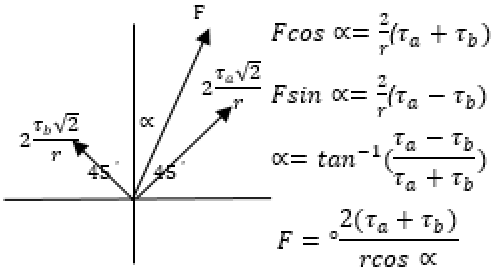
$$F\cos\propto = \frac{\sqrt{2}}{r}(\tau_a + \tau_b)$$

$$F\sin\propto = \frac{\sqrt{2}}{r}(\tau_a - \tau_b)$$

$$\propto = tan^{-1}\left(\frac{\tau_a - \tau_b}{\tau_a + \tau_b}\right)$$

$$F = \frac{\sqrt{2}(\tau_a + \tau_b)}{r\cos\propto}$$

Figure 2: Force of Omni wheel with the torque.



$$F\cos\propto = \frac{2}{r}(\tau_a + \tau_b)$$

$$F\sin\propto = \frac{2}{r}(\tau_a - \tau_b)$$

$$\propto = tan^{-1}\left(\frac{\tau_a - \tau_b}{\tau_a + \tau_b}\right)$$

$$F = \frac{2(\tau_a + \tau_b)}{r\cos\propto}$$

Figure 3: Mecanum wheel force with torque.

There are four main types of installation method for Mecanum wheels as shown in Figure 4. My robot selects the common O-rectangle method, by which the rotation of wheels can generate yaw axis torque, and the torque's arm of force is also longer. It is the most common type of installation method.

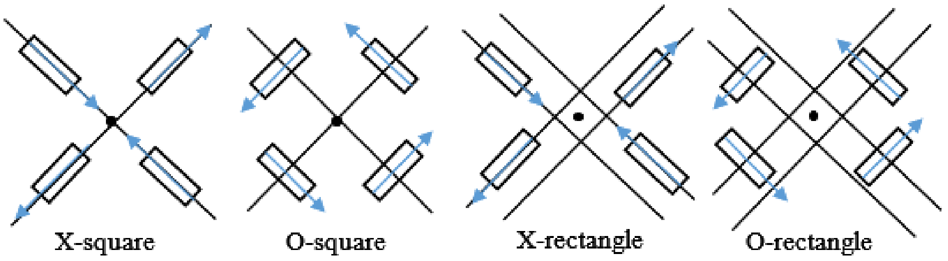


Figure 4: Four installation methods for Mecanum wheels.

2.2 Mechanical Structure

2.2.1 Overall Structure

Figure 5 is the demonstration of the robot's actual structure, from three sided views.


(a) (b) (c)

Figure 5: The overall structure of the robot from (a) Top view (b) Front view and (c) Side view.

2.2.2 Chassis and main body

The dimensions of the car's skeleton will be 400mm × 400mm × 260mm, and I am using aluminum alloy extrusions to construct the body, allowing the robot's movement and operations to be more stable and durable compared to 3D printing. The skeletal structure is made using four 400mm extrusions, four 340mm extrusions, and four 200mm extrusions. I then use corner pieces and screws to fix the extrusions together. Each Mecanum wheel is attached to the chassis by a flange plate and installed according to the O-rectangle method. Four motors are fixed onto the bottom of the chassis by L-shaped motor jointers. Figure 6 and Figure 7 offers a comparison of the robot's skeleton between the 3D design and actual model.

Figure 6: The 3D model of the car's body and chassis.

Figure 7: The real car body and chassis.

2.2.3 Conveyor unit

Figure 8 and Figure 9 illustrates the conveyor unit through 3D design and actual model. The detailed design of the 3D printed fixtures are displayed in Figure 10, directing to the component in the conveyor unit.

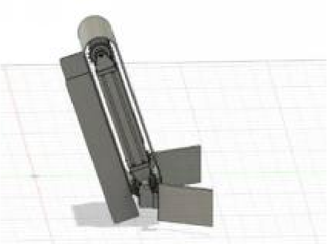


Figure 8: The 3D model for the conveyor unit.

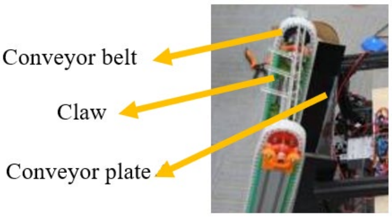


Figure 9: The real conveyor unit.

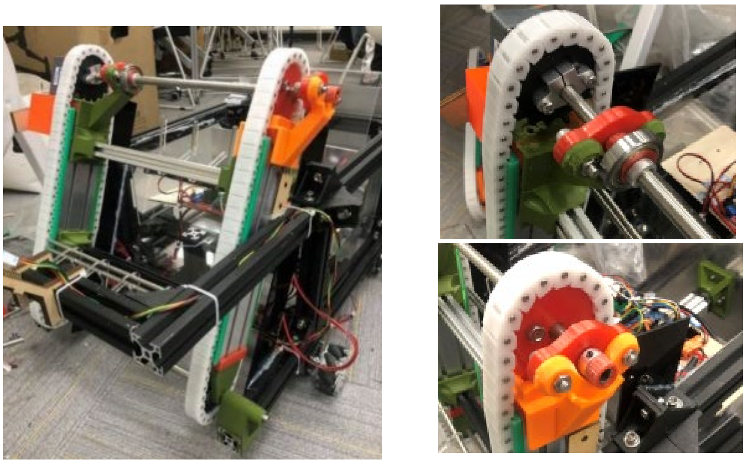


Figure 10: Design for the 3D printed parts used in the conveyor unit.

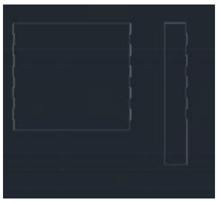


Figure 11: 2D design for the claw.

Figure 12: 2D design for conveyor plate.

The conveyor belt is constructed using aluminum extrusions, bearings, sprockets, and 3D-printed parts. The right and left units are fixed in parallel with two extrusions and corresponding 3D-printed components. Four pipes are inserted into the sprockets to allow simultaneous rotation of the two sides, with two lines of claws on the belt. Each claw has two holes for a tight fit onto the tube, as shown in Figure 11. The entire conveyor belt unit is attached to the car's body with 3D-printed fixtures, positioned 70mm from the ground to accommodate the largest common plastic bottle, ensuring claws are tangent to the ground during rotation.

Behind the conveyor belt is a conveyor plate unit made of one 340mm x 310mm and two 410mm x 65mm acrylic boards, as shown in Figure 12. The left and right boards are secured to the middle board using matching convex and concave cuts. This unit is parallel to the conveyor belt, also 70mm apart, with the plate's height preventing ground friction.

The conveyor belt rotates clockwise, moving the two lines of claws. When near a plastic bottle, the claws lift it and transport it to the conveyor plate. A foam strip is glued at the plate's edge to align with the claws. The loosely fixed sprockets allow the claws to push the bottle forward when slightly stuck against the foam, causing it to slide down an acrylic board into the chamber for compression.

2.2.4 Actuation unit

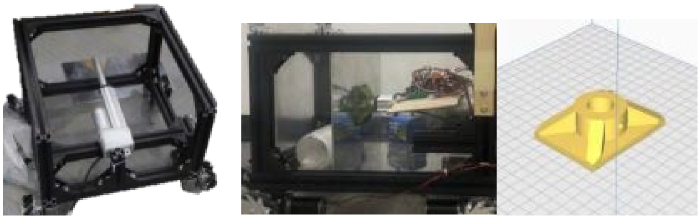


Figure 13: Illustrates the different components of the actuation unit.

In Figure 13, I first allow the rod of the electric actuator to extend to its fullest extent and record the location of the actuator where the tip of the rod just touches the back wall of the car. In this way, the bottle will be able to be compressed to the bottom at maximum extent, without breaking the back wall. The actuator is placed inside the car by fixing a 340mm long aluminum alloy profile and stabilizing it using a cable tie. The area of thrust surface for the single rod is too small. For the entire bottle to be compressed evenly, I add a 334mm X 210mm aluminum plate in front of the rod to increase the area of thrust surface. The aluminum plate is connected to the rod using a 3D-printed part.

2.2.5 Visual Module

I connect a 200mm long aluminum alloy profile to the front of the car so that the camera can extend outward to detect bottles in the front, demonstrated in Figure 14. The camera is fixed to the profile by creating a fixing board design, shown in Figure 15, which is then laser cut out on a wooden plate. The camera is installed at an angle of around 45, allowing it to detect bottles on the ground more easily.

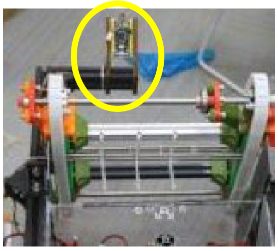


Figure 14: Installation of the camera.

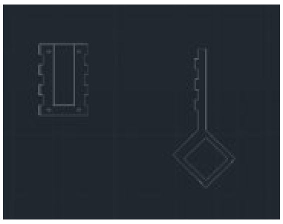


Figure 15: 2D design of fixing board for the camera.

2.3 Electronics

Figure 16 is a procedure illustration of how the robot's full process occurs. Blinker App is connected to the MEGA 2560 via the Bluetooth module so that each button controls the corresponding actions of the robot directly. OpenMV camera communicates with the MEGA 2560 via the visual module. Then, the MEGA board sends these messages to the different motors (four motors on the chassis, motor of the conveyor belt, and motor of the electric actuator). Each motor supplies energy to its connected device for it to perform various functions. The four Mecanum wheels can move forward, backward, leftward, rightward, rotate, or stop. The conveyor belt can rotate clockwise, counterclockwise, or stop. The electric actuator can push the rod outward or return it inward.

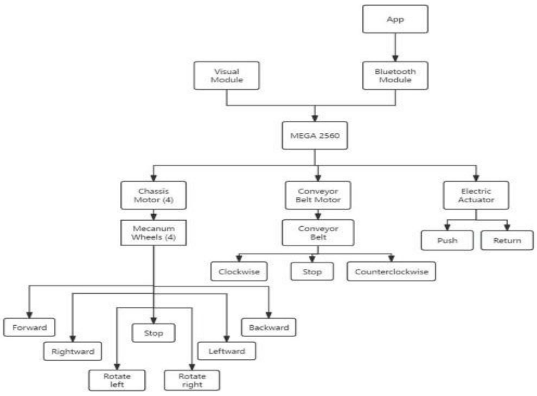


Figure 16: Installation of the camera.

2.4 Programming

2.4.1 Blinker

The Blinker app communicates with the Arduino board so that I could control the robot via the buttons. There are 14 buttons on the Blinker app page, each controlling a different action of the robot indicated by its corresponding function. The 7 grey buttons control different movements of the car, including moving forward or backward, translating leftward or rightward, rotating leftward or rightward, or stopping. The row of green buttons controls the movement of the conveyor belt, including rotating in a clockwise direction, rotating in a counterclockwise direction, or stopping. The final row of blue buttons controls the movement of the electric actuator, including pushing out the rod, retracting the rod, or stopping.

2.4.2 Motor control

Equations (1) to (4) demonstrate the movement of each wheel in omni direction, with the term v_x controlling forward and backward movement, the term v_y controlling leftward and rightward translation, and the term $\omega(a+b)$ controlling counterclockwise and clockwise rotation.

$$v_{w1} = v_y - v_x + \omega(a+b) \tag{1}$$

$$v_{w2} = v_y + v_x - \omega(a+b) \tag{2}$$

$$v_{w3} = v_y - v_x - \omega(a+b) \tag{3}$$

$$v_{w4} = v_y + v_x + \omega(a + b) \tag{4}$$

v_x denotes the velocity of the X-axis motion (positive to the right).

v_y denotes the velocity of the Y-axis motion (positive forward).

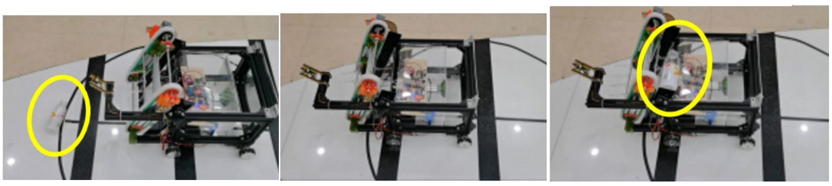
ω is the given wheel speed (radian/sec).

a is the horizontal distance between the center and each wheel.

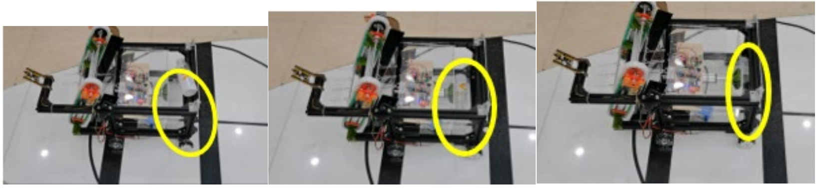
b is the vertical distance of that.

3. Results

3.1 Overall Experiment



Step 1: The camera detects the location of the bottle (left)
Step 2: The car moves toward the bottle (medium)
Step 3: The conveyor belt rotates and carries the bottle (right)



Step 4: The bottle slides down the acrylic board (left)
Step 5: The bottle falls into the chamber (medium)
Step 6: The actuator compresses the bottle (right)

Figure 17: Demonstration of the robot's complete recycling procedure.

Figure 17 demonstrates how a successful process of bottle-recycling operates. I then conducted three different experiments: movement of the car, identification of plastic bottles, and bottle transportation through the conveyor belt.

3.2 Movement of car

For ten trials, the car moves forward, moves backward, rotates left, and rotates right correctly according to my commands by clicking the corresponding button. The movement of translating leftward and rightward will be rarely used in the car's moving process, so the four functions in Figure 18-21 are enough for the car to move to the location of the plastic bottle.

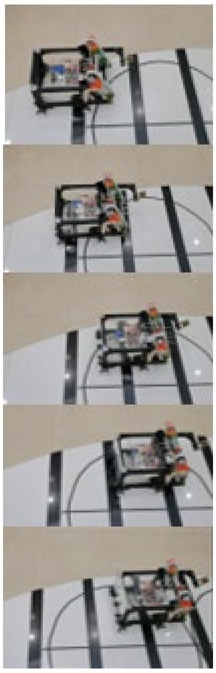


Figure 18: Continuous screenshots of the car moving forward.

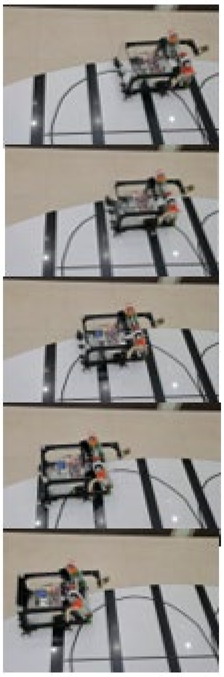


Figure 19: Continuous screenshots of the car moving backward.

Figure 20: Continuous screenshots of the car rotating left.

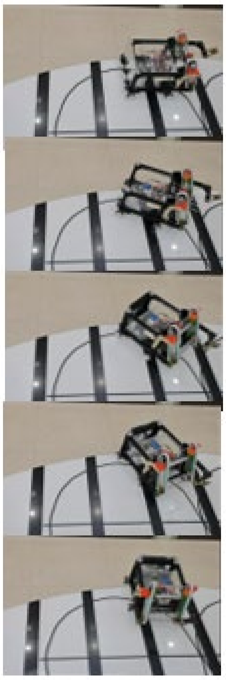


Figure 21: Continuous screenshots of the car rotating right.

3.3 Identification of plastic bottle

I choose one type of plastic bottle as my prototype. In total, I collected 131 photographs of the bottle from different distances, angles, and postures. After training the object detection model, the performance score is 86.5%, indicating a decent accuracy of identification.

3.4 Bottle transportation through conveyor unit

Table 1 illustrates the experiment result of 20 trials when transporting bottles through the conveyor belt. Succeed means the bottles are carried from the ground into the inner chamber successfully. Fails means the bottles aren't transported from the ground into the inner chamber.

Table 1: Result of bottle transportation experiment for 20 trials.

Trial 1	Succeed	Trial 6	Succeed	Trial 11	Succeed	Trial 16	Succeed
Trial 2	Succeed	Trial 7	Succeed	Trial 12	Succeed	Trial 17	Succeed
Trial 3	Succeed	Trial 8	Succeed	Trial 13	Succeed	Trial 18	Succeed
Trial 4	Succeed	Trial 9	Fails	Trial 14	Succeed	Trial 19	Succeed
Trial 5	Fails	Trial 10	Succeed	Trial 15	Succeed	Trial 20	Succeed

In the first ten trials, the claws occasionally got stuck at the brink of the acrylic board due to a decrease in conveyor belt rotation speed over time, which increased friction with the foam. Restarting the belt temporarily resolved the issue, but the problem recurred. To address this, I used a rasp to round the sharp tip of the claw, reducing friction. This adjustment led to more stable results, achieving eleven successful rotations in a row.

4. Conclusion and future works

The robot aligns with my theoretical model and performs four key functions: it features a camera with an object detection program to identify plastic bottles, a chassis with four Mecanum wheels for movement, a conveyor belt for transporting bottles to an internal chamber, and an actuation unit for compressing bottles. The process operates automatically via an Arduino board communicating with OpenMV and six motors, and can also be manually controlled using a Blinker app with 14 buttons for different actions. The robot effectively covers the entire plastic bottle recycling process, from identification to transportation and compression, reducing the volume of bottles for more efficient storage. It offers both automatic and manual operation modes, enhancing efficiency and economic value. The durable aluminum alloy construction adds to its robustness.

However, there are limitations. The diverse packaging of plastic bottles makes accurate identification challenging; I trained the model on one prototype bottle and plan to expand the dataset with 30-40 common beverage bottles. Additionally, the compression may not be complete due to insufficient force from a single actuator, so I plan to add another actuator for improved compression, ensuring synchronized operation to prevent deformation.

Currently, my robot automates the identification and transport of bottles, significantly enhancing economic value compared to traditional recycling machines. Future improvements in database size and compression efficiency will enhance its potential. This project aims to showcase innovative plastic bottle recycling methods, promote sustainable resource management, and support the development of a circular economy.

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