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Robot-assisted automated sorting techniques for plastic recycling

Doris Aschenbrenner, Cecilia Colloseus, Rana Khoury, Nicole Fangerow*

Aalen University - Technology and Economics, Beethovenstraße 1, 73430 Aalen, Germany

* Corresponding author. *E-mail* address: nicole.fangerow@hs-aalen.de

Abstract

This report discusses the current state of the art of robot-assisted sorting and separation systems in waste processing for the recovery of recyclable materials. The sorting methods addressed here are limited to the waste disposed of by households and include the sorting of pre-sorted municipal waste, e. g. plastic sorting. The focus is on the challenges of proven material recovery facilities and why manual sorting is still a necessity for efficient waste sorting. Solutions are sought to eliminate the employment of humans partially or completely for waste sorting. Suitable gripping components are to be found since one of the biggest challenges in waste sorting is gripping objects with different shapes, sizes, weights, positions, and materials. Not only existing techniques in the waste industry are addressed, but a broad spectrum is searched for possible universal grippers. This paper aims to provide a comprehensive overview of the state-of-the-art robotic systems in the waste industry and presents different types of grippers that can lead to a possible solution to the described challenge. Through an evaluation system, the presented grippers were compared, revealing that the combination of individual gripping mechanisms is promising for waste handling. Furthermore, it was found that sufficient degrees of freedom in the wrist area of a robotic arm can facilitate better gripping quality.

Keywords: *Waste management; recycling, robot-assisted sorting; grippers*

1. Introduction

To recycle waste, especially paper, metal, and plastics, it has to be sorted by type, color, and size. Waste sorting is implemented in medium to large material recovery plants, which use automation techniques and partial manual sorting. At present, one of the most important issues in waste recycling, especially in the field of plastics and packaging recycling, is sorting accuracy. The more accurate the sorting, the purer the recyclable material will be, which in turn contributes to an optimal circular economy. The EU recycling targets create new challenges for EU member states around material recovery plant technologies. The target set by the European Parliament is to recycle at least 65% of European packaging waste by 2025. To meet these targets, the expansion of material recovery facilities in the form of new technologies is essential, as the ever-growing population means that the amount of waste is also constantly increasing. Accordingly, the material recovery plants must sort larger quantities of the waste, not only faster but also more precisely, to meet the requirements of the European parliament.

For the recovery and recycling process, waste is usually transported on a conveyor belt passing through various sorting and separation processes. Manual sorting is still used in most material recovery facilities, which entails a significantly lower

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separation performance and is not cost-efficient. One of the main reasons why manual sorting cannot yet be eliminated from waste sorting and separation plants is that manual sorting contributes to achieving the purity levels of recycled material in most cases. This is why without manual presorting, the number of impurities in the recycled material is much higher. Another reason, why manual sorting is employed, is that it tackles the problem of detecting multi-component materials, such as films, among others, which are included in plastic mixtures [1]. Therefore, it is crucial to further develop existing sorting and separation systems to improve sorting performance. In this paper, a systematic literature review on the topic is presented.

2. Methodology

This study poses the following four questions: (1) Which kinds of grippers are currently on the market and which grippers are discussed in literature? (2) Which of these grippers can be used for plastic waste gripping? (3) What are the criteria for evaluating grippers for plastic waste gripping? And (4) Which gripper solution is best for gripping plastic waste? Market research of proven robotic systems for plastic sorting was determined using publicly available information on manufacturers' websites. Furthermore, a search was conducted using the Google, Google Scholar, and Science Direct databases using key terms such as "gripper components," "gripper components for flexible materials," "universal grippers," "plastic sorters," "plastic sorting machines," "plastic recycling," "robotic systems," and "sorting and separation systems." It is expected that these keywords elicited a representative sample of relevant articles in these areas, but this cannot be guaranteed. The search was conducted in English and provides information from the last five years since similar reports were published. This information can also be used to assess whether the challenges reported by MRFs in our survey (see next paragraph) can be addressed by currently available or emerging technologies. The gap between the sorting efficiency reported by manufacturers and the sorting efficiency achieved in MRFs is also identified and reported here.

3. State-of-the-art of robot-assisted automatic sorting and separation systems for waste recycling.

Proven robotic systems for waste sorting, especially in the area of light waste such as packaging materials, include the Fast Picker, by the Finnish company ZenRobotics, which can demonstrate a purity level of 99%. The robot arm of the Fast Picker is equipped with a suction gripper and is controlled by a control system and sensor units. The Fast Picker system is capable of up to 80 accesses per minute in a working area of 1200 mm by 600 mm, with a maximum object size of length 400 mm, width 400 mm, height 240 mm, and a maximum weight of 1 kg. More detailed information about the robot arm and its degrees of freedom are not mentioned. [2]. Another possibility to sort different types of waste, such as plastic and metal containers, paper, cardboard, cartons, and residual materials, is offered by the Max-AI® AQCs. It offers selflearning using deep learning and can sort up to 80 accesses per minute, on a working space of 1600 mm. It has two robot arms with vacuum grippers, for which no further details were given. The possible object dimensions are a length/width of 250 mm, a height of 150 mm, and a weight of 250g [3]. A third system is the AI-controlled AMP Cortex™ Dual-Robot Systems ("DRS") produced by the American company AMP Robotics, which focuses on recycling municipal solid waste, especially paper and plastics, as well as electronic scrap and construction waste. The high-speed recycling robot features two robotic arms with vacuum grippers that sort at a rate of 160 pieces per minute [4]. The maximum dimensions are not documented here. Finally, also equipped with a vacuum gripper is the German robotics sorting system RoBB by Bollegraaf, which has an AI-guided vision system. This vision system is equipped with several optical sensors, such as height, nearinfrared, and RGB cameras, which make it possible to use it for different materials, such as plastic, paper, and others [5]. Again, the possible dimensions, details about the range, and information about the robot arms are not documented. Apart from vacuum grippers, two-finger robot grippers are also used in waste sorting. Examples are the sorting systems Heavy Picker by ZenRobotics [6] and SELMA by the Swedish company OP Teknik [7]. Both systems use deep learning to identify objects and can move different materials, such as wood, metal, plastic, and stone. The Heavy Picker can move maximum object properties of height of 1500 mm, a width of 500 mm, as well as a weight of 30kg and is therefore used for sorting industrial waste. The working range of its robot arm is 2700 mm by 2000 mm, although it is not mentioned what kind of robot arm it is. Unlike the Heavy Picker, SELMA's system can also be configured to handle objects such as light bulbs. The possible dimensions, details about the range, and information about the robot arms are not documented. The performance of the gripper arms is with both systems 30 to 40 accesses per minute, significantly below the possible performance of vacuum grippers. For AI-assisted robotic systems used in the field of waste sorting, one of the biggest challenges is the gripping ability of diverse objects to be sorted. In this regard, the grippers required for this purpose must be universally applicable, as objects with different shapes, positions, masses, and materials must be gripped [8]. Since the proven robot systems work through vacuum grippers that are specialized for light objects with flat surfaces [9], or two-finger grippers whose performance is very low, the remainder of the report will focus on finding a possible solution for the challenge described.

4. Grippers for robotic systems of waste sorting

An overview of possible selection criteria for robotic grippers and arms is provided for further discussion in the subsequent presentation of the components. Robotic grippers can be divided into three different categories: Mechanical finger grippers, vacuum grippers, and universal grippers [10]. Since well-established robot systems all use vacuum or two finger grippers, the basic structure, as well as their advantages and disadvantages, are presented below. Subsequently, other types of grippers for use in waste sorting are presented, which are seen as possible solutions to the challenge of gripping diverse objects. Finally, various robot arms that contribute to a secure grip are presented.

4.1. Selection criteria for robot grippers for handling waste

The problem of designing a solution for a particular gripping task lies in the choice of a suitable gripping mechanism and its kinematics [11]. For the selection of possible robotic gripper solutions, it is important to know which parameters are necessary for the design and construction of a robotic gripper for handling waste. Firstly, the parameters of the objects to be gripped must be considered, such as the dimensions, since the size ratios vary when sorting waste. Other parameters are the shape and surfaces of the objects to be gripped, which also show great variation, especially when it comes to separating plastic waste. Also to be considered about the surface is that trash is usually not clean objects. Rather their surfaces are dirty, which influences the safe grasp of a gripper. The variations in the dimension and shape of the objects to be gripped also lead to different object weights, which must be considered as a parameter, too. On the other hand, the accessibility of the objects to be gripped must be considered as a parameter. Grasping objects that lie on top of or inside each other requires different strategies than grasping objects individually without further restrictions. The environment in which a gripper must operate is important, too. Conditions such as a dusty environment must be taken into account [9]. In addition, economic aspects like cost and efficiency, which include speed and sorting accuracy, are also of great importance. In summary, a solution for a gripper should be chosen according to the following parameters:

- Grasping capability of a wide array of object dimensions and weights, and
- Handling of different object shapes and surface characteristics.

The following parameters are relevant for the combined robot arm:

- Handling capability of a wide array of weights,
- Flexibility of movement options and possible reach, and
- Possible robot speed and sorting accuracy.

Additionally, both the gripper and the robot arm should be energy-compatible, cost-effective, environmentally compatible, and low maintenance.

4.2. Proven gripper systems (Vacuum- and Two-finger-gripper)

The vacuum gripper consists of two components: The vacuum cup, which is used as a pick-up device, and the vacuum generator. The vacuum cup is generally made of polyurethane, which allows it to withstand temperatures ranging from -500°C to +200°C. The vacuum cup can be described as a type of suction cup, which is designed to create an airtight environment on the surface of the object to be gripped to lift it [12]. The vacuum gripper is prone to error, due to, e.g., misaligned suction cups that do not achieve an airtight seal. To create the vacuum, it is advantageous if the object’s surface is smooth. In the case of curved and sharp-edged object surfaces, there may not be sufficient surface contact, and the suction pad may not achieve the necessary force to lift the object. Furthermore, contamination of the object’s surface can cause problems when generating the vacuum. In addition, the vacuum gripper is not resistant to irritation in dusty environments, as the airlines of the vacuum generator can get clogged [12]. Nevertheless, the use of vacuum grippers offers both a cost-effective and robust solution for object movement, which is why this system is used in many industries [13]. A two-finger gripper mimics the "two-finger grip" of a human, which is considered the easiest and most effective. lucrative gripping design not only in human gripping but also in industrial gripping. Since most manipulation and assembly tasks can be performed by two-finger grip configurations, the mechanical two-finger gripper is among the most widely used gripping systems in the industry [14]. The basic structure of a two-finger gripper consists of two fingers, the gripping mechanism, and the actuator. The fingers, as in humans, have fingertips that contact the object surface to be gripped. They come in rigid, rigid-jointed, or elastic versions and can move parallel or at an angle to each other. The area between the fingers determines the size range of the objects to be gripped. The gripping mechanism establishes a transmission between the fingers and the actuator, which is the energy source of the gripper. The mechanism size, gripping configuration, and transmission characteristics of the gripper components affect the possible capabilities, such as gripping force and gripping size of the gripper [11]. Since the two-finger gripper already exists in every possible variation, it is only necessary to find a suitable mechanism with the right kinematics for the coordination of municipal waste.

4.3. Presentation of other robotic grippers that are seen as a possible solution for use in waste sorting.

For gripping irregular objects, universal grippers are normally used [9] Further studies attempt to merge different combinations of the individual gripper categories (mechanical finger grippers, vacuum grippers, and universal grippers) in order to take advantage of their respective benefits. Techniques of these composite gripping mechanisms are also presented and referred to as combined grippers.

Universal gripper

The universal gripper developed by A. Balaji, for example, is capable of gripping irregular objects in any orientation. The gripper is constructed from a thin, non-porous, circular membrane containing a granulate (here coffee powder). The function of the gripper is controlled by pressure in the membrane. When minimum pressure is applied, the granules in the bag are positioned accordingly, so that they take on an object's structure when they are pressed against it. When the pressure is removed from the membrane, the granules loosen, and the grasped object is released [15]. The study shows how a water bottle is lifted. No precise information is given about possible parameters to grasp objects, but this study can still be used to create a viable solution for universal object grasping. A similar design is used by the developers of the "bloodworm-inspired soft gripper", which employs the principle of the water snake wiggly (WSW) toy. This WSW is a cylindrical silicone tube that corresponds to the shape of a torus. The actual ends can take irregular shapes due to the fluid pressure, that allows the torus-shaped WSW to turn outside to inside or vice versa. With this flexible structure, the gripper can curve around an object when adapting to it. Static friction is created between the membrane and the object's surface, causing the object to be gripped and held. The gripper's benefits are in its flexibility, and its ability to easily grip different types of objects. Nuts, paper, and a beverage can, among others, have been successfully held during the experimentation [16]. The principles of the two aforementioned universal grippers with membranes allow many different shapes to be gripped, regardless of their location, surface area, and size. A disadvantage of this principle of universal gripper is that the objects to be gripped must be freely accessible and not superimposed. The studies do not describe how stable the surfaces of the membranes are and whether they can be easily damaged by pointy objects. Another flexible gripping option is the origami-inspired reconfigurable suction pad, which can effectively fold into three shapes, using compact actuators made of a shape memory alloy. The gripper consists of soft and rigid components to grip different shapes and sizes and a maximum weight of 5 kg. In the study, the gripper successfully grasped various objects, including a container with a large flat surface, a light bulb, a 9-V battery, an office pen with a diameter of 10 mm, and a Toblerone packaging. Under the contraction of the vacuum pressure, the presented prototype still faces limitations in sealing and suction forces. The proposed solution for this is a second functional material layer to strengthen the system, which can make this system relevant in the future [17].

Combined gripper

The design concept of Bonello for a gripper that is intended to sort waste involves a combination of clamping and vacuum grippers [18]. This gripper implements a vacuum suction cup between the two jaws of a synchronous, double-acting pneumatic gripper. The vacuum suction cup is used to support the two-finger gripper but can also be actuated alone by extending it via a movable tubular element. The gripper is mounted on an industrial robot, which uses optical sensors to detect the positions of the objects to be grasped. The combination of vacuum and two-finger grippers allows various materials and object shapes to be grasped, such as newsprint, plastic containers, beverage cartons, plastic bags or metal cans. The dimensions of the objects should be between 40 mm and 110 mm and may not exceed the maximum weight of 0.5 kg. Complications of the gripping process arise if the objects to be gripped are not freely accessible or if the objects are too porous or perforated. By combining the two-finger gripper and vacuum gripper, an increase in stability during holding and moving the objects can be realized compared to the individual gripping methods [19]. Sadeghian presents a triple-gripping system for waste sorting [20]. It utilizes three different mechanisms to grasp and manipulate various types of materials. The first one deploys nano-polyurethane adhesive gels, which provide a strong and durable bond for gripping a wide range of materials and even irregularly shaped objects. The gels are activated by a trigger mechanism, allowing for precise and controlled application. The second mechanism is that of the aforementioned vacuum gripper, which is useful for grasping objects that may be difficult to hold with traditional suction cups. The third mechanism employs radially deployable claws, which can be independently activated to provide a secure grip on objects with a small or limited gripping surface. The three gripping mechanisms can work independently as well as act together to support each other during grasping and holding. By integrating these three mechanisms, the triple-mode gripping system can handle a wide range of materials, from small and irregularly shaped objects to large and smooth objects. Depending on the mechanism, the maximum weight of the objects to be gripped is limited to 2.1 kg (claw mechanism), 1.03 kg (vacuum suction mechanism), and 0.7 kg (nano-PU adhesive mechanisms). Objects with a higher weight, than 2.1 kg were therefore classified as intangible. The object size is limited to a minimum of 12 cm and a maximum of 22 cm for the claw mechanism. For objects that are too small, such as a rubber band or a metal nut, the nano-PU bonding mechanism has problems releasing the objects, which is why they were classified as non-releasable. The different gripping mechanisms are controlled by a deep learning algorithm, which allows the system to adapt to different types of objects and optimize its grasping strategy.

4.4. Robot arm

Robots must have low energy consumption and also work quickly to save costs during sorting. For this reason, systems such as the Delta robot are often used for pick-and-place operations, as they are not only fast and cost-effective but also dust-proof and easy to install [21]. The parallel arm robot normally has at least three arms that form a triangle, reminiscent of the Greek letter Delta (Δ). The arms are suspended from the ceiling and connected at their ends to a smaller triangular platform where the gripper is located. The arms interact with each other and, together with the platform, form a closed kinematic chain that allows degrees of freedom in the X, Y, and Z directions, with the small plate always remaining parallel to the upper platform. This means that, by default, this robot does not allow rotation of the gripper and it is always parallel to the conveyor belt. The advantages of the Delta robot, besides its speed and cheap acquisition, are its aiming accuracy and flexibility of possible gripping components. Depending on the design, a maximum load of 15 kg can be achieved. The disadvantages are a relatively limited reach of 1600 mm, and a low mobility and flexibility [22], which provide for a limitation of the gripping orientation. Since the gripping decision depends on the approach direction and orientation, among other factors, a robot arm with wrist degrees of freedom is needed for an optimal grip. These degrees of freedom to control the end effector orientation can have a positive impact on the gripping quality, especially for vacuum grippers [23]. FANCU's M-2iA/3AL 6-axis delta robot has a 3-axis wrist, which provides maximum maneuverability, has a reach of 1130 mm, and can move a maximum load of 3 kg. The speed at which this robot can perform is not documented [24]. Gantry robots are also popular for pick-and-place operations. The simple design allows three degrees of freedom in the X-, Y-, and Z-axes and is similar to that of a milling machine. This design variant also allows additions to change the orientation of the gripper by extending the structure with rotary axes on the robot's wrist. The space-saving design of the robot's linear axes can be produced in a wide range of sizes, making it easy to integrate into overall systems. Furthermore, gantry robots can achieve high accuracies due to their precise manufacturing [25]. The company KUKA offers a wide portfolio of several gantry robots. The smallest variant can move a maximum nominal load of 16 kg in a workspace of 1500 mm. No speed is documented for this arm either [26]. A third variant is the jointed-arm robot, which has a large number of offers due to its popularity and is positioned with a wide range of models. The models can have an arm's length of less than one meter up to several meters and move payloads from 100 g to several tons. Normally, joint-arm robots are manufactured with six axes, allowing them to offer good accessibility. Due to its anthropomorphic kinematics, the robotic arm can be operated very well in workplaces designed for humans and similarly perform the work of humans. A disadvantage of the robot is the insufficient accuracy, which can be in the millimeter range [25]. One example is the HORST600 6-axis robot by Fruit Core Robotics, which has a maximum range of 584 mm and moves objects weighing up to 3 kg. The arm is versatile and can be combined with different grippers, but again it is not documented at what speed the arm can move [27].

5. Future perspectives and discussion

With regard to future studies of flexibly deployable robotic systems for waste sorting, a combination of the different gripping mechanisms is recommended, as is the case with Sadeghian. By activating all three gripping modes simultaneously, 96.96% of the items could be gripped [20]. Additionally, optimization of the gripper is seen when it is augmented with a suitable robotic system and a deep learning method to detect optimal gripping postures. Possible extensions may include the following: For the robotic system, a robotic arm with additional degrees of wrist freedom is recommended, such as FANCU's M2iA/3AL 6-axis delta robot. Since the degrees of wrist freedom contribute to flexible gripping orientation, more suitable and safer grips can be placed on the objects. Furthermore, compared to the gantry or jointed-arm robots, the Delta robots are more cost-effective, more accurate, and dust-proof, making them more resistant to the environment. For solid waste detection and sorting on fast-moving conveyors, high-speed sensors and mechanisms are needed to provide visual information about the contact area and possible gripping patterns, among other things. Most sorting units apply deep learning methods to detect possible grasping patterns. Since the input data of the deep learning model is usually limited to images, the gripping parameters (e.g., orientation, position, and opening width of the gripper) must be mapped onto the image. The grasping parameters are represented by grasping rectangles. Using a search algorithm, possible individual gripping postures on the object to be gripped are visualized on the input data. By passing these rectangles to the neural network, the optimal grasping posture of the object can be found. Through this deep learning method, the accuracy of robot grasping can be raised from 70% to 90% [28]. Although sensors analyze the shapes of the waste, it is difficult to find the best location for grasping. Sometimes misgrips occur due to the compression of the required grasp parameters into grasp rectangles. To determine a fixed grip on random shapes, an algorithm for suction pads based on a 3D point cloud for sorting plastic waste is generated by Sangwoo [23]. The 3D point cloud is scattered 3D points with color information. The information for generation comes from RGBD cameras that capture and compare color and depth of? images. This method requires geometry groups based on object clusters to distinguish interior surfaces from edges. If clustering is not possible, different surface parameters and object curvatures can be used to segment object surfaces. Since the method requires detailed computations to create possible handle patterns, the average computation time for a single object is 434 ms. However, this method leads to successful grasp patterns even for random objects without known parameters.

6. Conclusion

The main challenge of the proven robotic systems in the field of waste sorting lies in the properties of grasping irregular objects. The results show that many different approaches can lead to a solution to this challenge. Universally applicable grippers or combinations of individual gripping mechanisms can grip materials with different shapes, sizes, and weights. The gripping performance can be optimized by adding more degrees of freedom in the wrist area of the robot arm, which can improve the approach position and orientation of the gripper. Using a rating system, the possible solutions of universal and combined grippers were compared in the categories of possible sizes, weights, shapes, surfaces, and materials, as well as environmental resistances. It is recommended for future studies to further pursue the combination of single gripping mechanisms, as they are promising. Furthermore, sufficient degrees of freedom in the wrist area should be considered for the robotic arms to enable better gripping quality.

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