Trashformer

Noah Hathout, David Mok, Chaitanya Sai Nikith Rambha, Chaeson Sears II

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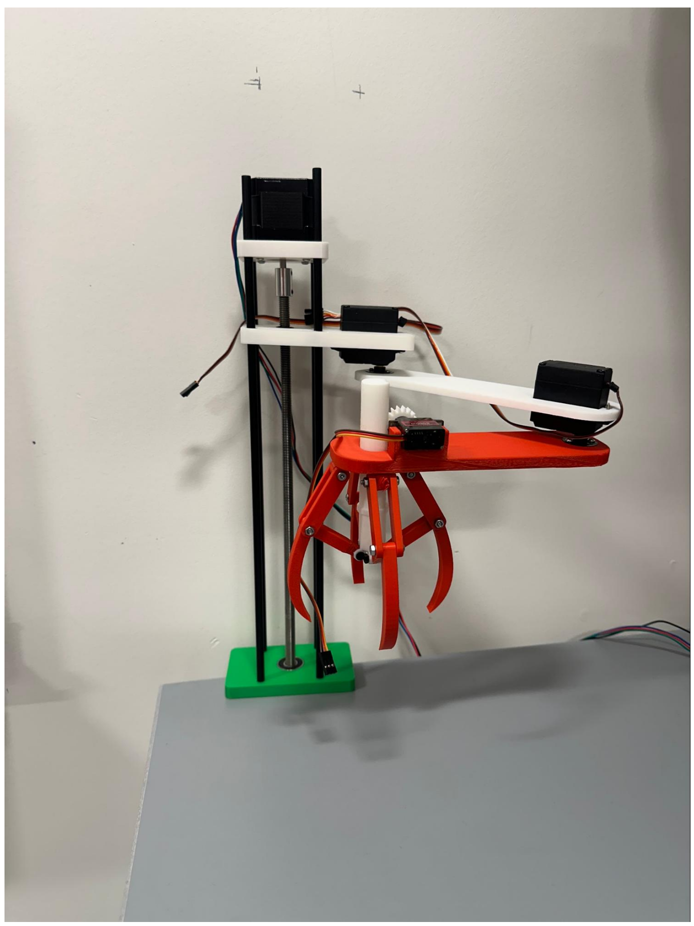

I. Introduction

A. Problem Motivation

Modern recycling systems depend heavily on consumers making correct choices in sorting their trash, but in reality this expectation often breaks down. Multi-bin recycling stations, though well intentioned, frequently confuse users with unclear labeling, overlapping material categories, and inconsistent bin layouts or consumers simply have no interest in making a proper decision. As a result, contamination in recycling streams has become a persistent global issue. A single misplaced item, such as food-soiled paper, mixed plastics, or organic waste, can spoil an entire batch of recyclables, leading to increased processing costs, lower material recovery rates, and more waste ending up in landfills. This challenge shines light on a clear issue: when recycling in public spaces error occurs from human behavior, which is naturally error-prone, rushed, or uninformed. As communities strive to meet higher sustainability standards, the need for a system that removes the guesswork for the user and ensures proper sorting is needed, that's exactly where the Trashformer comes in.

B. Background

Automated sorting technologies have emerged as a promising response to the increasing complexity of waste management and the rising cost of manual sorting. By reducing human reliance in the sorting process, such systems can dramatically decrease contamination rates, lower labor requirements, and improve overall material recovery efficiency. A well designed automated classifier ensures that recyclables reach the correct destination before they ever enter the waste cycle, ultimately creating cleaner output and more sustainable recycling loops. Beyond operational benefits, this technology also serves a social and environmental purpose making recycling easier and more engaging for everyday users. When people no longer feel uncertain or overwhelmed by multi-bin stations, they become more willing participants in sustainable habits.

C. Goal & Target Applications

This project aims to develop an autonomous, open-source tabletop sorting system capable of reliably classifying everyday waste items into four key categories: organic waste, paper and cardboard, plastics, and landfill/other. The system is designed to be compact, adaptable, and accessible, offering an efficient solution that can be integrated into public locations where waste is generated most frequently. By combining computer vision and classification, an adaptable end effector, and trajectory planning, the device minimizes user input and ensures accurate sorting at the point of disposal. The intended applications are environments where large numbers of people generate mixed waste such as airports, food courts or dining halls, where organic waste is commonly mixed with recyclables. In these spaces, a tabletop autonomous sorter can streamline waste management, reduce contamination dramatically, and encourage millions of users to engage in responsible disposal without extra effort.

II. Market Research & Comparison

A. Market Research

As waste generation increases globally and recycling facilities face mounting operational and labor pressures, the demand for automated sorting technologies has grown substantially. Industrial manipulator-arm systems have become central to improving recycling efficiency by automating tasks that are labor intensive or unsafe for human workers. Companies such as Waste Robotics, ZenRobotics, and Green Machine have established themselves as high level competitors in this domain, each offering high performance robotic sorting solutions built for large scale facilities. Despite the success of these systems in industrial environments, they remain inaccessible for public spaces creating a clear opportunity for compact, affordable, and autonomous sorting solutions designed specifically for consumer environments.

Each of these companies present different aspects of trash sorting robotics. Waste Robotics represents one of the most advanced players in the industrial sorting sector, focusing on AI driven classification systems integrated with custom grippers capable of handling irregular and heavy materials. Their robots are built for large mixed-waste streams commonly found in construction, demolition, or municipal recycling facilities. ZenRobotics follows a similar industrial scale but emphasizes extreme durability and heavy duty picking. Their robotic arms are designed to lift dense, irregular objects such as cement, rocks, bricks, and other debris found in construction waste streams. Green Machine's i-BOT system focuses on speed, offering some of the fastest pick rates available in the recycling industry. These robots rely on high speed manipulators and advanced detection systems to rapidly identify plastics, metals, fiber materials, and other recyclables as they move across industrial conveyor belts. Although these robots are each highly effective in their own right, they are nowhere near compatible for a public space. This is often due to their massive size, energy requirement, lack of general safety and impractical design for the target of this product. Instead the design needs to be optimized for its size, compactness, safety and low energy demands.

B. Market Comparison

A comparison across these industrial systems reveals common limitations. Their cost frequently exceeds \$150,000 per unit, and full installations can be significantly more expensive when factoring in conveyors, safety enclosures, and infrastructure upgrades. Their energy consumption is substantial, and their operational requirements assume a controlled industrial environment rather than spaces with unpredictable human-robot interaction. In contrast, the autonomous system developed in this project is intentionally designed for public deployment and consumer accessibility. With a prototype bill of materials totaling only \$73.00 in the first generation prototype, illustrated in Fig. 1 below, the device demonstrates that reliable autonomous sorting can be achieved at a fraction of the cost.

Its compact, tabletop form makes it appropriate for high traffic environments where proper waste disposal is essential but often performed incorrectly. Despite its simplicity, the system maintains full autonomy through integrated camera sensing, classification, and actuation, mirroring the functionality of industrial systems. Its adaptable end effector allows it to handle common everyday waste items rather than heavy industrial debris, and its simple open-source mechanical design ensures easier maintenance and user operation. Together, this market showcases a significant gap between high cost industrial systems and the absence of autonomous solutions for public environments. This proposed tabletop sorter directly addresses this gap by offering an accessible, open source, and user friendly system capable of improving waste sorting accuracy in high traffic locations where cross contamination is most likely to occur.

Category	Component	Qty	Notes	Approx. Price (USD)
Mechanical	PLA 3D-printed base plate	1	~150–200 g PLA	$3.00
	PLA Link 1	1		$1.50
	PLA Link 2	1		$1.50
	PLA Top plate	1		$1.00
	PLA Link bracket	1		$0.50
	8 mm Lead Screw (180 mm)	1	Stainless steel	$4.00
	6 mm Smooth Rods (180 mm)	4	Stainless steel	$6.00 (set)
	608RS Bearing	1	Standard skateboard bearing	$1.00
	M3 Bolts (assorted ~20 pcs)	20	For assembly	$3.00
Actuators	NEMA 17 Stepper Motor	1	Base prismatic joint	$12.00
	MG270 Servos	2	Shoulder & elbow joints	$18.00 ($9 each)
	MG90S Micro Servo	1	Gripper	$3.00
Electronics	Arduino Uno	1	Main controller	$12.00
	Misc. wires, connectors	—	Jumper wires / servo cables	$3.00
	Camera	1	Yolov10	$27.50
Total				$73.00

Fig. 1. Bill of Materials

III. System Overview

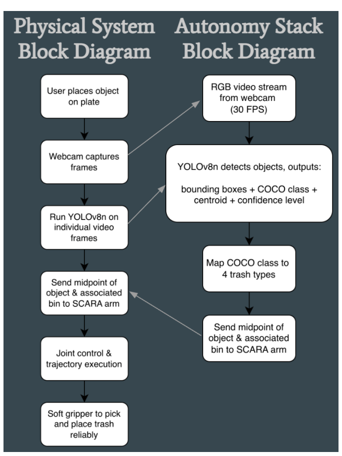

Fig. 2. Physical system and autonomy stack block diagram

A. Robot Kinematics

The input layer consists of the Denavit-Hartenberg (DH) parameters and the robot configuration. The DH parameters consist of the joint angle, the link length, the link offset, and the link twist. These parameters are used to define the geometric relationship between consecutive coordinate frames attached to each link of the robot. The robot configuration consists of the operational parameters including the axis working ranges and the physical arm segment lengths. The working range defines the allowable angular displacement for each joint which ensures that the robot operates within safe mechanical limits.

The control class contains the kinematics, trajectory, validation, and visualization modules. The kinematics module implements both forward and inverse kinematics algorithms using both geometric methods and numerical solutions using Jacobian-based iterative techniques. The trajectory module generates smooth motion paths between waypoints using interpolation methods. To ensure the generated paths are valid, the validation module performs reachability analysis to verify that the positions lie within the robot's workspace and the computed joint angles are within permissible limits. The visualization module renders the robot environment including the manipulator structure, sorting bins, workspace envelope, and motion sequences.

The output layer consists of the position data, the trajectory, and the simulation animation. The position data contains the current end-effectory Cartesian coordinates and joint angle values and the trajectory contains the complete path data as arrays of position coordinates. The simulation animation outputs a visual representation of the robot motion for documentation.

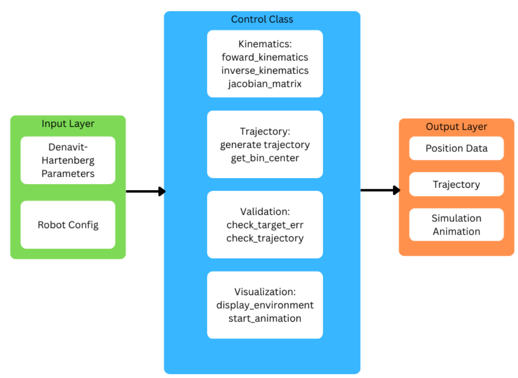

Fig. 3. Controls Block Diagram

B. Arm Design

The arm of the Trashformer is designed as a compact, lightweight 3-DOF SCARA-style manipulator, optimized specifically for small-scale pick-and-place operations associated with waste sorting. The arm consists of a prismatic vertical lift followed by a two-link planar mechanism, enabling a broad workspace while maintaining mechanical simplicity and robustness suitable for continuous demonstration environments. The CAD model of the robot is shown in Fig. 4.

The base of the arm houses the prismatic joint, which provides vertical translation for the entire SCARA assembly. This joint is constructed around a 2 mm-pitch 8 mm lead screw driven by a NEMA 17 stepper motor, allowing controlled vertical motion with high holding torque and minimal backdriving. Four 6 mm stainless-steel smooth rods guide the carriage and ensure stable, low-deflection motion along the Z-axis. The prismatic stage provides up to 160 mm of vertical travel, allowing the gripper to reliably reach objects of various sizes and adjust to different bin heights within the sorting area.

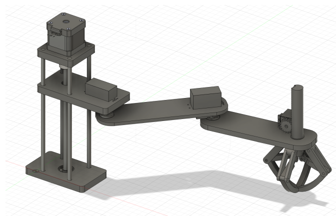

Fig. 4. CAD design of SCARA manipulator

Mounted on top of the prismatic carriage is the horizontal two-link SCARA mechanism, which provides the primary planar motion of the arm. Both links are 150 mm PLA-printed members, selected for their low weight, manufacturability, and sufficient stiffness for the required payload. Actuation is provided by two MG270 servo motors—one at the shoulder and one at the elbow—each capable of approximately 0°–180° of rotation. Together, these joints generate a total horizontal reach of 300 mm, allowing the Trashformer to access its entire sorting workspace while maintaining a mechanically simple and reliable configuration.

Both links are connected through vertically oriented servo joints, preserving the defining characteristic of SCARA arms where all rotational axes are parallel. This design ensures that the gripper maintains a consistent orientation throughout its horizontal motion, greatly simplifying the control strategy.

C. End Effectory Design

The trashformer features a rigid and soft robotic end effector modeled after the Pneu Net. The rigid body is an 8 link system that uses a MG90s servo motor attached to a pinion and rack allowing the claw to open and close, the claw can open up to a radius of 5 inches, allowing it to grasp objects with this radius or malleable items. The purpose of the rigid body is to serve as an effective prototype for the Trashformor, showcasing its complete utility while the soft end effector is in development. Fortunately this rigid claw can be substituted for the soft claw based on users preference. This model for the end effector is shown in Fig. 5.

Though the rigid claw is effective the soft claw is key when it comes to adaptability. This claw has a radius of 7 inches and also has the benefit of morphing around the items to conform to its shape and grasp more effectively. It does this by inflating each chamber along the appendages and curling inward. In order to manufacture this part a mold was designed and Dragonskin30 (silicon) was poured in until it cured. The base of the claw was coated in a rigid fabric that would not inflate during actuation, thus completing the soft claw as seen below in Fig. 6 along with a model of the mold.

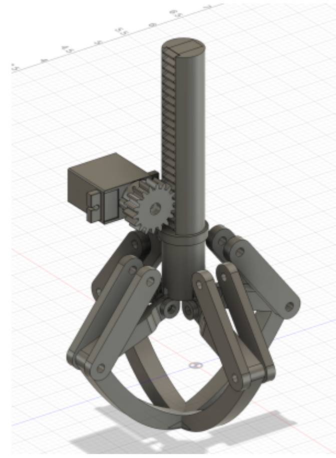

Fig. 5. CAD assembly of rigid claw

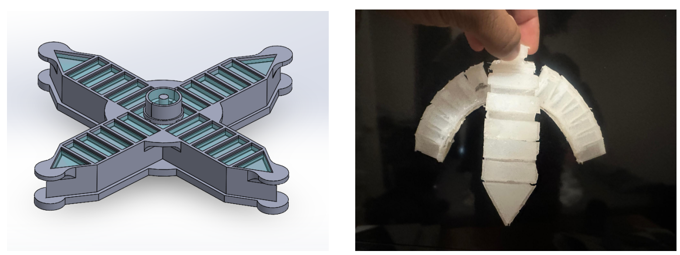

Fig. 6. Soft gripper with mold assembly

IV. Technical Contributions and Analysis

A. Vision System

Trashformer relies on a vision system that detects and classifies objects placed on the trash plate. This system then initiates the pick-and-place by communicating with the main arm. We 3D-modeled and printed a camera mount and trash plate, as shown in Fig. 7, to hold the Septekon[6] USB webcam directly above the center of the trash plate. The mount was designed around the following constraints: the mount and plate must be rigid enough to not move around, and the camera must be high enough to ensure sufficient detection and classification of numerous trash objects.

The video frames collected from the webcam (at 30 FPS) are then passed to YOLOv8n (nano), “an advanced algorithm for small object detection” [4] pretrained on a COCO dataset which recognizes most common objects in real time. The nano version of YOLOv8 was chosen for this project due

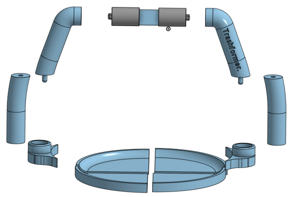

Fig. 7. Full CAD design of camera mount and detection plate

to its reliability, small size and low computational cost. YOLOv8 has multiple versions and it's easy to scale up to any of the more powerful versions (s, m, b, l, or x [5]) in Trashformer without touching the rest of the system pipeline. Since there were no pretrained datasets where the annotated labels or classes map to recycling bin categories, we introduce a category routing layer. We took the 80 COCO classes or labels and rerouted them to four recycling bins: organic waste, paper/cardboard, plastic, and landfill/other (default). One limitation of using the COCO dataset is its limited variety of detectable/classifiable objects. An example of this in Trashformer is that the paper/cardboard bin currently will stay empty due to there being no appropriate COCO classes that could be rerouted to that bin category. Fig. 8 displays a screenshot of YOLOv8n running live on the setup with the rerouted bin category labels overlaid.

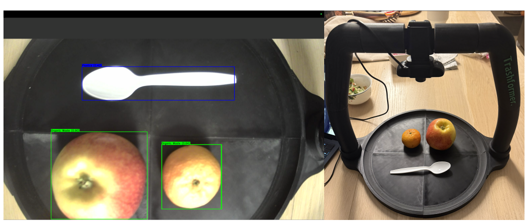

Fig. 8. Screenshot of webcam livestream with YOLOv8 overlaying bounding boxes, rerouted labels, and associated confidence levels

B. Kinematics

The coordinate frames follow the standard SCARA convention given in Table I.

TABLE I
JOINT VARIABLE TABLE

Joint	Type	Variable
1	Prismatic	$z = d_1$
2	Revolute	θ_2
3	Revolute	θ_3

C. Forward Kinematics

The forward kinematics of the SCARA manipulator describe how the joint variables one prismatic and two revolute map directly to the position of the end-effector in Cartesian space. This relationship forms the foundation for motion planning and simulation, enabling the robot to determine where the gripper will be located based solely on its joint inputs. The following equations express the end-effector's position (x,y,z) in terms of the link lengths and joint angles.

$$x = L_1 cos\theta_2 + L_2 cos(\theta_2 + \theta_3) \tag{1}$$

$$y = L_1 sin\theta_2 + L_2 sin(\theta_2 + \theta_3) \tag{2}$$

$$z = d_1 \tag{3}$$

D. Inverse Kinematics

Inverse kinematics provides the mathematical framework for determining the required joint values that allow the end-effector to reach a desired point in space. This is essential for autonomous pick-and-place tasks, where the robot must compute feasible shoulder, elbow, and prismatic motions to achieve precise object interaction. For the SCARA architecture, the IK solution is analytically tractable due to its planar geometry, resulting in closed-form expressions for both rotational joints and the vertical prismatic displacement. These expressions were used to generate smooth trajectories throughout the robot's reachable workspace.

Define:

$$r^2 = x^2 + y^2 \tag{4}$$

Elbow angle:

$$cos\theta_3 = \frac{r^2 - {L_1}^2 - {L_2}^2}{2L_1L_2} \tag{5}$$

Shoulder angle:

$$\theta_2 = tan^{-1}(\frac{y}{x}) - tan^{-1}(\frac{L_2 sin\theta_3}{L_1 + L_2 cos\theta_3}) \tag{6}$$

Vertical Motion:

$$z = d_1 \tag{7}$$

E. Denavit-Hartenberg Parameters

To formally represent the geometry of the Trashformer's SCARA arm, the Denavit–Hartenberg (DH) convention is used to assign coordinate frames and define the spatial relationship between consecutive links. This standardized formulation simplifies the derivation of both forward and inverse kinematics by expressing each joint using four minimal parameters: link length, link twist, joint offset, and joint angle. Table II below summarizes the DH parameters for the Trashformer's 3-DOF P–R–R configuration.

TABLE II
DH PARAMETER TABLE

Joint i	a_i	α_i	d_i	θ_i
1 (P)	0	0	d_1	0
2 (R)	L_1	0	0	θ_2
3 (R)	L_2	0	0	θ_3

F. Trajectory Planning

The simulation in Fig. 9 shows the trajectory planning of the robot placing a trash item in each of the four bins. The green dot on the right represents a trash item from the trash plate. After it is classified from the vision system, it will be assigned the associated bin to be placed into. The waypoint mapped to the robot is the center of the assigned bin to ensure that the trash item is successfully placed inside the bin. Through the control class from Fig. 3, the robot kinematics will be computed based on the current state of the robot and the target waypoint. Once the robot has successfully placed the trash item in the assigned bin, the next assigned waypoint is the trash plate to retrieve the next trash item. This process keeps repeating until there is no longer a trash item detected on the trash plate.

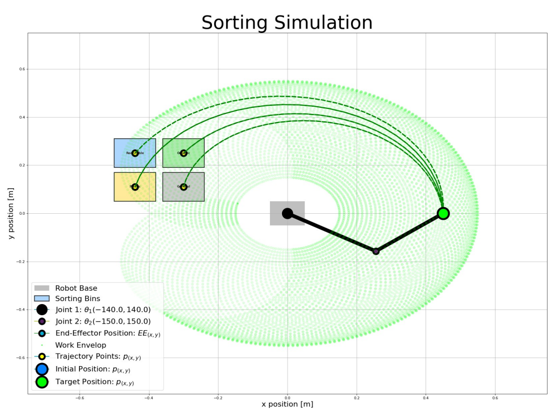

Fig. 9. Simulation of robot sorting into each bin

G. Limitations

Despite Trashformer's vision system working, there are definitely still limitations and failure points that can be improved in further versions and prototypes of Trashformer. We already discussed the limited number of predefined COCO classes which may label unknown objects with the default bin category "landfill/other". Another limitation to the project, in its current state, is that there is no way to handle numerous objects placed and detected on the detection plate. One trash object at a time is unrealistic in application settings; it is necessary to develop an algorithm to choose and order the objects (likely in a FIFO (First-In, First-Out) buffer) so the arm can perform the sorted pick-and-place one object at a time. The last of the limitations and failure cases of Trashformer's vision system pertain to the height, angle, and leg positions of the 3D-printed camera mount. Because of the static height of the camera, and its location directly above the centroid of the detection plate, a natural height limit is set on the trash objects (e.g. most water bottles tend to break this height limit). The camera is positioned so that the lens is pointing straight down at the centroid of the detection plate, which may limit detection accuracy by only providing a top-down view of the trash objects. This could be improved by shifting the camera mount away from the centroid of the detection plate, and increasing the angle of the camera so it is not pointing straight down. Finally, the position of the legs which hold the camera at its height may interfere with the movement of the arm. As you can see from Figure xx (sorting simulation), the arm will perform a "sweep" motion between the detection plate and the trash bins. The sweep-like motion may collide with one of the legs of the camera mount, therefore a redesign of the legs and camera mount would be necessary to mitigate this risk.

V. FUTURE WORKS

Though the Trashformer will perform a suitable task when deployed in public spaces, there is room for improvement. A few of the mechanical improvements include structural integrity, camera positioning, and soft gripper design. Improving the strength and rigidity of the arm will allow the robot to move with reliability and assure public efficiency. As mentioned earlier, Trashformer's camera is currently positioned too low, so increasing the height, and maybe even the viewing angle, will increase its field of view and make it more effective. Additionally, the camera stand may be in the way and cause collisions with the arm during initial trash pick-up from the detection plate. The company intends to improve the design of the soft end effector, optimizing it for various trash by field testing different prototypes. Advanced sensing can also be added increasing the Transformers speed and payload capacity. This can be done by integrating force sensors, giving feedback to the system and allowing the arm to adjust its grip manually for optimal control. Each motor can also give feedback and adjust its speed accordingly to provide quick and uniform motion throughout operation. Lastly, the Trashformer needs to be scaled to fit the needs of a public consumer. The current prototype is meant for a small showcase and demonstration, so in order to sell the Trashformer it should be optimized for a public space. This optimization includes increasing the size of the Trashformer and the safety parameters, assuring safe human robot interaction.

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