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AI, Data and Robotics for the Green Deal (IA)

AI-powered Robotic Material Recovery in a Box

RECLAIM

D4.1: Gripping mechanisms and RoReWo units for material recovery

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Editor:	Bart Engelen (KUL)
Contributors:	Fredy Raptopoulos (ROBENSO) Nikos Kounalakis (ROBENSO) Jef Peeters (KUL)
Quality Assurance:	Michail Maniadakis (FORTH)
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The *RECLAIM* Consortium

Part. No.	Short Name of Participant	Participant Organization name	Country
1	FORTH	Foundation for Research and Technology Hellas	EL
2	UoM	University of Malta	MT
3	KUL	Katholieke Universiteit Leuven	BE
4	HERRCO	Hellenic Recovery Recycling Corporation	EL
5	IRIS	Iris Technology Solutions, Sociedad Limitada	SP
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8	AXIA	Axia Innovation UG	DE
9	ISWA	International Solid Waste Association	NL
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Table of Contents

List of Abbreviations

Abbreviation	Definition
WP	Work Package
FEA	Fluidic Elastomer Actuation
EAP	Electro Active Polymer
SMA	Shape Memory Actuation
TSC	Temperature Stiffness Control
MCA	Magnetorheological Controlled Adhesion
prMRF	Portable Robotic Material Recovery Facility
RoReWo	Robotic Recycling Worker
RVF	Residual volume flow
DOF	Degree(s) Of Freedom
TRL	Technology Readiness Level
EVS	elastic vertical stroke
HAVCO	High Airflow Vertical COnveying
FEA	Fluidic Elastomer Actuation
EAP	Electro Active Polymer
PNP	Pick aNd Place
SMA	Shape Memory Actuation
TSC	Temperature Stiffness Control
LMPA	Low Melting Point Alloy
SMP	Shape Memory Polymer
MR	Magnetho-Rheological
VSEAF	Variable Stiffness Electro-Adhesive Fluidic
CAPEX	CAPital EXpenditure

1. Introduction

In recent years, to achieve more efficient and sustainable waste management, robots have been used for recyclable sorting in post-consumer waste streams. The use of robots provides highly efficient non-stop operation, high quality material outputs with low contamination and enhanced recycling rates without the need for people to work in hazardous environments.

RECLAIM focuses, among others, on the advancement of the robotic technology utilized for sorting recyclables. To this end, WP4 compares various gripper mechanisms applicable in waste treatment applications. This involves a comprehensive evaluation of the available options on the market, alongside the design and implementation of new grippers tailored to waste sorting.

Moreover, as opposed to using general-purpose, high-cost robots that are used today for waste recovery, RECLAIM considered the implementation of new robots, designed with the waste sorting application in mind. The so-called Robotic Recycling Workers (RoReWos) implemented in RECLAIM follow a simplified hardware design to achieve a significant reduction in implementation cost with only small reductions in performance and productivity. They can be easily installed inside the prMRF container and can operate in groups to achieve high efficiency in material recovery.

In addition, a new computational approach was developed to systematically examine the matching of grippers and RoReWos to certain waste recovery tasks.

1.1 Intended readership

The present report is a public (PU) document. Its readership is the European Commission, the RECLAIM Project Officer, the partners involved in the RECLAIM Consortium, beneficiaries of other European funded projects, and the general public.

1.2 Relationship with other RECLAIM deliverables

The selection of grippers and the design/implementation of RoReWos described in this report are guided by the prMRF requirements and specifications established under WP2. Moreover, the described developments will have a key role in the operation of the prMRF where they will need to collaborate with the AI-based waste identification localization and categorization component. RECALIM considers the technological developments summarized in this report as key exploitable results with their own potential for commercialization and need for dissemination and communication.

Table 1 shows the main deliverables consulted (in case of past work), and impacted by (in case of future work) by this report.

Table 1: Other RECLAIM deliverables related.

Del. No	Deliverable Name	WP	Month
D2.1	prMRF and RDG requirements and systems specification	2	M6
D5.1	Early prMRF development based on available enabling technologies	5	M9
D3.1	Material recognition based on RGB and Hyperspectral imaging.	3	M18
D5.2	Preliminary assessment of prMRF performance	5	M18
D3.2	prMRF operation monitoring and repeating advancement	3	M30
D4.2	Multi-robot/multi-gripper RoReWo-Team configuration	4	M30
D5.3	Final assessment of prMRF and sustainability plan	5	M36
D7.1	Plan for the innovation and exploitation activities	7	M6, M18, M36
D7.2	Plan for the innovation and exploitation activities	7	M6, M18, M36

2. Implementation of gripper systems

2.1 Introduction to gripper selection

2.1.1 Gripper overview

Gripper taxonomy plays a crucial role in selecting suitable grippers for waste sorting applications by providing a structured framework to evaluate and categorize the available options based on their characteristics and capabilities.

Recently, a taxonomy of the different gripping techniques was made [2] which can provide

a guide for RECLAIM to make informed choices regarding the optimal grippers for use in waste sorting applications, aiming to maximize durability, effectiveness, and cost-efficiency. The taxonomy groups the different grasping techniques based on their working principle. The structure of the taxonomy is shown in Figure 1. The different gripper classes are evaluated for the sorting of the specific waste classes and similar terminology is used.

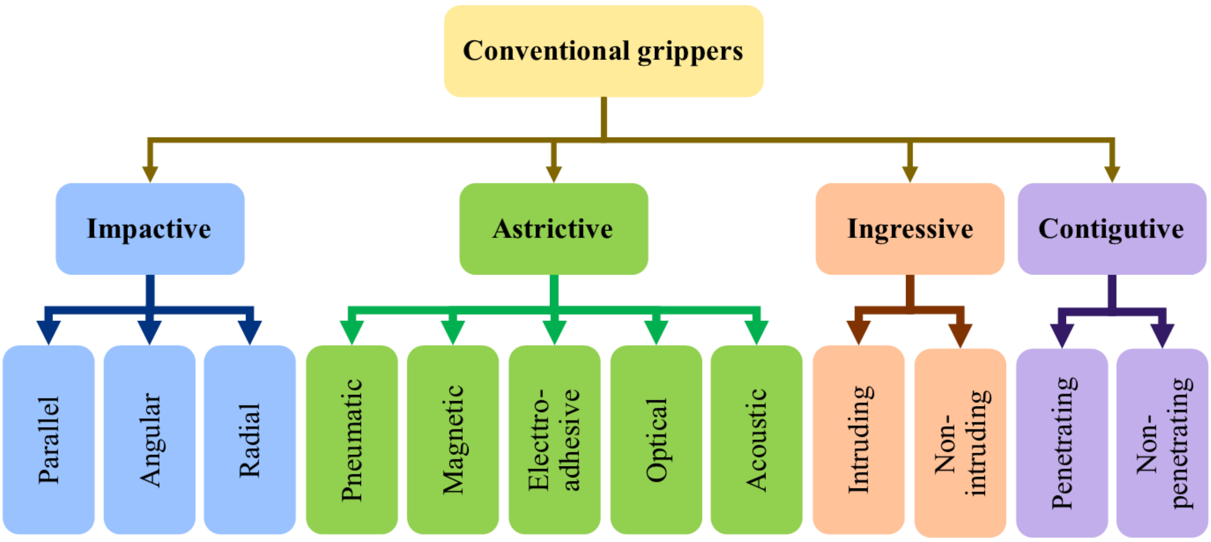


Figure 1: Conventional gripper taxonomy defined within the ACRO-grip project [2].

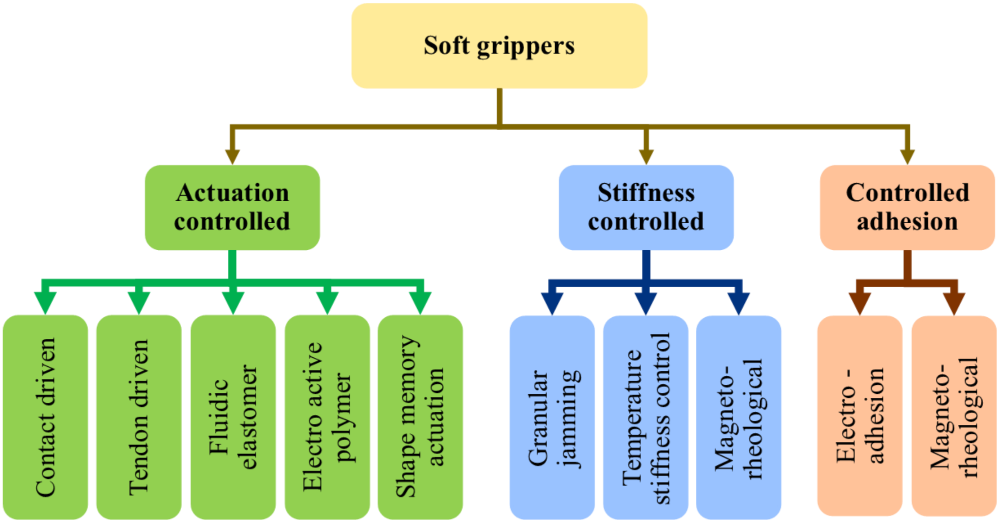


Figure 2: Soft gripper taxonomy defined within the ACRO-grip project [2].

2.1.2 Packaging waste & use case.

Table 1 is providedTable 1: Waste stream composition - materials by HERRCO and shows the composition of the stream of packaging waste which will be processed by the system developed in the RECLAIM project [1]. Table 1 shows the main target fractions and their presence as a weight percentage. From this target fraction, Polyethylene terephthalate (PET) (34%), Polyethylene films (FILM)(24%), Polypropylene (PP)(12%) and iron (FE)(13%) are the four biggest categories that together represent 83% of the waste stream.

Table 1: Waste stream composition - materials

Material	RECLAIM target stream (*t*)	RECLAIM target stream (*%*)	Recyclable weight (*gr/item*)
TETRAPACK	74	4,2%	39
PET	597	33,5%	33
HDPE - bottles	82	4,6%	104
LDPE - film	431	24,2%	48
Multilayer - film	23	1,3%	
PP	211	11,9%	40
PS	30	1,7%	40
ALUMINIUM	96	5,4%	15
FERROUS	236	13,3%	87
SUM	1780	100,0%	51

2.1.3 Grippers in packaging waste

Grippers can be characterized in a continuous spectrum between rigid and soft grippers [3] as can be seen in Figure 3. Rigid grippers are the more conventional grippers with less degrees of freedom and structural compliance but high force and precision. Soft grippers, however, are grippers with more degrees of freedom and, therefore, less precision, more compliance, and lower forces. Since gripper characteristics are often a compromise, gripper selection can be a challenge. Therefore, gripper selection is a widely researched topic. Previous research has shown that the gripper choice and design is dependent on the application and environment the gripper will be functioning in and the product that needs to be grasped [4], [5], [6], [7], [8], [9], [10]. Most of prior studies regarding gripper selection are in the context of the manufacturing industry. In a manufacturing environment the shape, size, nature, and material of products that are manipulated are mostly known, allowing the gripper to be selected or designed based on the product specifications. However, in some applications, including waste sorting, those specifications of the products broadly vary, which makes the gripper selection or design process more challenging. Chapter 0 will, therefore, describe a usability analysis of the different gripper types for the packaging sorting use case. All gripper types will be evaluated to assess their usability based on different parameters to select a range of grippers that will be used in further evaluation (Section 0). The parameters that are evaluated to assess the integrability of the gripper (integration parameters) in the packaging waste sorting use case are: the availability of a grasp planning algorithm, the ability to function in cluttered environments, the availability of compatible material in the product stream, the availability of a mechanism to release the products, the presence of possible risks (safety), the required degrees of freedom (DOF) to operate and the technology readiness level (TRL) of the gripper technique.

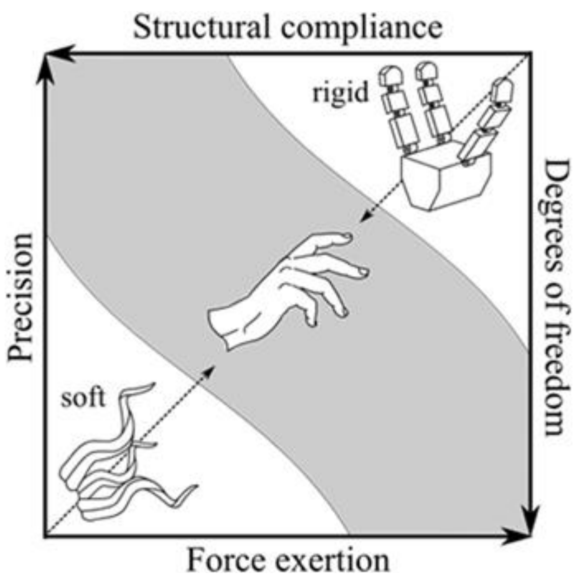


Figure 3 Rigid vs. soft grippers [3]

The grasping principles will first be evaluated based on their integration requirements and second on their operation requirements. The considered integration requirements are whether the technique has a compatible grasp planning algorithm available, can operate in a cluttered environment, has compatible products available, has a release mechanism, is safe to operate in the specific environment, does not require more than the available degrees of freedom (DOF) from the robot and has a technology readiness level (TRL) of at least 6-7. The grasp planner for a specific gripper is the software used to define where and in which orientation in relation to the object the gripper should be positioned to get the most successful pick possible. Since the use case considers the gripper to be used to pick packaging waste from a filled conveyor belt, the gripper should be able to grasp an object with limited space around the object. Some of the gripper principles require the objects to be made of a specific material to be effective, in this case the specific material should be available in the packaging waste stream to be applicable. In the use case for instance, there will be an overhead magnet conveyor belt, therefore, theoretically there will be no magnetic products available for the grippers, hence no gripping techniques relying on magnetism can be considered. Once the object is grasped with the specific technique, it must be dropped in a sorting bin. Therefore, the grasping technique must be able to release the object. To safeguard the system and the operators the gripper should be safe to operate in a polluted environment, high voltages for example can yield potential danger for operators, damage electronics in other subsystems or produce sparks which can lead to explosions in dusty environments. Since some of the gripper technologies need to be positioned in a more specific location and orientation on an object, more DOF for the positioning might be required, restricting the types of robots that can be used. In the use case robots with a maximum of 3 DOF are available. Since the use case develops a sorting machine, which requires relatively robust and proven technologies to be reliable, only TRL 6-7 are considered applicable, so grippers can be bought from the shelve or produced with high reliability.

The rigid grippers will be subdivided in 4 subclasses: impactive grippers, ingressive grippers, astrictive grippers and contigutive grippers. The soft grippers will be classified into actuation controlled, controlled stiffness and controlled adhesion.

2.1.4 Grasp planning algorithms

Before the different gripper subcategories will be assessed in the application on packaging waste sorting, some insight in grasp planning algorithms will be provided. Grasp planning consists of two tasks, first a possible grasp pose must be determined. The grasp pose is defined by the definition of the grasp location and orientation. Second, the path for the robot to perform a grasp must be determined. The second is widely explored by other researchers and is considered out of the scope of this deliverable.

The process of determining possible grasp configurations can be done with two methods, by using the analytic approach and by using deep learning. The analytic approach is shown in Figure 4. Grasp determination consists of detecting the object and if needed abstracting the product to for instance primitive shapes. Not only the products will be abstracted, also the gripper and the environment. For this abstracted environment different grasp poses are calculated and evaluated. The evaluation of the different poses consists of checking for obstructions and using a grasp metric to predict the success of a specific pose. After this evaluation all the obstructed grasp positions are restrained, and the best remaining grasp pose will be selected. The evaluations of the grasp poses can be done in many ways depending on the application, this can be for example based on different parameters like risk for collision, required time, energy consumption, risk for slippage.

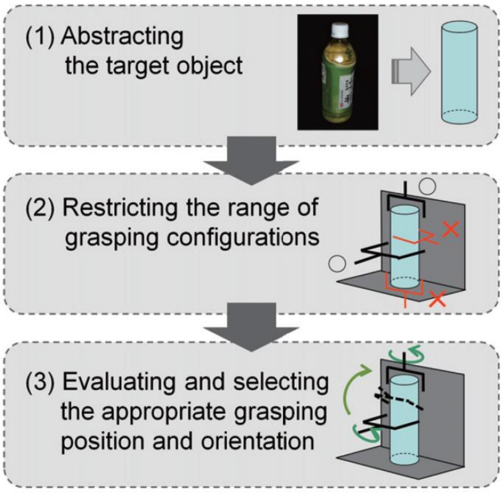


Figure 4: Defining the best grasp configuration in steps [11].

To detect grasps with deep learning, a network must be trained to detect and evaluate grasp configurations or directly servo a robot into a good grasp configuration. Gasp detection is a widely studied field with some good progress made already [12], [13], [14], [15]. The most common models are supervised learning model which require a large and labeled dataset to be trained, which can be resource demanding to acquire. Some deep learning approaches servo the robot to the picking configuration in a complete autonomous way [16]. Since controlling the robot fully autonomous and servoing the robot towards a grasping pose is robot and gripper specific and is rather slow in its operation, it is not considered valuable for the robotic sorting application.

2.1.5 Robot degrees of freedom

To grasp an object with a gripper, the gripper must be aligned with the object in the grasping pose. Depending on the complexity of the grasping pose this can require many degrees of freedom (DOF). In the following chapters, the required DOF of the different gripper technologies will be discussed. The DOF can be achieved with solely the robot or by including other elements that facilitate a motion or 1 DOF. For instance, a conveyor belt can move the objects towards the robot, this can be seen as 1 DOF. Additionally, the authors consider the possibility of a half DOF when a DOF is realized without precise positioning control. As an example, when a gripper requires 3 DOF, the gripper requires to be positioned above the object in the right X-, Y- and Z-position without the requirement of any rotational alignment.

In this case, 1 DOF (X-direction) could be realized by a conveyor belt system, since in one moment in time, the object will be moved though the right X position, so only a 2 DOF robot is required, to align the gripper pose to the right Y- and Z-positions. Additionally, when a collision with the product is allowed, for instance when the robot or gripper is equipped with a compensator, one DOF can possibly be realized without position control. In the example, the Z-position can be reached by moving the robot down to a predefined Z-position above the conveyor belt, possibly colliding with the object. While colliding with the object and using the compensator to compensate for the object height difference, the right Z-position will be reached as well. In this case a robot with only 1,5 DOF is required.

2.2 Rigid/conventional grippers

2.2.1 Impactive grippers

Rigid impactive grippers are grippers which exert forces with impact against the object surface by using an actuator to move rigid fingers against the surface of the object. The actuations can be linear, angular, or radial and can be powered electrically, pneumatically, or hydraulic. The actuator usually has two or more mounting surfaces to mount gripper fingers. The gripper fingers have the function to transform the gripping force and generate a lifting force. This can be done by creating a closure to the object surface. This can be either form closure or friction. With form closure the shape of the gripper must match the shape of the object to fixate the object. This can be done with either a premade shape or by using a deformable object as contact with the objects. Since the objects in packaging waste do not have a homogeneous surface structure, this closure type is not considered applicable. However, with friction the gripper exerts a force on the surface of the object which will generate a static friction force which depends on the surface material of the gripper finger, the object and the conditions of the contact surface and the magnitude of the exerted contact force.

Friction formula:

$$\boldsymbol{F_f = N * \mu_s}$$

F_f is the static friction force generated by the normal force N with a contact friction coefficient of μ_s.

Integration requirements:

A. Grasp planning algorithm:

Since impactive grasping is one of the most conventional techniques of grasping, a big variety of grasp detection algorithms are available. Grasp configurations for impactive grippers can be defined by both the analytic and deep learning method [14], [16], [17], [18].

B. Cluttered environment:

Since impactive gripper fingers can be design such that they can fit in small spaces, impactive grippers are considered functional in cluttered environments.

C. Compatible products material:

Impactive gripping technology is practically independent of the grasped material, aside from the friction properties of the surface which are defined by the material and surface contaminations. However, the product requires volume, allowing it to be grasped from the sides. The shape has a big impact on the grasp success.

D. Release mechanism:

By removing or inversing the force of a specific actuator the grasped product can be released without extra hardware.

E. Safety:

Impactive grippers do not require, hot or cold surfaces that could yield danger in case of contact with an operator. Neither does the technique require high voltages that could be dangerous for the operator or introduces sparks with a hazard for explosions or fire. Since impactive grippers use closure to fixate objects and high grasping forces are often used, impactive grippers yield a risk for the clamping or crushing of body parts. By not intruding the grasp space of the gripper and disabling the power source of the gripper when performing maintenance risk can be prevented.

F. DOF:

Given the fact that a robotic system for the sorting of packaging waste involves conveyor belts with unpredictable conveyor belt filling, collisions must be prevented. To position an impactive gripper in a cluttered environment, a requirement or at least four DOF can be assumed. Three DOF are required to position the gripper above the product. The Fourth degree of freedom is required to align the gripper with the most graspable orientation of the product. Due to the presence of the conveyor belt only a three DOF is required of which one DOF can be realized by installing a swivel actuator in between the gripper and the robot if rough alignment with the product is sufficient which means an extra DOF can be removed from the robot. Considering that the gripper fingers are longer than the product is high, accurate high positioning remains obsolete which means a minimum of 1.5 DOF is required to enable the robot to perform a PnP operation.

G. TRL:

Impactive grippers are the state of the art gripper system used in the robotic recycling systems of today [20]. Therefore, the TRL is nine which is sufficient for the packaging sorting application.

2.2.2 Astrictive grippers

Astrictive grippers are grippers that exert a continuous holding force to the product object without introducing a compressive stress into the product [21]. There are three types of astrictive grippers: pneumatic, magnetic, and electrostatic.

2.2.2.1 Pneumatic

Pneumatic astrictive grippers use a vacuum to attract the object. Vacuum can be generated using a vacuum pump or blower, the venturi or Bernoulli effect, suction bellows, and pneumatic cylinders. The characteristics of the most common vacuum generation techniques are shown in Table 1 and Figure 5.

Table 1: Comparison of the characteristics of different vacuum generators [23].

	Pump	Blower	Venturi vacuum generator (ejector)
Vacuum	High	Low	Medium – High
Volume	Low	High	High – Medium
Operation cost	Low	Medium	High
Noise	Low	High	High
Initial cost	High	Medium	Low
Size & weight	High	High - (medium)	Low
Direct integrability	Low	Low	High

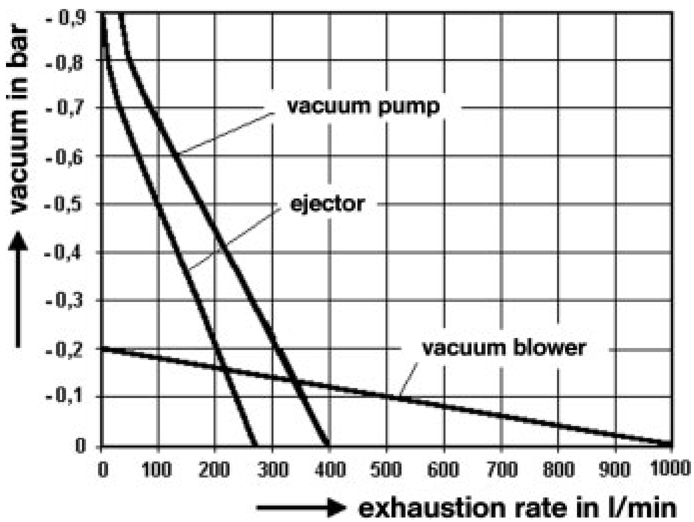


Figure 5: Different types of typical vacuum generators and their performance [22].

While pneumatically manipulating objects with low porosity is relatively easy, permeable, or porous objects or objects with very rough surface topology remain a challenge. In order to generate good abstriction, high volume flow needed to overcome the leakage of vacuum through the object or due to bad sealing of the gripper[23].

Suction cup grippers

Suction cup grippers work by first creating a seal with the surface of the product and next use an external vacuum source to generate a vacuum in the cup which astricts the product. This type of gripper is commonly used in industry and exist in multiple shapes, types, materials and can have inserts like filters or extra lips to cover perforations in the product. Traditionally, the shape of a suction cup is carefully defined or designed to fit the specific product it is intended to pick [22]. However, since waste products rarely have a consistent shape a more generic suction cup shape, oval or round, should be considered. Additionally, to the shape, there are four main suction cup types, suction cups with a flat suction cap, ribbed suction cap, with double lips and with bellows. An overview of the characterization of the types is shown in Figure 6. The different types are selected based on the forces that the cup is required to transmit in horizontal and vertical direction, the elastic vertical stroke (EVS) and the allowed leakage or residual volume flow (RVF). The magnitude of those characteristics is shown in circles where a full circle represents very good behavior and an empty circle very bad behavior [22].

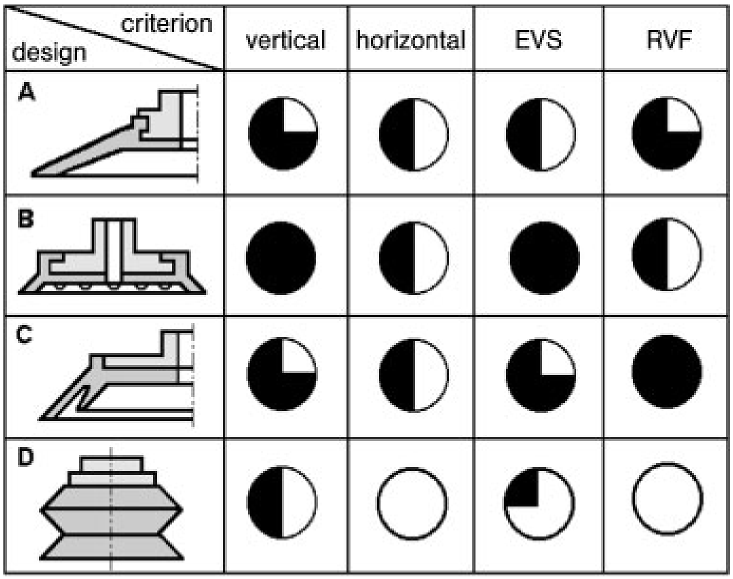


Figure 6: The characteristics of the four suction cup types: flat suction cap (a), ribbed suction cap(b), double lipped suction cup (c) and bellows (d) [22].

Integration requirements:

A. Grasp planning algorithm:

Since suction cups operate by creating a vacuum seal on the surface of an item, they can be placed anywhere on the item's surface if it is relatively smooth and non-porous such the RVF is smaller than the capacity of the vacuum generator. Since the positioning of the suction cup is relative flexible, the suction-based gripping method is considered to effectively operate from above the object. Traditionally, suction cup grasping configurations are detected with analytical method [24], [25]. However, with the acceleration of the development of the field of deep learning, multiple other techniques are available [13], [26], [27], [28], [29].

B. Cluttered environment:

Since the gripper can be positioned top down on the object, cluttered environments are not considered to be a problem.

C. compatible products material:

Suction cups require a seal to operate. Therefore, objects with limited permeability or porosity and relatively smooth object surfaces can be grasped with suction cup grippers. A major fraction of packaging waste is made of materials with relatively low permeability or porosity which indicates suction cups can be used. However, since the shape of packaging waste is non-homogeneous and unpredictable it can be challenging to find a smooth surface on the object on which a good seal can be generated. A high-performance grasp configuration planner might be appropriate.

D. release mechanism:

Grasped objects can be released by suction cups by removing the vacuum in the cup. This can be done by stopping the suction air flow after which the leakage or RVF will restore atmospheric pressure in the cup. Even though a very good seal on the deformed packaging waste is not expected, a good seal can create a slow release. Therefore, pressured air can be blown into the suction cup, introducing an overpressure in the cup which quickly removes the objects.

E. safety:

Since suction cup grippers only require vacuum to function properly and are often made of elastic polymers, direct danger to operators is rather minimalistic.

F. DOF:

Three and more DOF are sufficient to position the suction cup gripper top down onto an object. Since suction cups are flexible, they have the capacity to self-align to surfaces with a small angle. Since no accurate positioning of the picking height is required and a conveyor belt is used to move the objects towards the robot, 1.5 DOF robots can be used with this gripper type.

G. TRL:

Suction cup grippers are widely implemented in industry and are one of the oldest gripping methods used [22]. The technology is well proven in the field and therefore has a TRL of nine which is sufficient for the application in robotic sorting equipment.

Bernoulli & vortex grippers

Both Bernoulli and vortex grippers use the inertial properties of air flow to generate negative relative pressure. Li et al. performed a comparative study to analyze the function of both the Bernoulli and Vortex gripper [30]. Within this work the functioning of those grippers is shown (Figure 7) and described. Within the Bernoulli gripper an airflow is injected axially into the gripper surface around an optional deflector. The airflow gets deflected radially by either the objects that needs to be grasped or the deflector. Sequentially the airflow slows down since the cross section of the radial air gap increases which increases the pressure according to the Bernoulli's law principle. Since the external pressure is equal to the atmospheric pressure the pressure in the gripper must be lower than the external pressure which allows objects to be astricted. Since the airflow, from a Bernoulli gripper, escapes between the object and the gripper, external air cannot flow towards the low-pressure zone, this allows for objects with rougher surfaces to be picked whereas rougher surfaces would introduce RVF when using suction cup grippers. While also the vortex gripper uses airflow to create negative relative pressure, as visible in Figure 7, the air gets injected tangentially. Due to the centrifugal force on the airflow the pressure in the middle of the gripper reduces. The rotating airflow escapes radially through a slot in the gripper.

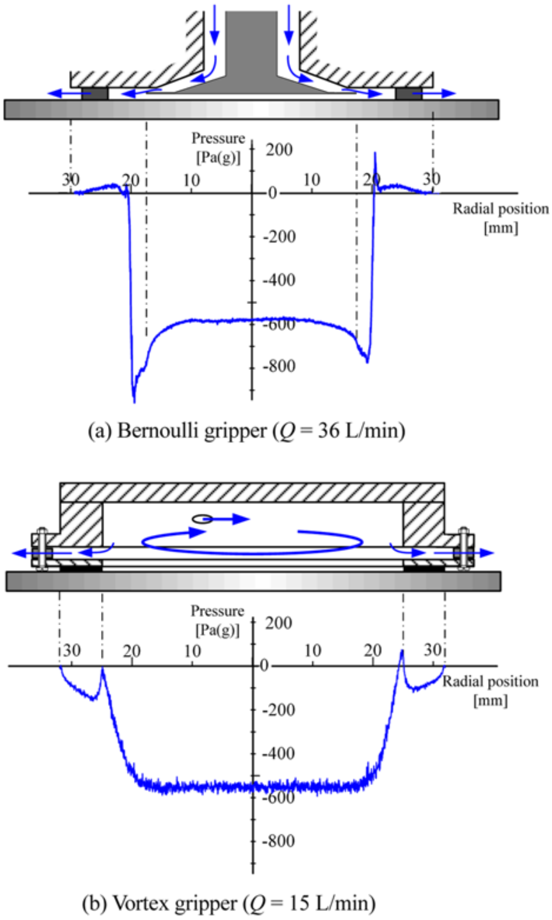


Figure 7: Schematic overview of Bernoulli gripper (top) and vortex gripper (bottom) [30].

Integration requirements:

A. Grasp planning algorithm:

Much like suction cups, which are versatile in their positioning on smooth, non-porous surfaces, Bernoulli and vortex grippers should also be strategically placed on a target object, with the additional flexibility to handle slightly rougher flat surfaces. Given the similarities between the Bernoulli and vortex gripper and astrictive grasping with suction cups, it can be hypothesized that methods for detecting grasps for Bernoulli and vortex grippers can be borrowed from the knowledge base of suction cup grippers. Which is well-studied and contains a big variety of possible grasp detection methodologies.

B. Cluttered environment:

Since the grippers grasp configuration is hypothetically analogue to the suction cup gripper it is assumed to function top down which allows for the gripper to operate in a cluttered environment.

C. compatible products material:

The gripper will be able to operate if the grasp target has relatively flat surfaces the size of the gripper that are not majorly distorted or porous. This should be the case with the sorting of waste packaging.

D. release mechanism:

The gripper only functions when there is a present airflow. In case the airflow is disrupted, the object will be released.

E. safety:

like suction cup grippers (Section 3.2.2.A.1) the Bernoulli and vortex grippers are safe to operate.

F. DOF:

While we hypothesize that the pose planning methodology for Bernoulli and vortex grippers can be borrowed from suction cup grippers, the Bernoulli and vortex grippers are not flexible and can't compensate themselves for inclinations in the grasping surface. Therefore, this gripper technology is less forgiving and additional DOF are required to successfully position the gripper in a specific grasping configuration. 5 DOF are assumed to be required to position the gripper, such that the gripper can be successful. Even considering the conveyor belt and allowing for inaccurate height positioning of the gripper, a minimum of 3.5 DOF robot is required to perform a PNP operation.

G. TRL:

Commercial Bernoulli and vortex grippers are available but not tested in industrial waste sorting environment. With therefore a TRL of six.

Coanda

Coanda grippers rely on the Coanda effect to generate an air flow by using the adhesion effect [31], [32], [33] which creates an astriction force by generating a vacuum. The main component of a Coanda gripper is a Coanda ejector which is shown in Figure 8. This ejector functions by injecting high pressured air, delivered by the input channel into an annular nozzle. This nozzle generates a primary airflow that adheres to the ejector wall in the direction of the diffuser. The acceleration of this adhered airflow generates a secondary airflow in the center of the Coanda ejector which interacts with the surrounding air and drags in air from the ejector inlet which can be used to grasp objects. Modeling from Ameri and Dybbs [32], [34] show that the secondary airflow can have a magnitude in the order of 10 times the primary airflow which makes the Coanda ejector a good candidate to generate suction for porous materials which have more RVF [33]. Coanda grippers can be equipped with suction cup or metal gauze elements to improve sealing properties and therefor reduce RVF or to prevent pollution and objects from entering the ejector [35].

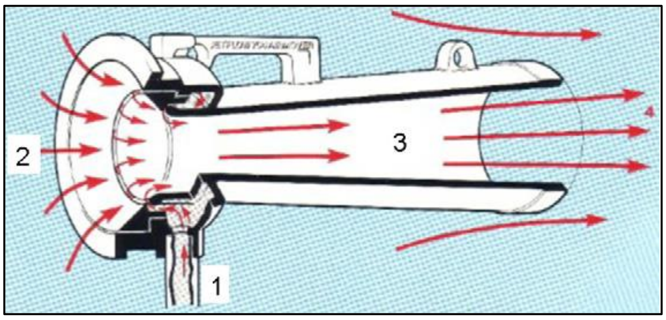


Figure 8: Coanda ejector principle [33] with input channel and annual nozzle (1), ejector inlet (2) and diffuser (3).

Integration requirements:

A. Grasp planning algorithm:

Analogously to Bernoulli and vortex grippers no grasp detection or planning algorithms are found. Therefore, the same hypothesis, approaches can be borrowed from the suction cup grippers, is made.

B. Cluttered environment:

Since the Coanda gripper works top down and does not require the gripper to intrude in between the products, the Coanda gripper is considered to work in cluttered environments.

C. Compatible products material:

The Coanda gripper has no specific material restrictions.

D. Release mechanism:

When the primary airflow gets interrupted the Coanda ejector does not generate suction. This will release the object.

E. Safety:

Coanda grippers have the same safety concerns as suction cup grippers and are, hence, considered sufficiently safe for the waste sorting application.

F. DOF:

As described before, the hypothesis is that Coanda can be positioned on products with a similar approach as suction cup grippers. Coanda grippers can have flexible elements installed which allow for compensation in case of misalignment, corresponding to suction cup grippers. This leads to the assumption that Coanda gripper could be effective while using at least 3 DOF. Since the conveyor belt is available and accurate positioning of the gripper in the vertical direction is not required, a 1.5 DOF robot is considered sufficient to position the gripper in the use case.

G. TRL:

While Coanda grippers are not proven in any waste sorting applications, Coanda grippers are available of the shelve and are relatively easy to construct due to their low number of mechanical components DOF within the gripper design. Therefore, Coanda grippers are considered to have a TRL of 6.

High Airflow Vertical Conveying (HAVCO) grippers:

HAVCO grasping is a new grasping technology which similarly to the Coanda gripper uses pressured air to generate an airflow which can be used to manipulate the waste products. The HAVCO gripper, conversely, is not intended to only astrict objects. Since the gripper technique can aside from conveying away the products also astric objects, this gripper technique has a double function and can possibly be classified as a new subclass. The HAVCO gripper of which the first prototype is developed at the KU Leuven, shown in Figure 9, mostly intents to convey objects from the conveyor through a tube to a sorting bin or launch them into the direction of the bin [36].

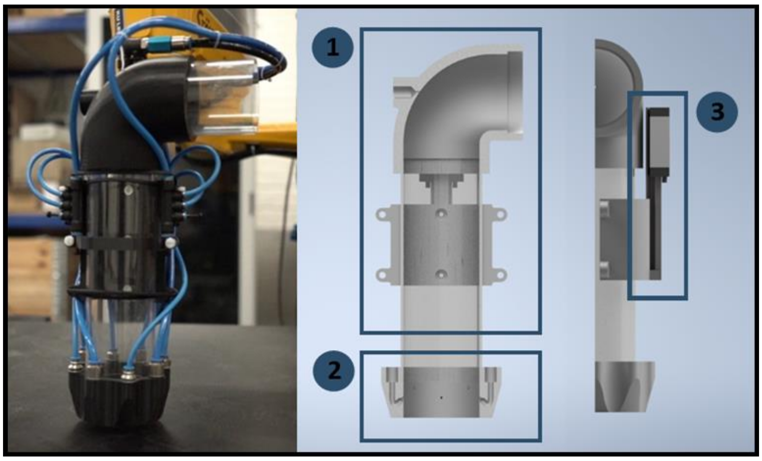


Figure 9: HAVCO gripper with conveying tube (1), airflow generator (2) and linear compensator (3) [36].

Integration requirements:

A. Grasp planning algorithm:

To successfully grasp an object and move it to a container, the HAVCO gripper must fit around the object and be positioned with the product in the center of the gripper opening. Given that the product can be detected the gripper can be positioned above the centroid of the object with a simple heuristic, as is described in [36].

B. Cluttered environment:

Since the gripper needs to be positioned around the product, it may collide with any clutter surrounding the target. However, this collision is not necessarily problematic, as the gripper can be equipped with a linear compensator, as shown in Figure 7. This feature prevents damage to either the gripper or the robot while still allowing the target object to be picked. At the same time, making contact with the surrounding objects can also be advantageous, as applying pressure on the surrounding clutter ensures that only the targeted product will be conveyed by the gripper.

C. Compatible products material:

Picking targets for the HAVCO gripper must be smaller than the inside diameter of the gripper to convey them. Since, no other material constraints are known, the HAVCO gripper is considered interesting for the sorting of waste.

D. Release mechanism:

Since the HAVCO gripper principle automatically moves the product to the target location without real closure, no release mechanism is required.

E. Safety:

Compared with suction cup grippers, Coanda grippers, Bernoulli, and vortex grippers, only the ejection of objects could generate additional risks while grasping objects with the HAVCO grasping technique, as objects can be launched by the gripper. Since no operators are allowed in proximity to a traditional industrial robot in operation and a tube can be used to convey the objects, the risk is not considered to be sufficient to classify this gripper as not usable.

F. DOF:

Since the gripper can be positioned top down with the product in the opening from the gripper only 3 DOF are required. With the availability of a conveyor belt and the tolerance for imprecise positioning only 1.5 DOF remain required from the robot.

G. TRL:

The gripping technique is successfully tested with a prototype at the outset of the RECLAIM project on packaging waste materials at lab scale and is, therefore, considered on a TRL of 5 meeting the requirement.

2.2.2.2 Magnetic

Magnetic grippers are end effectors that contain either a permanent magnet or an electromagnet which can attract magnetic materials so they can be moved [22].

Integration requirements:

A. Grasp planning algorithm:

Since magnetic grippers do not require precise positioning, one can assume that a heuristic is sufficient to pick objects with a magnetic gripper when the object is detectable.

B. Cluttered environment:

Grasping a specific object in a cluttered environment where multiple objects are magnetic can be problematic since the clutter will be attracted to the magnet as well. When the clutter is not magnetic clutter is not problematic for this grasping technique.

C. Compatible products material:

Due to the waste packaging material being mostly non-magnetic and the installed overhead magnetic conveyor belt, magnetic grippers are considered not appropriate.

D. Release mechanism:

Most magnetic grippers are developed such that the gripper can be demagnetized, releasing the grasped objects. Demagnetizing can be both electrically and magnetically.

E. Safety:

Magnetic grippers with a relatively low magnetic field are considered safe to operate due to the lack of pointy or moving components, cold or warm surfaces, high voltages, and highly dynamic parts.

F. DOF:

Since products can be attracted from a relatively long distance and the gripper therefore does not have to be positioned precisely, the gripper requires a minimum of 3 DOF to be positioned above the product which results in a 1.5 DOF robot due to the availability of the conveyor belt and the tolerance for imprecise positioning.

G. TRL:

Magnetic grippers are used on robots and in the field of metal sorting but are not specifically proven for the sorting of packaging waste. Therefore, a TRL from 6 to 8 is considered.

2.2.2.3 Electro-adhesive gripper

Electro adhesion grippers are grippers that attract objects utilizing a phenomena called electro adhesion [37]. To lift the product with electro adhesion, a potential in the range of several thousand volts is applied over the product and the gripper while being separated by a dielectric material. For safety reasons the product is mostly earthed. The retention force is defined by the applied voltage [22].

Integration requirements:

A. Grasp planning algorithm:

The same hypothesis as made for Bernoulli, vortex and Coanda grippers can be made. Therefore, it is assumed that solutions for grasp planning can be borrowed from the other grasping techniques with minimal adaptation.

B. Cluttered environment:

Electro adhesive grippers can be operated in cluttered environments since the elements that generate the astriction can be very small or can be positioned top down on the products.

C. Compatible products material:

All materials can be manipulated given that they are relatively flat and light. However, retention pressures on conductive materials are substantially higher while the majority of the packaging materials are not conductive [22].

D. Release mechanism:

By removing the potential over the product and the gripper the retention force should mostly be relieved, releasing the product from the gripper.

E. Safety:

Since high voltages (several kilovolts) are required for the gripper to function the gripper is considered too dangerous to be utilized in a waste sorting environment.

F. DOF:

Since this grasping technique attracts objects, the technique is considered to compensate for misalignment, three DOF is assumed to be sufficient to position the gripper. This results in the requirement of a robot with a minimum of 1.5 DOF within the use case, due to the availability of the conveyor belt and tolerance for misalignment (Section 3.1.5).

G. TRL:

Electro adhesive grippers are used in wafer production industries for the retention of wafers during the manufacturing process [22] but are not used in the waste sorting industry. For this reason, electro-adhesive grippers are considered at a TRL of 3 for waste sorting.

2.2.2.4 Optical

Optical grasping is a grasping concept in which optical radiation is used to fixate and/or move an object. It is demonstrated that objects on nanoscale can be lifted while utilizing radiation forces [38]. However, since the technology for grasping objects with this technology is to the knowledge of the authors not yet developed for applications in industry and the objects that could be manipulated are on nanoscale which makes this technology not usable for waste sorting.

Integration requirements:

A. Grasp planning algorithm:

Since the technology is not yet well developed, no grasp detection or planning techniques can be associated or are available.

B. Cluttered environment:

The impact of the clutter on the grasp ability of a product cannot be estimated since the grasping technology is not yet developed.

C. Compatible products material:

Products manipulated with optical radiation require to be lightweight and small.

D. Release mechanism:

By removing the optical radiation, the product will be released.

E. Safety:

Lasers are used to manipulate the objects. Laser light and the reflection of lasers bring complications with the integration in environments with operators.

F. DOF:

This cannot be assessed since the technology is not brought to sufficient TRL.

G. TRL:

Since the technology only exists on a concept level, there is only a TRL of 1/2, which is considered not useful for waste sorting.

2.2.3 Acoustic

A gripper with the ability to manipulate small objects and liquids by utilizing acoustic waves is developed by Röthlisberger et al. [39]. Acoustic wave generators are positioned in a specific geometry to trap or move objects. However, the shown technology is very product specific. Since the development of the gripper focusses on very small products, the gripper has limited potential for the sorting of waste products.

Integration requirements:

A. Grasp planning algorithm:

Since the development of the gripper is still in progress, no planning algorithms are developed specifically for this gripper. Additionally, since the final shape and function is unknown it is hard to assess whether grasp detection or planning methods are available.

B. Cluttered environment:

Similar to the grasp planning algorithms for this gripper (Section 0) the shape and functioning of the gripper defines whether the gripper can perform in cluttered environments. At this moment the technology is not developed enough to assess the compatibility with cluttered environments.

C. Compatible products material:

The gripper technology as designed today is developed for very small products in contradiction to the bigger materials found in waste streams and forces exerted on the products are in the mN ranges [39]. Therefore, the gripper technology seems not capable of the manipulation of waste products.

D. Release mechanism:

With the absence of acoustic waves there are no forces on the product. Therefore, the products can be released.

E. Safety:

Upon initial observation, the sound intensity appears to be the primary risk in the use of acoustic grippers. However, research indicates that the gripper utilizes intensities of up to around 80 dB(A) at a frequency of 30 kHz to 100 kHz [39]. This intensity complies with European safety and health standards for workers [40], and the frequency is beyond the range of human auditory perception. Therefore, it can be concluded that the sound associated with the operation of this gripper does not pose a risk to potential operators, suggesting that its use does not appear to carry significant risks.

F. DOF:

The DOF required to perform a robotic pick is heavily dependent on the gripper geometry. Since this is not defined, the DOF required for the integration of this gripper technique is undefined.

G. TRL:

The TRL of acoustic grasping of waste materials is 1/2 which is not sufficient.

2.2.4 Ingressive grippers

Ingressive grippers are grippers that permeate the surface of a given product with pins, needles, or hackles under an angle to fixate the product. The gripper type is mainly designed for products with a fibrous structure or soft products of which the surface can be easily pierced. There are two types of ingressive grippers, intrusive grippers, and non- intrusive grippers. The intrusive grippers permeate the objects and go deeper under the product surface to a set depth. The non-intrusive grippers work on or slightly in the surface of the product. Since there are soft packaging waste products, ingressive grippers could be used. However, only the ingressive grippers utilizing pins are robust enough since needles are fragile and the non-intrusive grippers that use pinching with hackles seem to be rather unproven/unpredictable. The actuation of the pins, needles or hackles can be hydraulic, electric, and pneumatic, of which pneumatic is by far the most common actuation method.

Integration requirements:

A. Grasp planning algorithm:

Since ingressive grippers require to permeate the products surface the gripper can be positioned anywhere on the surface of the product given that the surface of the product is permeable. The pins, needles or hackles must be pushed into the surface of the product which will induce force on the product, which could move the object. Therefore, there must be a support structure behind the object which could be the conveyor belt. Subsequently the gripping technique will work from the top down on the object similar to astrictive suction cup grippers (Section 3.2.2.A.1). It can be assumed that grasp pose detection software for those techniques could be used as a starting point for the development of grasp pose planning software for ingressive grippers.

B. Cluttered environment:

The gripper can work from the top down onto the object. Therefore, a cluttered environment is not considered problematic.

C. Compatible products material:

The packaging waste fraction contains objects that can be penetrated by pins, needles, or hackles.

D. Release mechanism:

Similar to the impactive gripper the ingressive gripper can release the grasped object by inversing the actuator and moving the pins, needles or hackles out of the product.

E. Safety:

Since the intruding elements from the ingressive grippers generally move more than a couple of centimeters and are contained within the gripper while the gripper is not actuated, the grasping technique is not considered dangerous to operators. Education of the operators can limit the risk for exposure to the intruding elements. During maintenance or any operation close to the gripper, the actuator of the ingressive gripper should be blocked and deactivated.

F. DOF:

Since the gripper can successfully be positioned top down on the object a minimum of three DOF are required. With the available conveyor belt motion and the integration of a height compensator, the gripper can be pressed against the surface of the product which would only require a robot with 1.5 DOF.

G. TRL:

Ingressive grippers are available of the shelve and tested on similar materials. However, this grasping technique is not found in sorting machinery to date a TRL of 6 is estimated.

2.2.5 Contigutive grippers

Contigutive grippers are grippers that attach to a product by contacting and utilizing tension forces or chemical/thermal adhesion. Grippers that use thermal adhesion are often called cryogenic grippers. This type of gripper uses a temperature difference to create a bond between the gripper and the product by freezing small droplets of water between the product and the gripper. A Peltier element, cryogenic carbon dioxide or cryogenic nitrogen can be used to freeze the product to the gripper in less than a second, while a heating element or warm spray can defrost the connection [22]. A manipulation device specifically designed for the manipulation of textiles was patented [41], [42]. Alternatively, chemo-adhesion grippers use chemical adhesion to attract products by the usage of disposable chemical adhesives [22]. Chemical adhesions are often available in the shape of tapes that are fed into the gripper [46]. Gripper can use surface tension to attach the product to the gripper [45].

Integration requirements:

A. Grasp planning algorithm:

Since contigutive grippers only require a single contact point to attach to a product comparable to how suction cup grippers attach to an object, the hypothesis can be made that grasp detection techniques can be used like those developed for suction cups.

B. Cluttered environment:

The grasping technology only requires one contact point to grasp a product. Therefore, this grasping technology is suitable for operating in cluttered environments.

C. Compatible products material:

Cryogenic contigutive and surface tension techniques are not depending on the products material. However, chemical adhesion is depending on the adhesive used and the product material [43]. Surface tension techniques are dependent on the surface of the product.

D. Release mechanism:

Contigutive techniques relying on thermal adhesion and surface tension can release the products singe the adhesive behavior can be influenced. On the other hand, chemical adhesion is not influenceable, therefore an external structure is required to remove the product from the gripper.

E. Safety:

Cryogenic surfaces can be dangerous for the operator. Additionally, the presence of possible failure of high-pressure gas lines can be considered a risk. Also, chemical adhesives can utilize solvents. The evaporation of those solvents can introduce risks to the health of the operators as well as introducing a risk for explosion in case the evaporated solvent saturates the atmosphere in a sorting machine. Grippers using surface tension are considered risk free.

F. DOF:

Since only a contact point is required, the grippers are less demanding on their positioning. The gripper requires three DOF to position the contigutive gripper on the object. Considering the conveyor belt and the lower requirement for precision, a 1.5 DOF robot is considered sufficient.

G. TRL:

Some of the techniques are rather experimental and none of the proposed techniques are demonstrated in a waste sorting environment. Therefore, the TRL of those techniques is considered not to be higher than 3

2.3 Soft grippers

Unknown and unstructured environments, as well as assemblies with non-solid parts, are challenging for conventional rigid robotics and may require non rigid manipulators. Those soft manipulators enable soft interactions on a large variety of objects without losing the ability to apply significant force. Catalyzed by the fast advances in soft robotics, material science, stretchable electronics soft structures are more often exploited in robotic manipulators. With inspiration from nature and the soft structures found in the manipulation of objects by insects and animals various soft grippers have recently been developed. The soft structures and mechanical compliance allow for superior manipulation, reduced complexity in control and safer interaction with humans and natural environment. This compliance can be introduced in three ways: by controlling the actuation, stiffness or adhesion form the gripper [3], [46], [47], [48], [49], [50], [51].

2.3.1 Grasping by controlled actuation

According to Shintake et al. soft grippers can perform a grasp on an object through the adaptation of compliant structures deformed by external or integrated actuators. When utilizing external actuators, the passive structure will be deformed by contact with the product. Alternatively, the integrated actuators, often in the form of tendons, can adapt the shape of the gripper. Alternatively, Grippers with fluidic elastomer actuators (FEA), electro active polymers and shape memory polymers are also actuation controlled grippers [47].

2.3.1.1 Passive structure – contact driven.

Passive structures in soft grippers can deform under externally applied mechanical stress. By controlling the actuation of the gripper, the magnitude of this deformation can be controlled. One example is the Fin Ray structure, a structure inspired by fish fins, curves around a contact point which enables a grasp with an enhanced form closure [47]. C. H. Liu et al. show that, with topology synthesis and optimal design, compliant mechanisms are capable of the manipulation of a big variety of objects [52]. Other variants of this mechanism exist [53], [54]. Research is conducted about including sensor elements [55], [56], [57]. Commercial grippers with contact driven passive structures are available [58], [59], [60], [61].

Integration requirements:

A. Grasp planning algorithm:

Almanzor et al. used a fin ray gripper in combination with visual servoing-based technique to position the gripper over waste products to pick litter. Additionally, analogies with rigid impactive finger grippers can be observed, leading to the hypothesis that similar grasp detection and planning algorithms can be used.

B. Cluttered environment:

The most common contact driven passive structures are based on the fin ray structure which is triangular [54], [57], [59], [61]. Due to the pointy structure, the gripper can be positioned around the product in relatively small spaces near clutter. Aside from this, the grippers are made from elastic materials which allows for compliance in the case of a collision with the clutter. Therefore, the contact driven passive structures are considered applicable on waste products.

C. Compatible products material:

Since the gripper still functions similarly to a rigid impactive grippers with the addition of soft structures adapting to the product, the gripper is applicable to all structures with volume that fit within the fingers of the gripper in the open position.

D. Release mechanism:

By opening the gripper and removing the contact force the grasped object can be released.

E. Safety:

Due to the soft and compliant structures the gripper is considered safe to use in a packaging sorting operation.

F. DOF:

Analogue to impactive finger grippers (Section 0) 4 DOF are required to position the gripper around a product in a cluttered environment. However, due to the availability of the conveyor belt, allowance for imprecise vertical positioning and by installing a swivel actuator, a minimum of 1.5 DOF are required from the robot within the use case.

G. TRL:

Since the grippers are commercially available but not yet tested on the specific packaging waste sorting a TRL of 5-6 is considered which is sufficient for the use case.

2.3.1.2 Passive structure – tendon driven.

Various soft grippers with passive, tendon activated, structures are developed [62], [63], [64], [65], [66], [67], [68], [69], while grippers with only two or three fingers exist, grippers with more fingers, dexterous grippers, tend to be popular. Commercial variants of tendon activated soft grippers are available [70], [71], [72]. However, commercially available soft grippers with tendon actuation have a high mechanical and control complexity which results in a higher cost. Additionally, more mechanical complexity introduces more possible points of failure making the gripper more fragile. Since this study compares different gripper technologies with the purpose of manipulating waste materials, the higher cost and fragility are difficult to motivate.

Integration requirements:

A. Grasp planning algorithm:

When considering dexterous grippers, the high kinematic complexity introduces complexity in the control of the gripper. A high DOF needs to be controlled to perform successful grasps. Recent works show approaches to control such complex end effectors [73], [74]. However, when only 2 or three fingers are considered, similar planning techniques as with conventional impactive grippers could hypothetically work.

B. Cluttered environment:

Depending on the finger size, count and position, soft grippers with tendon actuation could work in cluttered environments. Due to the soft/compliant nature of the structures, the gripper should be more resistant to collisions while protecting the robot from excessive forces as well.

C. Compatible products material:

Since this gripper type utilizes friction/form closure or caging strategies to fixate the product, the gripper type is material independent. However, the structure/surface roughness and material have an impact on the magnitude of the friction and can have an impact on the lifetime of the gripper, often made from soft materials.

D. Release mechanism:

By opening the gripper, the product can be released from the gripper.

E. Safety:

Since the gripper is constructed from soft materials or with compliance in the actuators, the gripper is considered safer than impactive grippers.

F. DOF:

Due to the high DOF within the gripper itself, only 3 DOF are assumed to be required to position the gripper above the object. Due to high DOF within the gripper, the gripper is considered compliant to imprecise gripper positioning. The conveyor can provide one DOF, therefore only a 1.5 DOF robot is required.

G. TRL:

There are commercially available grippers available, but the grippers are not tested on waste material, therefore, a TRL of 5/6 is considered.

2.3.1.3 Fluidic elastomer actuator (FEA)

Fluidic elastomer actuator (FEA) grippers are widely studied [49], [75], [76], [77], [78], [79], [80], [81]. This type of gripper is produced from an elastic polymer and is actuated by over or under pressurizing a fluid in a void or chamber that is integrated in the design of a gripper. Specific constructions introduce strain in the gripper design which causes the gripper to open and close. Four major constructions are observed: constructions with eccentricity, slits, bellows and fiber-constraints [79].

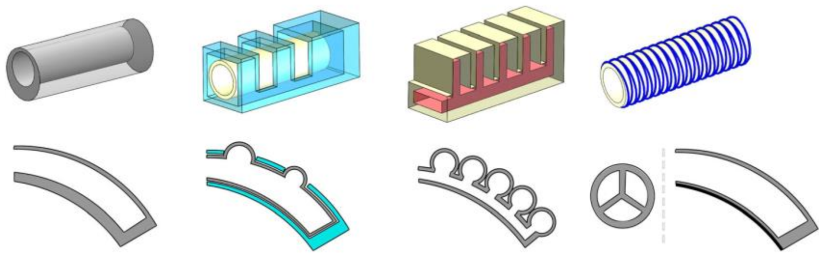


Figure 10: Four construction types for FEA's from left to right designs with: eccentricity, slits, bellows and fiber constraints [79].

A gripper with the fiber-constraint structure is developed specifically for the manipulation of food and vegetables capable of holding objects up to 10kg [78]. Alternatively, the development of pneumatic networks (pneu-nets) is exploited. Pneu-nets are soft elastomeric actuators in which small voids are embedded with a specific shape, forming a pneumatic network. Over- or underpressure in those voids introduce stress and, therefore, strain into the actuator, introducing movement in specific directions, depending on the shape of the pneumatic network. Recently, a method for the analytical modeling of and a design approach for generalized pneu-net soft actuators enabling both bending and twisting deformation is proposed [75].

Integration requirements:

A. Grasp planning algorithm:

Precise modeling, planning and control of an FEA gripper remains challenging due to the fact that FEA grippers are highly compliant, often under actuated, have many DOF, complex deformation and complex geometries [50], [51]. However, due to the compliance of soft grippers, soft grippers adapt better to the inhomogeneity and variety in the product surface allowing for easier manipulation and grasping of unknown objects with simple control schemes [51]. Additionally, it is demonstrated that more complex data driven approaches can be used for pick and place operations with FEA grippers [50], [77].

B. Cluttered environment:

Due to the compliant nature of the FEA grippers, collisions with clutter are not threatening for the mechanical structure. Additionally, the size of the FEA grippers is comparable with impactive finger grippers.

C. Compatible products material:

Since the gripper uses the principle of controlled actuation, the gripper is less suitable for flat objects and more for voluminous convex or non-convex shapes [47]. Since sufficient variety in shapes is expected, this gripper principle is suitable for waste sorting.

D. Release mechanism:

By opening the gripper, the object can be released.

E. Safety:

Since, the FEA grippers are comparable to impactive finger grippers but in the contrary the moving parts of the gripper are manufactured from flexible elastomers, the gripper is considered safe to integrate.

F. DOF:

To perform pick and place (PNP) operations with this gripper a minimum of 3 DOF for a gripper with a minimum of 3 fingers or 4 DOF for two finger grippers is required. 1.5 DOF can be externally solved by the conveyor belt and the allowance for imprecise vertical positioning. The remaining DOF have to be solved by the robot.

G. TRL:

Since there are variants of this gripper on the market but the grippers are not tested in a waste sorting applications, the TRL is considered 5/6 which is sufficient.

2.3.1.4 Electro active polymers (EAP) grippers

Comparable with the electro-adhesion grippers, electro-active polymer soft grippers are grippers that use electrostatic forces to perform grasping. However, with electro-adhesion grippers the grasping is mainly performed by attracting the object with the gripper while for electro-active polymer soft grippers the grasping is mainly performed due to the actuation of a polymer due to electrostatic forces. There is, however, a thin line between the grasping principles since sometimes it is hard to distinguish whether the grasping force is generated due to the contact force because of the electrostatic force of the gripper against the products surface or due to the electrostatic adhesion force itself. Most electro active polymer grippers are used on micro scale. For instance in the manipulation of fish eggs [82]. However, recent work shows the development of electro active polymer soft fingers [83], [84], [85] based on HASEL actuators [86] which utilize electrohydraulic transduces to transform electrical potential into mechanical motion.

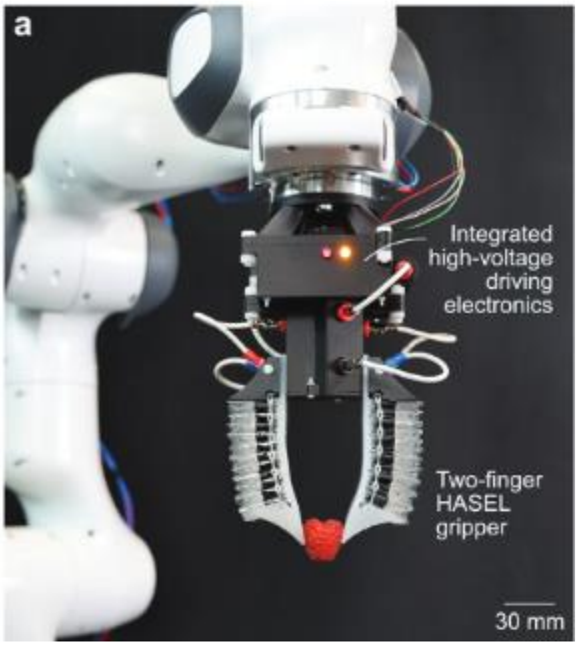


Figure 11: A soft electro-active polymer gripper developed by Yoder et al. [83].

Integration requirements:

A. Grasp planning algorithm:

Since the soft electro-active polymer grippers are mostly realized in the shape of fingers, the assumption can be made that grasp planning algorithms applicable on impactive finger grippers can be used or used as a starting point for the development of new grasp pose planning algorithm.

B. Cluttered environment:

Assuming that there is some unoccupied space around the products, finger grippers can be used to grasp objects in cluttered environments. Therefore, soft electro-active polymer grippers are assumed to work in cluttered environments.

C. Compatible products material:

When the products fit between the gripper fingers and the fingers can be positioned next to the object the product is compatible with the gripper. The material of the product does not play a role in the grasp ability aside from the static friction coefficient.

D. Release mechanism:

By opening the gripper, the products can be released after grasping.

E. Safety:

Soft electro-active polymer grippers yield no more danger than impactive finger grippers. Since EAP grippers are manufactured with soft flexible materials the gripper can be considered safer.

F. DOF:

To operate a finger gripper, the robot must have 4 DOF. By installing a swivel actuator and using the conveyor belt to both fulfill the requirement of one DOF, two DOF remain. Due to the compliance in the soft structure of the gripper, precise vertical positioning might be obsolete. A minimum of 1.5 DOF is required to grasp objects with this gripper type.

G. TRL:

EAP grippers are not commercially available and since EAP grippers are to our knowledge not tested on waste products in specific, this gripper type has a TRL of 3-4 which is considered insufficient.

2.3.1.4 Shape memory actuation (SMA) grippers

Grippers using shape memory actuation are grippers that contain an alloy or polymer which can be influenced with temperature by utilizing a Peltier element, hot plates, or electric current. Most of the known applications are for micro grippers in very precise applications [63], [87], [88], [89]. However, due to thermal inertia, grippers using this actuation method have response times with a magnitude of 10s or more rather than 1s [87], [89].

Integration requirements:

A. Grasp planning algorithm:

Since the gripper technology is only deployed in micro applications, no solutions for macro applications have been observed. No work regarding grasp planning or detection specifically for SMA grippers are found. However, depending on the specific construction of the gripper, hypothetically, grasp planning algorithms designed for other gripper principles, for example impactive grippers, could also work.

B. Cluttered environment:

Due to the fact that this gripper technology is mostly deployed in micro applications, very small gripper designs should be constructable which theoretically could be used in cluttered environments.

C. Compatible products material:

Depending on the specific gripper design, the targeted products and materials will change.

D. Release mechanism:

By altering the heat generation, the gripper can release products.

E. Safety:

The hot or cold surfaces might yield an additional risk for the operator upon contact. However, operators should be separated from the operating gripper due to the highly dynamic robot on which the gripper is mounted. Therefore, the gripper technology is considered safe to be integrated.

F. DOF:

Depending on the number of gripper fingers 3/4 DOF are required to align or position the gripper with or on the specific product. Again, the conveyor belt, a swivel actuator and less precise vertical motion actuation leaves 1.5 DOF to be required from the

G. TRL:

The gripper technology is researched, demonstrated, and used in specific application fields. Since the gripper technology is not widely exploited and not used in any macro application yet, a TRL of 3-5 is considered which is not sufficient for the waste sorting application.

2.3.2 Grasping by controlled stiffness

Grippers that work with the principle of controlled stiffness place the gripper over or around the product in a soft state. Thereby the gripper gets deformed by the product after which the gripper will be stiffened. By stiffening the gripper after being deformed by the product, a form closure will be generated also known as caging [47]. Stiffness can be controlled by performing granular jamming (Section 0), heating, or cooling a low melting point alloys (Section 0) and by influencing electro and magnetorheological properties of the gripper material (Section 0).

2.3.2.1 Granular jamming

Granular jamming is a well-researched gripping technique in which a soft container is pushed into an object after which the soft container is solidified to create a form closure with the product [47], [90], [91], [92], [93], [94], [95], [96], [97]. Traditional granular gripper strategies where developed more than a decade ago [90], [94]. However, more recent, finger grippers with pneumatic actuation and controlled stiffness, by integrating granular jamming, are being developed [91], [92]. Additionally, the shape of the granular filling of the grippers have major impact on the performance of the grippers, multiple studies are conducted to examine the impact of the granular shape on the gripper performance [93], [96]. Mishra et al. have shown that the addition of vibration while pressing the gripper over a product improves the holding force of the gripper while lowering the required downwards force to press the object into the product and making the install of a pressure source to release the objects obsolete [97]. Mingzhu et al. show how granular jamming can be integrated into an FEA gripper to ensure higher possible accelerations without losing the products which allows higher productivity [98].

Integration requirements:

A. Grasp planning algorithm:

H. Zhang et al. have shown how a formhand gripper [94] can be manipulated using a gripping attention convolutional neural network (GA-CNN) [27]. Additionally, assumably heuristics can be used to perform grasp detection and planning.

B. Cluttered environment:

Since granular jamming grippers require to be deformed by the products to enable the caging of the product, unoccupied space around the product is required to enable this gripper type to be functional.

C. Compatible products material:

Granular jamming gripper's function when the gripper can envelop the product. Therefore, the grasp success is only depending on the size of the products, not on the material.

D. Release mechanism:

By unjamming the granulate in the gripper the product can be released.

E. Safety:

Granulate jamming does not involve safety risks.

F. DOF:

Since the gripper can be positioned top down on the product 3 DOF or more have to be available. By realizing one DOF with the conveyor belt and allowing for imprecise vertical motion, only 1.5 DOF are required from the robot.

G. TRL:

Industrial granulate jamming grippers are available. However, those grippers are not proven in industry or tested on the waste sorting application yet. Hence the TRL level of 4/5

2.3.2.2 Temperature stiffness control (TSC) grippers

The stiffness of grippers can be controlled with temperature in two ways: By integrating Low melting point alloy (LMPA) elements [99], [100] or shape memory polymers (SMP) [101], [102] in the gripper structure. The stiffness of both integrated structures can be controlled by regulating the temperature. Hao et al. allowed very localized temperature control which allows the stiffness control of specific finger parts allowing the control of the gripper finger curvature.

Integration requirements:

A. Grasp planning algorithm:

Finger grippers with LMPA or SMP elements can assumably be positioned to grasp products similar to impactive finger grippers. Therefore, there is an abundancy of grasp planning algorithm available for this gripper type.

B. Cluttered environment:

Assuming that the TSC gripper fingers are not bigger than traditional impactive grippers and TSC gripper fingers are more compliant then impactive finger grippers, TSC grippers can work in cluttered environments.

C. Compatible products material:

The grasp efficiency of TSC grippers is not influenced by the product material. Only the product size and shape play a major role in the grasp efficiency of the grippers.

D. Release mechanism:

By removing the contact force between the gripper and the product the product can be released from the gripper.

E. Safety:

STC grippers do not yield increased risk over traditional impactive gripper. Due to compliance these grippers can be even considered safer.

F. DOF:

Analogue to impactive finger grippers a minimum of 3 DOF is required to position the finger gripper actuated with TSC elements. Which results in the use case in a robot with a minimum of 1.5 DOF.

G. TRL:

Since no TSC gripper is commercially available a TRL of 4 is considered which is not sufficient.

2.3.2.3 Magnetorheological

The last method to control the stiffness of gripper elements is by the utilization of magnetic fields and magnetic influence media such as magnetorheological (MR) fluid. The potential of using magnetically controllable segments in grippers is explored by Cramer et al. [103]. These controllable elements can be found in the fingertips of finger grippers [104] or in adapted suction cups [105]. Other studies show the simulation of the magnetorheological behavior to determine the design of magnetorheological grippers [106].

Integration requirements:

A. Grasp planning algorithm:

Finger, suction cup and bellow grippers are found that utilize magnetorheological effects to control the stiffness of specific gripper elements. Finger and suction cup grippers are commonly used in the state of the art. For those, grasp pose planning algorithms are abundantly available. For bellow grippers no grasp planning algorithms are available to the knowledge of the authors.

B. Cluttered environment:

Finger grippers and suction cups are known to work in cluttered environments. However, since bellow grippers require the surrounding of the product, more space is required. For this reason, bellow grippers are more difficult to operate in cluttered environments.

C. Compatible products material:

The implementation of magnetorheological grippers is product material independent.

D. Release mechanism:

By opening the finger gripper, removing vacuum from the vacuum cup or removing the pressure from the bellow gripper objects can be released.

E. Safety:

Magnetorheological grippers yield no increased risks compared to traditional impactive finger grippers, suction cup grippers or bellow grippers.

F. DOF:

Depending on the gripper type on which the magnetorheological structures are integrated, 3 or more DOF are required to function which requires the robots in the case study to have at least 1.5 DOF.

G. TRL:

Since magnetorheological soft grippers are not validated in a relevant industrial use case and are not available of the shelve, a TRL of 4 is assigned.

2.3.3 Grasping by controlled adhesion

Grasping by the utilization of adhesion is based on the interaction between two surfaces as a result of an external force which leads to a normal pressure which generates a proportional shear stress [47]. There are four types of soft grippers using controlled adhesion: dry, wet, electro and magnetorheological adhesion grippers. Academic work on the dry [89] and wet [107] variants is very limited and does not give insight into the controllability of the adhesion. Therefore, these gripper types will not be further considered. Electro controlled adhesion and magnetorheological adhesion control are more developed and will be further discussed.

3.3.3.1 Electro adhesion to soft structures

Electro controlled adhesion grippers are grippers that utilize a potential difference to generate a forcefield which causes the adhesion of the gripper elements to the products. Recent work shows the utilization of tapes with electro-active elements that create normal Maxwell stress on the contact surface [108], [109]. Another application of these electro-active layers is in the variable stiffness electro-adhesive fluidic (VSEAF) gripper [110] which is utilizing an electro-adhesion and LMPA layer on the contact surface of a FEA gripper in the shape of a pneu-net which results in a pneumatically actuated soft finger with variable stiffness and electro-adhesion.

Integration requirements:

A. Grasp planning algorithm:

Since the electro adhesion grippers are mostly finger shaped, grasp pose planning algorithms specifically designed for impactive finger grippers can be borrowed or adapted.

B. Cluttered environment:

Since most of the electro adhesive grippers are very thin or at least low profile, grasping in cluttered environments is not considered problematic.

C. Compatible products material:

Electro adhesive grippers have no incompatible materials.

D. Release mechanism:

By removing the electrical potential from the gripper, products can be released.

E. Safety:

Since electro adhesive grippers require very high voltage. Electro-adhesive grippers are not considered safe in polluted and possible dusty environments close to operators.

F. DOF:

Since electro-adhesive grippers are mostly finger grippers a minimum of 3 DOF is required to grasp products which, in the use case, results in a robot with at least 1.5 DOF.

G. TRL:

No electro adhesive grippers are available off the shelve and they are not tested in related environments outside of the lab. Therefore, a TRL of 4 is assigned.

2.3.3.2 Magnetorheological controlled adhesion (MCA)

Magnetorheological (MR) fluid has been demonstrated useful to generate controllable wet adhesion. The fluid is applied to the gripper on the contact surface between the gripper and the surface after which the adhesion of this fluid to a product can be influenced by controlling the magnetic field through the fluid [111]. However, due to the high cost and the contamination of the product due to the metal particles in the MR fluid MCA is not often used and, therefore, not yet industrially developed.

Integration requirements:

Since the specific shape, form and functioning of this gripper type is unknown, no further information or estimation on integration requirement parameters can be disclosed, MCA grippers are considered underdeveloped and, therefore, not usable for the specified use case.

2.4 Overview of results

Table with all the options and their integration requirements. The specific options that are not considered a fit for the use case are indicated in red.

	critiria: (green if quantifyable)	grasp planning	clutter obstruction	compliant materials available	release mechanism	grasp DOF requirement	safety	TRL
	treshold:	/	/	1	0	4	0	6/7
hard grippers								
impactive grippers								
parallel - 2 - finger	friction closure	1	0	1	1	4	1	9
parallel - 2 - finger	form closure	1	0	1	1	4	1	9
angular - 2 - finger	friction closure	1	0	1	1	4	1	9
angular - 2 - finger	form closure	1	0	1	1	4	1	9
angular - 3 - finger	friction closure	1	0	1	1	3	1	9
angular - 3 - finger	form closure	1	0	1	1	3	1	6
radial gripper	form closure	1	0	1	1	3	1	6
ingressive gripper								
intrusive	thick needles	1	1	1	1	3	0,5	6
non intrusive	pinching/fine needles	1	1	1	1	3	0,5	6
astrictive								
pneumatic vacuum	suction cup	1	1	1	1	3	1	9
pneumatic flow	bernoulli & vortex	1	1	1	1	5/6	1	6
pneumatic flow	coanda	1	1	1	1	3	1	6
pneumatic flow	HAVCO	1	1	1	1	3	1	6
magnetic	permanent magnet	1	1	**0**	0	3	1	6
magnetic	electromagnet	1	1	**0**	0	3	1	7
electro-adhesion	tapes that move under electronic charge	1	1	1	1	4	**0**	**4/5**
optical	pressure diff. radiation pressure	/	1	1	1	3	/	**1/2**
acoustic	pressure diff. acoustic waves	/	1	1	1	**4+**	/	**1/2**
contigutive								
penetrating	freezing	1	1	1	1	3	1	**5**
non- penetrating	chemical/fluidic	1	1	1	**0**	3	/	**5**
non- penetrating	dry (gecko tape)	1	1	1	**0**	3	/	**5**
soft grippers								
actuation controlled								
passive structures	contact driven	1	0	1	1	4	1	5/6
passive structures	tendon driven	1	0	1	1	4	1	5/6
fluidic elastomer actuato	inflatable structure	1	0	1	1	4	1	5/6
electroactive polymer	dielectric polymer	1	0	1	1	3	0	**4**
shape memory material	with temp influencable	/	0	1	1	3	1	**3/4**
controlled stiffness								
grannular jamming	flexible container/ grannular filling	/	0	1	1	3	1	**4**
magnetorheological	flexible container/ magnetic fluid filling	/	0	1	1	3	1	**4**
temperature stiffness co	low melting point alloy/polymer?	/	0	1	1	3	1	**4**
controlled adhesion								
magnetorheological	magnetorheological fluid	1	1	1	1	3	/	/
dry adhesion	adhesive material	1	1	1	**0**	3	/	/
electro-adhesion	static charge?	1	1	1	1	3	**0**	**4/5**

Figure 12: Overview of results of integration evaluation.

From the 7 different subclasses, 3 subclasses within the gripper taxonomy are underdeveloped. Therefore, contigutive, controlled stiffness and controlled adhesion grippers will not be further considered for the packaging waste sorting case. From the other gripper classes not all gripper types are withheld, the remaining rejected technologies from both the conventional and soft grippers will be discussed below.

From the astrictive conventional grippers, magnetic, electro-adhesive, optical and acoustic grippers will be withheld. Since the application consists of mostly non-magnetic materials and there is an overhead magnetic conveyor belt installed, there will not be sufficient materials available that can be picked with magnetic gripper technology. Electro-adhesive grippers are not further considered due to the insufficient TRL, aside from this the gripper technology operates with very high voltages which introduces safety risks. Additionally, the gripper technology has higher retention forces on conductive materials while most of the materials within the packaging waste stream consist of non-conductive materials. Finally, within the conventional grippers, optical and acoustic grippers are not further considered since these grasping techniques are in the initial phase of their development which makes them not mature enough to serve in the application case, additionally these gripper techniques are focused on the grasping of very small objects.

Within the soft grippers two more gripper types will not be further considered: electro-active-polymer and shape memory material grippers. Both those gripper techniques are not further considered since they are underdeveloped and not ready to be implemented in grippers for the sorting of packaging waste.

For the application case of the sorting of packaging waste material, five major gripper types remain applicable, three conventional grippers and two soft grippers. From the conventional grippers, impactive grippers, intrusive grippers, astrictive grippers remain. From the soft grippers, the actuation-controlled grippers and fluidic elastomer grippers remain.

Impactive grippers are common in the state of the art in the shape of two finger grippers and will be also considered for the case study.

Ingressive grippers are available in two types: intrusive and non-intrusive grippers. Non-intrusive grippers function by pinching or only slightly penetrating the surface with small needles. Intrusive grippers have more robust pins that intrude deep in the objects to fixate the products. Since, pinching doesn't work on stiff material and small needles are fragile, only intrusive ingressive grippers will be considered for the use case.

Various astrictive gripper principles can be considered. Suction cup, vortex and Bernoulli, and Coanda grippers are grippers that generate a vacuum to astrict a product to the gripper. The major difference between these gripper types is the method to generate the vacuum. Since suction cup and Coanda grippers can be constructed such that, they are more compliant to object surface irregularities and vortex and Bernoulli grippers are mostly used on very flat materials, vortex and Bernoulli grippers will not be further considered since very flat products are not common in packaging waste streams. Coanda grippers are bigger and heavier than suction cup grippers, but they can withstand more RVF. However, by generating vacuum with a blower when using suction cups, suction cups can withstand RVF as well. This makes them a lighter and smaller alternative. For this reason and the fact that suction cups are basically the state of the art in waste packaging sorting, only the suction cup grippers will be proposed and evaluated. The HAVCO gripping principle is the last astrictive alternative. Since the HAVCO gripping principle is rather new and not solely astricting objects, but also conveying objects to the sorting bin directly, which yields majorly reduces PNP cycle times, the HAVCO principle will be further developed and tested next to the suction cup grippers.

Soft, action-controlled, grippers are the last category of grippers that are considered for the waste sorting application. Two major types within this category are identified, grippers with passive structures and fluidic elastomer structures. The grippers with passive structures can be actuated by contact or by tendons. Only the contact driven passive structure soft grippers will be further considered since tendon grippers come with a much higher cost and, both actuation and mechanical, complexity due to the high DOF within the grippers that are available in the state of the art. Grippers with fluidic elastomer structures can be actuated by changing the pressure on the fluidum withing the structures. Since the fluidic elastomer grippers are becoming present in other automation solutions these will be further considered within the project.

3. RoReWo implementation

Robotic waste sorting has gained popularity and is increasingly being recognized as a valuable tool in waste management [112]. The majority of existing solutions on robotic waste sorting use general purpose, highly efficient yet also high cost robots to implement the physical sorting of recyclables. This is for example the case with the use of Delta robots [113, 114, 115], robotic arms [116, 117], gantry robots [118]. These robots are designed to provide precise and delicate movement capabilities, which are critical for many applications, but are less relevant for waste sorting. For example, sorting plastic waste does not require fine and accurate manipulation as it is often compressed and highly deformed while being transported in garbage trucks.

The implementation of various types of Robotic Recycling Workers (RoReWos) with differing degrees of freedom considered in RECLAIM, stems from a fundamental need to optimize efficiency and adaptability within recycling facilities. Therefore, RECLAIM’s RoReWos are are designed with the waste sorting application in mind.

Each degree of freedom represents a distinct level of mobility and flexibility that directly influences robot's ability to reach, pick and sort recyclable materials. By deploying robotic systems with varying degrees of freedom—1.5, 2.5, and 3.0—recycling facilities can tailor their automation solutions to match specific operational requirements and challenges. This approach not only enhances productivity and throughput but also minimizes the capital expenditure (CAPEX), downtime and resource wastage, ultimately contributing to a more sustainable and efficient recycling ecosystem.

In Deliverable 2.1, we conducted a theoretical analysis comparing various robotic technologies, examining implementation costs and anticipated performance. The decision was made to adopt a cartesian approach for developing RECLAIM's RoReWos as this strategy could potentially lower implementation costs while offering the flexibility to develop and evaluate both simple and more complex robots. These assessments will allow RECLAIM to draw meaningful conclusions about the effectiveness of different RoReWo architectures for material recovery within the prMRF context.

Early developments summarized in Deliverable 5.1 considered the use of industrial solutions provided by Festo which combine high speed, large working area, high robustness, ease of programming, acceptable investment and operational cost. These cartesian robots can be designed in distinct configurations, of 1.5, 2.5 and 3.0 DOF allowing components to be individually purchased and subsequently assembled into fully operational systems. This modular design approach facilitates the customization of RoReWos to meet specific operational needs, incrementally enhancing their functionality and efficiency for waste processing tasks.

In short, RoReWos designed with 1.5 degrees of freedom exhibit controlled linear movement along a single axis being able to move with high precision across the whole width of the conveyor belt and they are combined with an additional "0.5 DoF'' that refers to a binary state piston that can rapidly change state using compressed air to provide a fixed pneumatic movement on the vertical axis (motion towards the belt). Although relatively simple in design, these robots can achieve high performance at tasks involving the picking and sorting of objects. The RoReWos exhibiting 2.5 degrees of freedom possess additional controlled movement along a second axis that is parallel to the movement of the conveyor belt, thus enabling more complex treatment of the objects transported on the belt e.g., follow the objects and align the gripper to improve grasping. The second degree of freedom empowers RoReWos to tackle a wider range of material sorting situations, including the active motion towards the objects as opposed to pathetically waiting for objects to arrive at the proper location, in the case of the 1.5 DoF RoReWo. Finally, robots with 3.0 degrees of freedom offer the highest level of mobility and dexterity, enabling them to perform intricate movements and easily adapt to dynamic conditions. These advanced robotic systems can host a range of different grippers and thus they are well-suited for tasks requiring fine manipulation, such as separating mixed materials or processing fragile items.

By conducting a systematic comparison of these robotic systems across various performance metrics, including speed, accuracy, and resource utilization, RECLAIM aims to provide valuable insights into how different degrees of freedom influence a robot's efficiency, adaptability, and overall effectiveness within recycling operations. Ultimately, the goal is to determine the best robotic configurations that, when paired with certain gripping mechanisms, optimize the efficiency-per-cost ratio for the recovery and sorting of different materials. This is particularly relevant in the context of the circular economy and the decentralized waste processing model advocated by RECLAIM.

3.1. System architecture and components

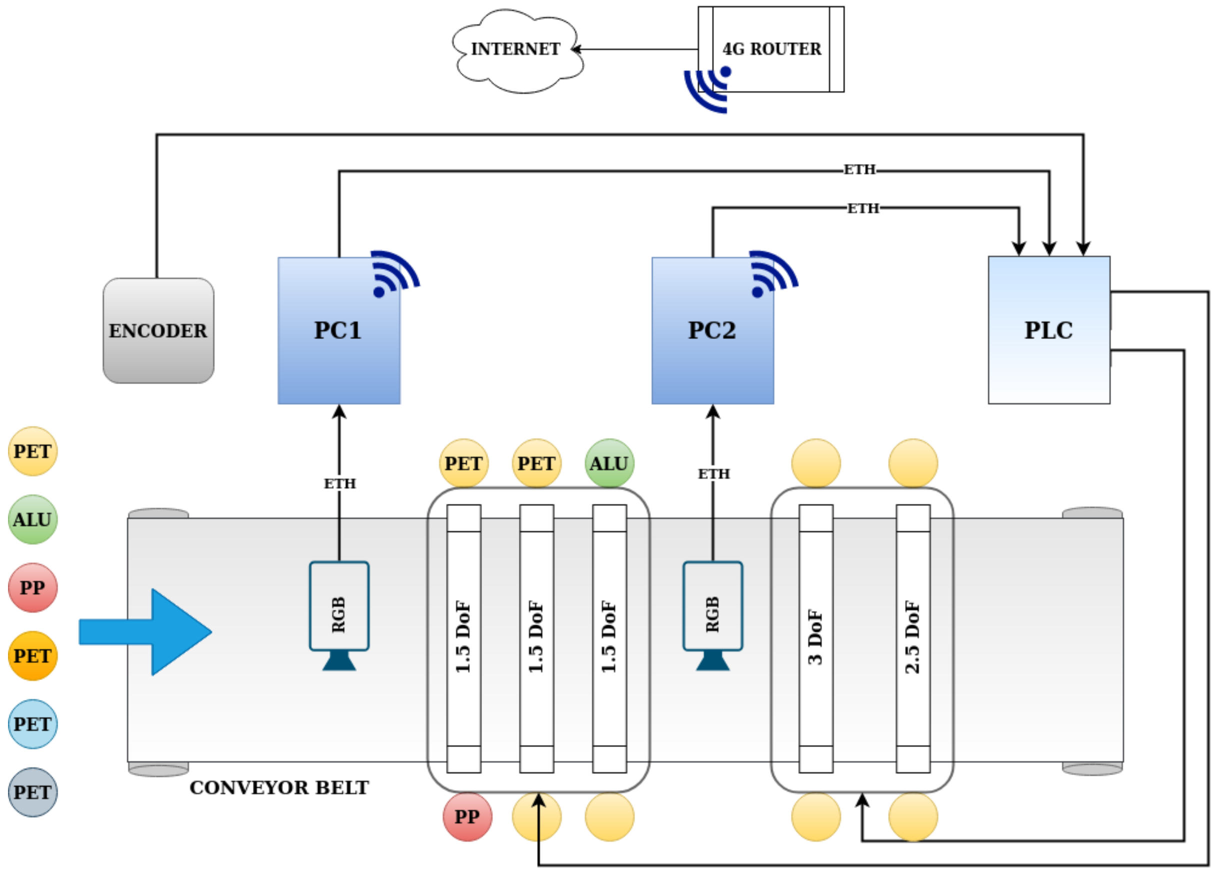


Figure 13. Overview of the autonomous waste sorting system integrated in the prMRF.

The RoReWo system used in RECLAIM is fully custom creation made by ROBENSO. It combines hardware components, (Programmable Logic Controller - PLC, PCs, motors, valves, vacuum system, pneumatic system, button strip, encoders, and software components (PLC program, robot control, interface with the vision software, goal management module) to effectively perform the sequence of actions required to support waste sorting tasks.

In short, the key components installed in the prMRF to enable intelligent and autonomous recyclable sorting, include:

- A PLC Controller serves as the central control unit that manages and orchestrates the operation of the mechanical parts, such as motors and valves. The PLC operation is enabled by custom made programs that serve as ready-to-execute, properly parameterized modules. used as properly parameterized ready to execute modules, to control the behavior of the motors and pneumatic actuators based on input signals and domain-specific programmed logic.

- Two Ubuntu 20.04 PCs are used are used with identical setups to run the RGB-based AI-ILC components described in Deliverable 3.1 (the module responsible for processing hyperspectral images runs in a separate PC). Each PC handles one of the two RGB cameras and is responsible for capturing and processing the corresponding the corresponding images (one of these PCs is additionally responsible for the synchronizing and combining the information coming from the RGB and Hyperspectral cameras). Mask R-CNN is used for recyclable identification, localization, and categorization, which are communicated to the robots through the PLC controller.
- For each RoReWo a separate blower is used, which provides vacuum to the suction cup to securely pick and hold recyclables during their transfer to the corresponding collection bin.
- A compressed air network is installed in the prMRF and is linked to the robot's 0,5 DOF linear actuators and, if necessary, the end-effectors, to supply compressed air for the operation of all all-pneumatic valves and actuators. Additionally, compressed air powers the movement of the mechanical components in grippers and, when necessary, facilitates the object ejection/disposal to accelerate the cycle of material picking and sorting. It also helps clean the suction cups from dirt and sticky materials.
- An encoder is used to measure the speed of the conveyor belt. It provides feedback on the velocity of the belt, which is communicated to the PLC and used for synchronizing RoReWo actions with object location.
- Five Robotic Recycling Workers with different configurations, three of which with 1.5 DoF, one with 2.5 DoF and one with 3 DoF.

3.3. ReRoWo robots

Following the theoretical comparison of alternative robotic architectures summarized in Deliverable 2.1, three different types of linear robots have been studied and implemented in RECLAIM. All robots were designed targeting the development of cost-effective, high productive waste pickers. To ensure a minimum of operational effectiveness, RoReWos were originally designed under the assumption that they will carry suction cups. Therefore, without eliminating RoReWo usability, the presentation that follows assumes that robots are equipped with vacuum grippers. However, in the sections that follow, it will be outlined how the robot's carriage has been suitably modified to accommodate multiple grippers supplied by KUL.

The key characteristics of the different RoReWo architectures considered in RECLAIM are summarized below.

3.3.1 Linear 1.5 DoF Robotic Recycling Worker

The linear 1.5 DoF RoReWo [119], incorporates various low-cost components that enable waste picking through the two-dimensional movement of the robot's end-effector vertical to the movement of the conveyor belt (see Figure 14). In other words, the 1.5 Dof RoReWo can pick objects located in the line created after the hypothetical projection of its X axis on the conveyor belt.

The X-Axis is composed of a Motorized industrial linear toothed belt (ELGA-TB-KF-80-1500) with a working stroke of 1500mm. It utilizes a Servo motor (EMMT-AS-100) with a maximum rotational speed of 4790 rpm and a nominal torque of 6.3 Nm, mounted on the linear drive and driving the linear toothed belt axis. The movement on the X-Axis allows the robot to travel along the whole width of the belt that transfers recyclables.

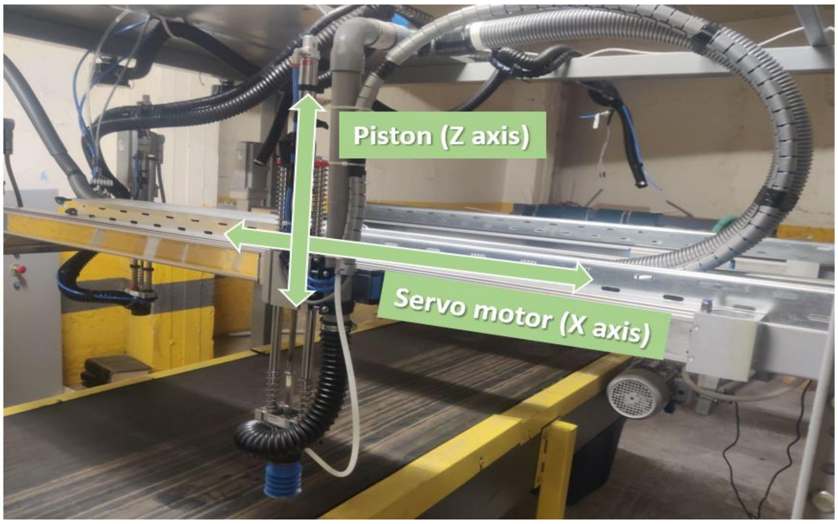


Figure 14. The low-cost architecture of RoReWos, specialized in waste sorting.

The Z-Axis is implemented by a Pneumatic piston (TMIC L 20X250 SG) with a working stroke of 250mm to provide vertical movement along the Z-axis. The piston operates with a working pressure of up to 10 bar. A Double cylinder guide is connected to the pneumatic piston and mounted on the X-axis. It provides stability and guidance for the vertical movement. Springs are installed on the cylinder guide to act as smooth passive brakes, aiding in the controlled stopping of the movement. The vertical movement of the piston along the Z-axis allows the end-effector to descend towards the conveyor belt to reach specific waste items, then retract upwards to collect the waste and enable its placement into a collection bin for sorting. Terminal switches are present on the X-axis for homing and safe operation. They provide reference points for the positioning and safe operation of the X-axis. A terminal switch is also present on the Y-axis. It is used to close the loop and retract the pneumatic piston after reaching the target position.

Two air pressure tubes are used to control the movement of the pneumatic piston in the Y-axis. One additional compressed air tube is used to support object manipulation e.g., for fast object ejecting, but also to remove dirt and enable cleaning of the suction cup. A Multicore electrical cable is used to provide power supply and control signals to the terminal switches.

A cable carrier is utilized for the management of components that move during RoReWo operation. In particular, it guides and organizes the electrical cables and pneumatic tubes during movement in a controlled manner, ensuring their proper positioning and protection.

3.3.2 Linear 2.5 DoF Robotic Recycling Worker

The 2.5 Degrees of Freedom (DoF) RoReWo expands upon the capabilities of the linear 1.5 DoF system by incorporating additional movement along the Y-axis, which is aligned with the direction that the conveyor belt moves. This augmentation extends the working range of RoReWos and enhances their versatility and adaptability in handling materials across the 2D plane of the belt.

The Y-Axis is composed of a Motorized industrial linear toothed belt (ELGA-TB-KF-80-700) with a working stroke of 700mm. It utilizes a Servo motor (EMMT-AS-100) with a maximum rotational speed of 4790 rpm and a nominal torque of 6.3 Nm.

The Y-axis is used to actively move the robot towards the targeted objects and additionally, while the gripper operates on waste, to track the object by synchronizing the end-effector's movement with the conveyor belt. This synchronization, maintained for a brief period, enhances the probability of successfully picking up objects.

This synchronized movement is considered, depending on the gripper mechanism mounted on the RoReWo, either advantageous or required. For example, for vacuum suction cups, the alignment of the suction cup with the motion of the object on the belt facilitates sealing, and improves material picking efficiency. For other gripper mechanisms, such as parallel gripping, this alignment is considered a prerequisite for successful gripping because of the longer time needed by the gripper to act on the object.

3.3.3 Linear 3.0 DoF Robotic Recycling Worker

The 3.0 DoF RoReWo builds upon the foundation laid by the 2.5 DoF system, further enhancing its capabilities with the inclusion of a motorized Z-axis. The introduction of the motorized Z-axis enables precise vertical position control to accommodate varying material heights and waste treatment requirements. Utilizing a motorized linear actuator with a working stroke of 300mm, this axis provides dynamic control over the vertical movement, enhancing the system's adaptability and versatility.

Similar to the 2.5 DoF system, the Y-axis is dedicated to synchronized movement with the conveyor belt, ensuring alignment with the movement of the incoming targets.

The Z-Axis, newly introduced in the 3.0 DoF system, comprises a motorized industrial linear toothed belt (ELCC-TB-KF-70-300) with a working stroke of 300mm. It is driven by a Servo motor (EMMT-AS-100) boasting a maximum rotational speed of 4790 rpm and a nominal torque of 6.3 Nm. This motorized Z-axis empowers the system with precise vertical adjustment capabilities, facilitating seamless treatment of materials at varying heights.

The inclusion of motorized control over the Z-axis constitutes a RoReWo advancement resulting in a very flexible 3.0 DoF system, which enhances prMRF capabilities in recyclable handling tasks across three dimensions. This addition provides increased motion precision and control, allows for the mounting and evaluation of various grippers for waste sorting activities (also with higher weights), and further enables the system to adapt to various industrial applications beyond the sorting of post-consumer waste. On the other side,

the capability for precise movement in three-dimensional space makes the 3.0 DoF RoReWo heavier, which slightly reduces the speed of the end-effector.

3.4. Robot control

The Festo CPX-C1 PLC serves as the central control unit for the robotic waste sorting system and is responsible for the execution of the control scheme. The implementation of the control logic is realized through CODESYS Structured Text, a powerful programming language tailored for industrial automation applications.

The control scheme operating the robotic material handling process is designed for seamless coordination and efficient target management. Upon detection by the vision systems, the targets' coordinates and the estimated time until they reach RoReWos are transmitted to the Programmable Logic Controller (PLC) for processing.

The PLC employs a precise calculation algorithm dedicated to the 1.5 DoF, 2.5 DoF and 3.0 DoF RoReWos to determine the optimal timing for the initiation of robot movements. For example, in the case of the 1.5DoF ReReWo, the time required for the robot to traverse horizontally to align with the target in the X-axis is computed together with the time for the pneumatic piston to extend and reach the target in the Z-axis. By subtracting these values from the estimated arrival time of the target under the first robot, the PLC can ensure that all movements are properly synchronized and commands to the robots are timely triggered, allowing for accurate material reach and pickup.

To maintain efficient target distribution and robot utilization, a round-robin technique is currently employed to evenly distribute targets among the available robots. Future work will investigate the implementation of more advanced task planning algorithms to optimize both the work distribution and overall efficiency of the RoReWo.

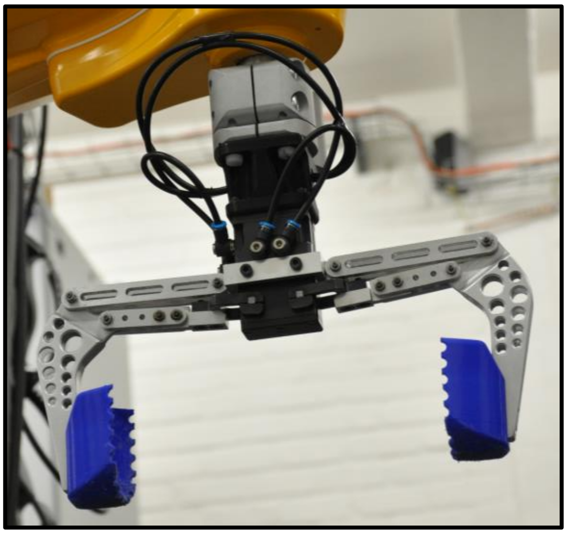
For all 1,5 and 2,5 DOF robots each picking cycle starts with the gripper moving towards the object in the horizontal plane. Upon the robot reaching its designated position on the X-axis (1.5 DOF) or X and Y axis (2.5 DOF), the movement along the Z-axis is initiated. To implement this action, the PLC commands the opening of the valve, prompting the pneumatic piston to commence its downward motion. As the piston descends, it continues until it makes contact with the bottom terminal switch or a delay timing is surpassed. Upon contact, the valve closes, halting the downward motion, and subsequently, the piston begins its upward ascent. The piston continues to ascend until it reaches the upper limit switch, signaling the completion of the vertical movement. Once the upper limit switch is triggered, the movement towards the deposit bin is initiated, allowing for precise positioning of the robot above the designated class bin for target deposition. It should be noted that currently, the Z-axis movement commences only after the X and Y axes have completed their motion. However, it is anticipated that simultaneous operation of the motorized (X, Y) and pneumatic (Z) RoReWo components could significantly reduce the time of the waste sorting cycle, and enhance the performance of the composite system.

In the case of the 3.0 DOF robot, the motion of the end-effector is implemented by simultaneously moving all axis to the target location. When the target location is reached, the object on the conveyor belt is tracked for a predefined time (depending on the operating gripper) and then the motion towards the collection bin is initialized.

4. Proposed gripper ReRoWos combinations and implementation

4.1. Impactive gripper design

Parallel gripper design with four-bar linkage



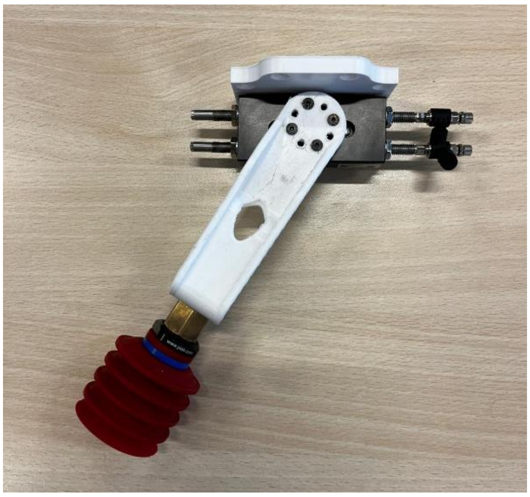
Gripper mounted on SCARA robot in KU Leuven laboratories

The parallel gripper design has been installed in the prMRF with the passive structured fingers, but not with the soft fingers, as these soft fingers do not provide the needed compensation for unintended collisions with objects on the conveyor. During initial tests the gripper was found to frequently collide with the objects, which would lead to damage to either the fingers, gripper or mounting brackets. To prevent such collisions a 3D imaging system would be required, which is today not available. Therefore, no further tests are planned with this gripping mechanism in the context of the Reclaim project.

4.2 Astrictive gripper design

Suction cup gripper design

Suction cup gripper with blower generated vacuum installed in the Reclaim Pr-MRF



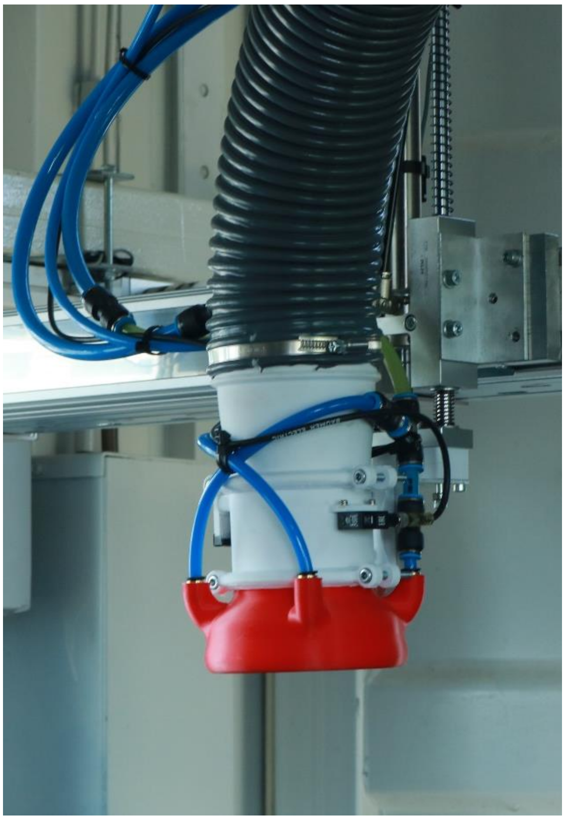
Piab suction cup installed on a swivel arm powered by a Zimmer swivel actuator.

To allow for misalignment of the gripper on the products, a multi bellow silicone suction cup grippers are installed on the 3 first 1.5 DOF robot in the pr-MRF. The vacuum in the suction cups is generated with 3 separate blowers, which allow for better grasping of irregular shaped objects (higher RVF).

A module designed to aim objects at the bin and eject them with overpressure was also developed to allow for the reduction of picking times. Where a prototype of this system is available for installation, this was not prioritized, as a distinct motion profile is to be programmed to enable the correct testing of this pick and blowing/throwing principle.

Therefore, further tests will in first instance be performed with the suction cup grippers, with vacuum generation by blowers and without the launching module. These suction cup grippers are installed on the 1.5 DOF robots, since these grippers are fast and, hence, do not require tracking during grasping.

HAVCO gripper design



HAVCO gripper designed and developed by the KU Leuven

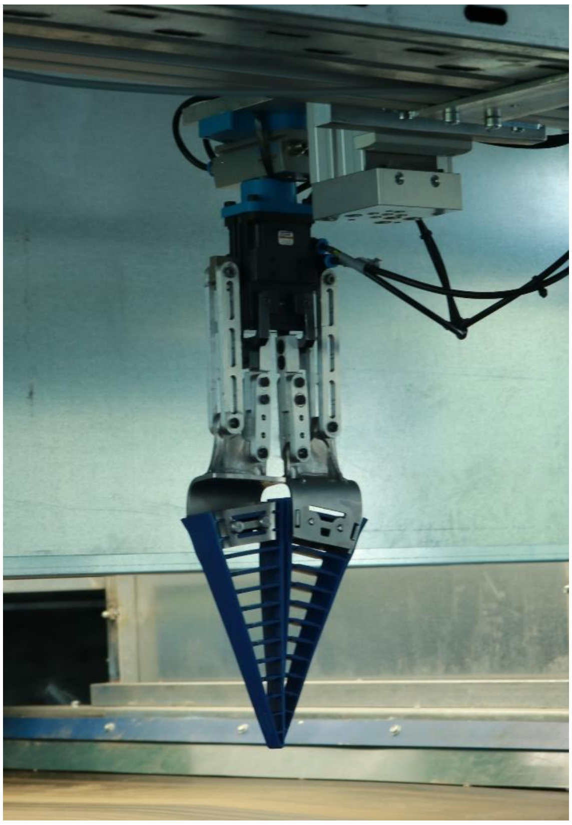
The HAVCO gripper prototype is further developed for the RECLAIM project by KU Leuven. A concentric Coanda nozzle is implemented instead of the 6 individual nozzles. By interchanging the heavy metal threaded inserts with push lock connectors with pneumatic push lock inserts that press directly in the accepting material a substantial weight reduction is realised. Additionally, the design of the gripper is altered to enable a redesign keeping in mind production technology, serviceability, weight, and cost. The HAVCO design has also been made modular, allowing for the separation of the nozzle, diffusor, and mounting equipment. This allows for fast replacement of the nozzle which might collide with clutter on the conveyor belt. Two different diffusors have been designed. One with an open troth aimed in a direction up which intends to launch objects into the drop of location. The second with a straight design ending in an interface to mount a hose. The intention is to use the hose to convey the objects directly into the sorting bin making a substantial part of the robotic motion obsolete. Within the diffusor, a laser sensor is installed which can confirm when an object is picked or detect whether the nozzle of the gripper is blocked.

Another nozzle is installed in the diffuser, pointed at the nozzle opening. This nozzle will activate (“sneezing”) when blockage is detected in the nozzle of the gripper. Un-blocking the gripper can be performed above a sorting bin, this introduces a secondary function similar to the function of a suction cup or Coanda gripper, where the grippers airflow is intentionally blocked with a bigger item to allow for the creation of vacuum (with or without high RVF) in order to attract the objects and move them from the conveyor belt to the sorting bin.

The HAVCO gripper is installed and tested on the last 2.5 DOF robot, which is only used in 1.5DOF functionality, since tracking or precise positioning of the gripper on the product is not required. Installation on the last robot is also selected, as this allows the HAVCO gripper to work in on a conveyor with least dense filling to prevent unintended picking of multiple objects or the moving of other object with the high airflow created during activation of the HAVCO.

4.3 Soft-actuated gripper design

Passive structure gripper design

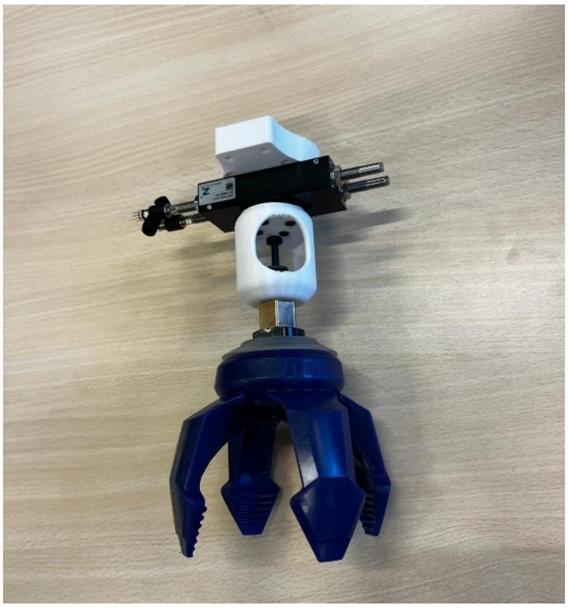


Festo Finray fingers mounted on the four-bar linkage finger gripper designed by KU Leuven.

A parallel gripper utilizing a pneumatic angular actuator in combination with a four-bar linkage is installed on the 3DOF robot that is equipped with soft compliant fingers. The pneumatic actuator allows for integration with low effort and low upfront investment cost. The integrated four-bar linkage yields two major advantages: a wide grasping range and beneficial motion trajectory. Due to the circular motion path of the gripper fingers, the fingers move down while they close. With traditional parallel grippers the fingers have a linear motion path while they close. Therefore, a linear space equal to the maximum grasp dimension must be free on the conveyor belt. Due to integration of the four-bar linkage with a circular motion path and good pose planning, the integration of the four-bar linkage allows for the grasping of wide object while requiring less free space around the objects. For maintenance and development purpose the contact surfaces of the gripper fingers are interchangeable. To enable operation on a 3 DOF robot and as an interface between the robot and the gripper body, a pneumatic swivel mount is installed to align the gripper with the grasping posed defined for the object. This swivel mount can change the orientation of the gripper to two predefined orientations.

The finger grippers are installed on the 3 DOF robots for several reasons: 1. For successful grasping it is essential that sufficient space is available around the objects for the fingers to close. As the 3DOF robot is installed as the 4th robot, after 3 1.5DOF robots, the conveyor filling will be less dense. 2. The parallel griping mechanism is expected to be most successful for the grasping of 3D shaped objects, which are also known to be prone to move after imaging on the conveyor. As the 3DOF robot is positioned directly after the second camera system, the time between imaging and grasping is limited and, hence, also the movement of the object prior to grasping. 3. The 3DOF robot allows for the synchronization of the gripper with the object prior to grasping which is beneficial due to the slower actuation of this gripper compared to suction cups or the HAVCO gripper. due to the requirement of tracking

Fluidic elastomer gripper design



Piab Pi-Grip fingers mounted on a Zimmer swivel actuator.

Piab developed a series of fluidic elastomer grippers. The finger grippers include a cavity which can be brought in under- or overpressure, introducing stress on the gripper. Due to the designed structure of the gripper this stress, closes the gripper when the cavity under pressure is applied on the gripper. When bringing the cavity to atmospheric pressure, the gripper returns to its rest position, which is opened. When the two or four fingered variants of this gripper are used, the gripper must be aligned with the product. For this reason a swivel actuator is mounted on top of this Piab fluidic elastomer gripper. However, the main disadvantage of these grippers are their limited reach and, hence, the limited size of objects they can grasp. As a result, only specific object classes could be considered, such as cans. For this reason, priority is given to the testing of the soft actuated parallel gripper design, whereas this gripper is also available to be interchanged and mounted in a similar manner to the 3 DOF robot.

5. Conclusions

From the 25 gripper technologies identified in literature, only four gripper types were selected for further investigation in RECLAIM, after careful consideration and filtering based on the integration parameters. Within these four types, an impactive gripper 2 finger gripper, suction cup gripper, HAVCO gripper, passive structure two finger gripper and fluidic elastomer gripper have been developed and transported to Crete to be installed and tested in the prMRF. Additionally, one launching mechanism for the suction cup gripper has been provided.

At the same time RECLAIM has designed and developed different versions of the Robotic Recycling Workers (RoReWos) which we consider as a new low-cost alternative to the use of general purpose, high cost robots for waste sorting. Five distinct RoReWos have been created, installed in the prMRF and are now fully operational, effectively performing waste sorting tasks (3 x 1.5DoF RoReWo, 1 x 2.0 RoReWo, 1 x 3.0 RoReWo).

From the provided grippers, the passive structure finger gripper, HAVCO gripper and suction cup gripper have been installed on RoReWos and tested inside the prMRF. On these robots the grippers have been tested on more than 1000 objects with a heterogeneous shape. The test results are described in deliverable 5.2.

4. References

1] "RECLAIM - AI-powered Robotic Material Recovery in a Box." Accessed: Jun. 14, 2023. [Online]. Available: https://reclaim-box.eu/

[2] "ACROGRIP – KU Leuven." Accessed: Jun. 14, 2023. [Online]. Available: https://acrogrip.be/

[3] J. Hughes, U. Culha, F. Giardina, F. Guenther, A. Rosendo, and F. Iida, "Soft Manipulators and Grippers: A Review," *Front. Robot. AI*, vol. 3, 2016, Accessed: Aug. 23, 2023. [Online]. Available: https://www.frontiersin.org/articles/10.3389/frobt.2016.00069

[4] J. Schmalz and G. Reinhart, "Automated Selection and Dimensioning of Gripper Systems," *Procedia CIRP*, vol. 23, pp. 212–216, Jan. 2014, doi: 10.1016/j.procir.2014.10.080.

[5] V. P. AGRAWAL, A. VERMA, and S. AGARWAL, "Computer-aided evaluation and selection of optimum grippers," *Int. J. Prod. Res.*, vol. 30, no. 11, pp. 2713–2732, Nov. 1992, doi: 10.1080/00207549208948186.

[6] D. T. Pham and S. H. Yeo, "A knowledge-based system for robot gripper selection: criteria for choosing grippers and surfaces for gripping," *Int. J. Mach. Tools Manuf.*, vol. 28, no. 4, pp. 301–313, Jan. 1988, doi: 10.1016/0890-6955(88)90045-4.

[7] D. T. Pham and S. H. Yeo, "A knowledge-based system for robot gripper selection: Implementation details," *Int. J. Mach. Tools Manuf.*, vol. 28, no. 4, pp. 315–324, Jan. 1988, doi: 10.1016/0890-6955(88)90046-6.

[8] D. T. PHAM and S. H. YEO, "Strategies for gripper design and selection in robotic assembly," *Int. J. Prod. Res.*, vol. 29, no. 2, pp. 303–316, Feb. 1991, doi: 10.1080/00207549108930072.

[9] G. Fantoni *et al.*, "Grasping devices and methods in automated production processes," *CIRP Ann.*, vol. 63, no. 2, pp. 679–701, Jan. 2014, doi: 10.1016/j.cirp.2014.05.006.

[10] J. Cramer, E. Demeester, and K. Kellens, "Development of an assistive webtool for robotic gripper selection," *Procedia CIRP*, vol. 106, pp. 250–257, Jan. 2022, doi: 10.1016/j.procir.2022.02.187.

[11] N. Yamanobe and K. Nagata, "Grasp planning for everyday objects based on primitive shape representation for parallel jaw grippers," in *2010 IEEE International Conference on Robotics and Biomimetics*, Dec. 2010, pp. 1565–1570. doi: 10.1109/ROBIO.2010.5723563.

[12] J. Ichnowski, Y. Avigal, J. Kerr, and K. Goldberg, "Dex-NeRF: Using a Neural Radiance Field to Grasp Transparent Objects." arXiv, Oct. 27, 2021. Accessed: Mar. 29, 2023. [Online]. Available: http://arxiv.org/abs/2110.14217

[13] J. Mahler, M. Matl, X. Liu, A. Li, D. Gealy, and K. Goldberg, "Dex-Net 3.0: Computing Robust Robot Vacuum Suction Grasp Targets in Point Clouds using a New Analytic Model and Deep Learning." arXiv, Apr. 13, 2018. doi: 10.48550/arXiv.1709.06670.

[14] J. Mahler *et al.*, "Dex-Net 2.0: Deep Learning to Plan Robust Grasps with Synthetic Point Clouds and Analytic Grasp Metrics." arXiv, Aug. 08, 2017. Accessed: Mar. 07, 2023. [Online]. Available: http://arxiv.org/abs/1703.09312

[15] J. Mahler *et al.*, "Learning ambidextrous robot grasping policies," *Sci. Robot.*, vol. 4, no. 26, p. eaau4984, Jan. 2019, doi: 10.1126/scirobotics.aau4984.

[16] S. Levine, P. Pastor, A. Krizhevsky, J. Ibarz, and D. Quillen, "Learning hand-eye coordination for robotic grasping with deep learning and large-scale data collection," *Int. J. Robot. Res.*, vol. 37, no. 4–5, pp. 421–436, Apr. 2018, doi: 10.1177/0278364917710318.

[17] P. Fan, B. Yan, M. Wang, X. Lei, Z. Liu, and F. Yang, "Three-finger grasp planning and experimental analysis of picking patterns for robotic apple harvesting," *Comput. Electron. Agric.*, vol. 188, p. 106353, Sep. 2021, doi: 10.1016/j.compag.2021.106353.

[18] Q. Bai, S. Li, J. Yang, M. Shen, S. Jiang, and X. Zhang, "Robot Three-Finger Grasping Strategy Based on DeeplabV3+," *Actuators*, vol. 10, no. 12, Art. no. 12, Dec. 2021, doi: 10.3390/act10120328.

[19] J. Bohg and D. Kragic, "Learning grasping points with shape context," *Robot. Auton. Syst.*, vol. 58, no. 4, pp. 362–377, Apr. 2010, doi: 10.1016/j.robot.2009.10.003.

[20] R. Bogue, "Robots in recycling and disassembly," *Ind. Robot*, vol. 46, no. 4, pp. 461–466, 2019, doi: 10.1108/IR-03-2019-0053.

[21] G. J. Monkman, "An Analysis of Astrictive Prehension," *Int. J. Robot. Res.*, vol. 16, no. 1, pp. 1–10, Feb. 1997, doi: 10.1177/027836499701600101.

[22] G. J. Monkman, S. Hesse, R. Steinmann, and H. Schunk, *Robot Grippers*, 1st ed. John Wiley & Sons, Ltd, 2006. doi: 10.1002/9783527610280.

[23] G. Fantoni *et al.*, "Grasping devices and methods in automated production processes," *CIRP Ann.*, vol. 63, no. 2, pp. 679–701, Jan. 2014, doi: 10.1016/j.cirp.2014.05.006.

[24] V. Lippiello, "Grasp the Possibilities: Anthropomorphic Grasp Synthesis Based on the Object Dynamic Properties," *IEEE Robot. Autom. Mag.*, vol. 22, pp. 1–1, May 2015, doi: 10.1109/MRA.2015.2394711.

[25] A. J. Valencia, R. M. Idrovo, A. D. Sappa, D. P. Guingla, and D. Ochoa, "A 3D vision based approach for optimal grasp of vacuum grippers," in *2017 IEEE International Workshop of Electronics, Control, Measurement, Signals and their Application to Mechatronics (ECMSM)*, May 2017, pp. 1–6. doi: 10.1109/ECMSM.2017.7945886.

[26] H. Zhang, J. Peeters, E. Demeester, and K. Kellens, "A CNN-Based Grasp Planning Method for Random Picking of Unknown Objects with a Vacuum Gripper," *J. Intell. Robot. Syst.*, vol. 103, no. 4, p. 64, Dec. 2021, doi: 10.1007/s10846-021-01518-8.

[27] H. Zhang, J. Peeters, E. Demeester, and K. Kellens, "Deep Learning Reactive Robotic Grasping With a Versatile Vacuum Gripper," *IEEE Trans. Robot.*, vol. 39, no. 2, pp. 1244–1259, Apr. 2023, doi: 10.1109/TRO.2022.3226148.

[28] P. Schillinger, M. Gabriel, A. Kuss, H. Ziesche, and N. Vien, Model-free Grasping with Multi-Suction Cup Grippers for Robotic Bin Picking. 2023.

[29] T. Zhang, C. Zhang, S. Ji, and T. Hu, "Robot suction region prediction method from knowledge to learning in disordered manufacturing scenarios," *Eng. Appl. Artif. Intell.*, vol. 120, p. 105928, Apr. 2023, doi: 10.1016/j.engappai.2023.105928.

[30] X. Li, N. Li, G. Tao, H. Liu, and T. Kagawa, "Experimental comparison of Bernoulli gripper and vortex gripper," *Int. J. Precis. Eng. Manuf.*, vol. 16, no. 10, pp. 2081–2090, Sep. 2015, doi: 10.1007/s12541-015-0270-3.

[31] "Coanda Effect - an overview | ScienceDirect Topics." Accessed: Aug. 30, 2023. [Online]. Available: https://www.sciencedirect.com/topics/earth-and-planetary-sciences/coanda-effect

[32] M. Ameri, "An experimental and theoretical study of Coanda ejectors - ProQuest." Accessed: Aug. 30, 2023. [Online]. Available: https://www.proquest.com/openview/5f1b488c9ba2f7f1dc4b108c443d9fd9/1?pq-origsite=gscholar&cbl=18750&diss=y&casa_token=kJIs3RGALIMAAAAA:sahMlhbZQtBKHK50jwi6w9lGYD5LsPiFP3gcwU-KLERduDpn4wjV2s7q4QRjcxXTFW3DbuFlPczQ

[33] T. K. Lien and P. G. G. Davis, "A novel gripper for limp materials based on lateral Coanda ejectors," *CIRP Ann.*, vol. 57, no. 1, pp. 33–36, Jan. 2008, doi: 10.1016/j.cirp.2008.03.119.

[34] M. Ameri and A. Dybbs, "Theoretical Modeling of Coanda Ejectors," *Fluid Mach.*, vol. 163, pp. 43–48, 1993.

[35] "Flow Grippers | Schmalz." Accessed: Aug. 31, 2023. [Online]. Available: https://www.schmalz.com/en/vacuum-technology-for-automation/vacuum-components/special-grippers/flow-grippers/

[36] B. Engelen, D. De Marelle, J. R. Peeters, and K. Kellens, "High airflow vertical conveying gripper for robotic sorting of shredded metal residues," *Procedia CIRP*, vol. 116, pp. 396–401, Jan. 2023, doi: 10.1016/j.procir.2023.02.067.

[37] R. P. Krape, "Applications study of electroadhesive devices," NASA-CR-1211, Oct. 1968. Accessed: Sep. 01, 2023. [Online]. Available: https://ntrs.nasa.gov/citations/19680028434

[38] L. P. Neukirch, E. von Haartman, J. M. Rosenholm, and A. Nick Vamivakas, "Multi-dimensional single-spin nano-optomechanics with a levitated nanodiamond," *Nat. Photonics*, vol. 9, no. 10, Art. no. 10, Oct. 2015, doi: 10.1038/nphoton.2015.162.

[39] M. Röthlisberger, M. Schuck, L. Kulmer, and J. W. Kolar, "Contactless Picking of Objects Using an Acoustic Gripper," *Actuators*, vol. 10, no. 4, Art. no. 4, Apr. 2021, doi: 10.3390/act10040070.

[40] Directive 2003/10/EC of the European Parliament and of the Council of 6 February 2003 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (noise) (Seventeenth individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC). 2019. Accessed: Sep. 05, 2023. [Online]. Available: http://data.europa.eu/eli/dir/2003/10/2019-07-26/eng

[41] G. Schulz, "Grippers for flexible textiles," in *Fifth International Conference on Advanced Robotics 'Robots in Unstructured Environments*, Jun. 1991, pp. 759–764 vol.1. doi: 10.1109/ICAR.1991.240584.

[42] R. K. Sutz, "Cryogenic pickup," US3611744A, Oct. 12, 1971 Accessed: Sep. 05, 2023. [Online]. Available: https://patents.google.com/patent/US3611744/en

[43] A. C. Marques *et al.*, "Review on Adhesives and Surface Treatments for Structural Applications: Recent Developments on Sustainability and Implementation for Metal and Composite Substrates," *Materials*, vol. 13, no. 24, p. 5590, Dec. 2020, doi: 10.3390/ma13245590.

[44] L. Ge, S. Sethi, L. Ci, P. M. Ajayan, and A. Dhinojwala, "Carbon nanotube-based synthetic gecko tapes," *Proc. Natl. Acad. Sci.*, vol. 104, no. 26, pp. 10792–10795, Jun. 2007, doi: 10.1073/pnas.0703505104.

[45] G. Fantoni, H. N. Hansen, and M. Santochi, "A new capillary gripper for mini and micro parts," *CIRP Ann.*, vol. 62, no. 1, pp. 17–20, Jan. 2013, doi: 10.1016/j.cirp.2013.03.005.

[46] S. Makris, F. Dietrich, K. Kellens, and S. J. Hu, "Automated assembly of non-rigid objects," *CIRP Ann.*, vol. 72, no. 2, pp. 513–539, Jan. 2023, doi: 10.1016/j.cirp.2023.05.003.

[47] J. Shintake, V. Cacucciolo, D. Floreano, and H. Shea, "Soft Robotic Grippers," *Adv. Mater.*, vol. 30, no. 29, p. 1707035, 2018, doi: 10.1002/adma.201707035.

[48] S. Kim, C. Laschi, and B. Trimmer, "Soft robotics: a bioinspired evolution in robotics," *Trends Biotechnol.*, vol. 31, no. 5, pp. 287–294, May 2013, doi: 10.1016/j.tibtech.2013.03.002.

[49] S. Hirai, R. Niiyama, T. Nakamura, T. Umedachi, T. Nakata, and H. Tanaka, "Soft Manipulation and Locomotion," in *The Science of Soft Robots: Design, Materials and Information Processing*, K. Suzumori, K. Fukuda, R. Niiyama, and K. Nakajima, Eds., in Natural Computing Series. , Singapore: Springer Nature, 2023, pp. 59–106. doi: 10.1007/978-981-19-5174-9_4.

[50] "Soft Pneumatic Actuators: A Review of Design, Fabrication, Modeling, Sensing, Control and Applications." Accessed: Sep. 25, 2023. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/9785890/

[51] D. Rus and M. T. Tolley, "Design, fabrication and control of soft robots," *Nature*, vol. 521, no. 7553, Art. no. 7553, May 2015, doi: 10.1038/nature14543.

[52] C.-H. Liu, G.-F. Huang, C.-H. Chiu, and T.-Y. Pai, "Topology Synthesis and Optimal Design of an Adaptive Compliant Gripper to Maximize Output Displacement," *J. Intell. Robot. Syst.*, vol. 90, no. 3, pp. 287–304, Jun. 2018, doi: 10.1007/s10846-017-0671-x.

[53] C.-H. Liu, S.-Y. Yang, and Y.-C. Shih, "Optimal Design of a Highly Self-Adaptive Gripper with Multi-Phalange Compliant Fingers for Grasping Irregularly Shaped Objects," *IEEE Robot. Autom. Lett.*, pp. 1–8, 2023, doi: 10.1109/LRA.2023.3313877.

[54] J. Yao, Y. Fang, and L. Li, "Research on effects of different internal structures on the grasping performance of Fin Ray soft grippers," *Robotica*, vol. 41, no. 6, pp. 1762–1777, Jun. 2023, doi: 10.1017/S0263574723000139.

[55] M. Issa, D. Petkovic, N. D. Pavlovic, and L. Zentner, "Sensor elements made of conductive silicone rubber for passively compliant gripper," *Int. J. Adv. Manuf. Technol.*, vol. 69, no. 5, pp. 1527–1536, Nov. 2013, doi: 10.1007/s00170-013-5085-8.

[56] A. Zapciu, G. Constantin, and D. Popescu, "Adaptive robotic end-effector with embedded 3D-printed sensing Circuits," *MATEC Web Conf.*, vol. 121, p. 08008, 2017, doi: 10.1051/matecconf/201712108008.

[57] S. Q. Liu, Y. Ma, and E. H. Adelson, "GelSight Baby Fin Ray: A Compact, Compliant, Flexible Finger with High-Resolution Tactile Sensing," in *2023 IEEE International Conference on Soft Robotics (RoboSoft)*, Apr. 2023, pp. 1–8. doi: 10.1109/RoboSoft55895.2023.10122078.

[58] M. Wilson, "Festo drives automation forwards," *Assem. Autom.*, vol. 31, no. 1, pp. 12–16, Jan. 2011, doi: 10.1108/01445151111104128.

[59] W. Crooks, G. Vukasin, M. O'Sullivan, W. Messner, and C. Rogers, "Fin Ray® Effect Inspired Soft Robotic Gripper: From the RoboSoft Grand Challenge toward Optimization," *Front. Robot. AI*, vol. 3, 2016, Accessed: Sep. 19, 2023. [Online]. Available: https://www.frontiersin.org/articles/10.3389/frobt.2016.00070

[60] "Adaptieve grijpvinger DHAS Online kopen | Festo BE." Accessed: Sep. 19, 2023. [Online]. Available: https://www.festo.com/be/nl/p/adaptieve-grijpvinger-id_DHAS_GF/

[61] W. Crooks, S. Rozen-Levy, B. Trimmer, C. Rogers, and W. Messner, "Passive gripper inspired by Manduca sexta and the Fin Ray® Effect," *Int. J. Adv. Robot. Syst.*, vol. 14, no. 4, p. 1729881417721155, Jul. 2017, doi: 10.1177/1729881417721155.

[62] I. Hussain *et al.*, "Design and prototyping soft–rigid tendon-driven modular grippers using interpenetrating phase composites materials," *Int. J. Robot. Res.*, vol. 39, no. 14, pp. 1635–1646, Dec. 2020, doi: 10.1177/0278364920907697.

[63] J.-H. Lee, Y. S. Chung, and H. Rodrigue, "Long Shape Memory Alloy Tendon-based Soft Robotic Actuators and Implementation as a Soft Gripper," *Sci. Rep.*, vol. 9, no. 1, Art. no. 1, Aug. 2019, doi: 10.1038/s41598-019-47794-1.

[64] S. C. Mawah and Y.-J. Park, "Tendon-Driven Variable-Stiffness Pneumatic Soft Gripper Robot," *Robotics*, vol. 12, no. 5, Art. no. 5, Oct. 2023, doi: 10.3390/robotics12050128.

[65] J. Meng, L. Gerez, J. Chapman, and M. Liarokapis, "A Tendon-Driven, Preloaded, Pneumatically Actuated, Soft Robotic Gripper with a Telescopic Palm," in *2020 3rd IEEE International Conference on Soft Robotics (RoboSoft)*, May 2020, pp. 476–481. doi: 10.1109/RoboSoft48309.2020.9115986.

[66] A. K. Mishra, E. Del Dottore, A. Sadeghi, A. Mondini, and B. Mazzolai, "SIMBA: Tendon-Driven Modular Continuum Arm with Soft Reconfigurable Gripper," *Front. Robot. AI*, vol. 4, 2017, Accessed: Sep. 21, 2023. [Online]. Available: https://www.frontiersin.org/articles/10.3389/frobt.2017.00004

[67] A. Qiu, C. Young, A. L. Gunderman, M. Azizkhani, Y. Chen, and A.-P. Hu, "Tendon-Driven Soft Robotic Gripper with Integrated Ripeness Sensing for Blackberry Harvesting," in *2023 IEEE International Conference on Robotics and Automation (ICRA)*, London, United Kingdom: IEEE, May 2023, pp. 11831–11837. doi: 10.1109/ICRA48891.2023.10160893.

[68] M. G. Catalano, G. Grioli, A. Serio, E. Farnioli, C. Piazza, and A. Bicchi, "Adaptive synergies for a humanoid robot hand," in *2012 12th IEEE-RAS International Conference on Humanoid Robots (Humanoids 2012)*, Nov. 2012, pp. 7–14. doi: 10.1109/HUMANOIDS.2012.6651492.

[69] M. G. Catalano, G. Grioli, E. Farnioli, A. Serio, C. Piazza, and A. Bicchi, "Adaptive synergies for the design and control of the Pisa/IIT SoftHand," *Int. J. Robot. Res.*, vol. 33, no. 5, pp. 768–782, Apr. 2014, doi: 10.1177/0278364913518998.

[70] "Shadow Dexterous Hand Series - Research and Development Tool," Shadow Robot. Accessed: Sep. 21, 2023. [Online]. Available: https://www.shadowrobot.com/dexterous-hand-series/

[71] "faive robotics," faive robotics. Accessed: Sep. 21, 2023. [Online]. Available: https://www.faive-robotics.com

[72] W. T. Townsend, "BarrettHand Grasper: Programmably Flexible Part Handling and Assembly," in *Humanoid Robotics: A Reference*, A. Goswami and P. Vadakkepat, Eds., Dordrecht: Springer Netherlands, 2019, pp. 535–551. doi: 10.1007/978-94-007-6046-2_87.

[73] W. Wei *et al.*, "DVGG: Deep Variational Grasp Generation for Dextrous Manipulation," *IEEE Robot. Autom. Lett.*, vol. 7, no. 2, pp. 1659–1666, Apr. 2022, doi: 10.1109/LRA.2022.3140424.

[74] M. Bonilla *et al.*, "Grasping with Soft Hands," in *2014 IEEE-RAS International Conference on Humanoid Robots*, Nov. 2014, pp. 581–587. doi: 10.1109/HUMANOIDS.2014.7041421.

[75] G. Gu, D. Wang, L. Ge, and X. Zhu, "Analytical Modeling and Design of Generalized Pneu-Net Soft Actuators with Three-Dimensional Deformations," *Soft Robot.*, vol. 8, no. 4, pp. 462–477, Aug. 2021, doi: 10.1089/soro.2020.0039.

[76] R. K. Katzschmann, A. D. Marchese, and D. Rus, "Autonomous Object Manipulation Using a Soft Planar Grasping Manipulator," *Soft Robot.*, vol. 2, no. 4, pp. 155–164, Dec. 2015, doi: 10.1089/soro.2015.0013.

[77] Z. Xie, J. Y. S. Chen, G. W. Lim, and F. Bai, "Data-Driven Robotic Tactile Grasping for Hyper-Personalization Line Pick-and-Place," *Actuators*, vol. 12, no. 5, Art. no. 5, May 2023, doi: 10.3390/act12050192.

[78] O. Azami, K. Ishibashi, M. Komagata, and K. Yamamoto, "Development of Hydraulically-driven Soft Hand for Handling Heavy Vegetables and its Experimental Evaluation," in *2023 IEEE International Conference on Robotics and Automation (ICRA)*, May 2023, pp. 2577–2583. doi: 10.1109/ICRA48891.2023.10160629.

[79] K. Hagiwara, K. Yamamoto, Y. Shibata, M. Komagata, and Y. Nakamura, "On high stiffness of soft robots for compatibility of deformation and function," *Adv. Robot.*, vol. 36, no. 19, pp. 995–1010, Oct. 2022, doi: 10.1080/01691864.2022.2117574.

[80] B. Mosadegh *et al.*, "Pneumatic Networks for Soft Robotics that Actuate Rapidly," *Adv. Funct. Mater.*, vol. 24, no. 15, pp. 2163–2170, 2014, doi: 10.1002/adfm.201303288.

[81] "Universal soft pneumatic robotic gripper with variable effective length." Accessed: Sep. 26, 2023. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/7554316?casa_token=sSLdBvwn_mcAAAAA:td0WnDA94ZseD6DfSkXADZq-aZWmkhl_XBApGsx0ATEObZ9aWloo2nFvZmY1PK_A3ZXWiunvjPzruw

[82] G.-H. Feng and S.-C. Yen, "Electroactive polymer actuated gripper enhanced with iron oxide nanoparticles and water supply mechanism for millimeter-sized fish roe manipulation," in *2017 IEEE Electron Devices Technology and Manufacturing Conference (EDTM)*, Feb. 2017, pp. 216–218. doi: 10.1109/EDTM.2017.7947570.

[83] Z. Yoder, D. Macari, G. Kleinwaks, I. Schmidt, E. Acome, and C. Keplinger, "A Soft, Fast and Versatile Electrohydraulic Gripper with Capacitive Object Size Detection," *Adv. Funct. Mater.*, vol. 33, no. 3, p. 2209080, 2023, doi: 10.1002/adfm.202209080.

[84] Z. Yoder *et al.*, "Design of a High-Speed Prosthetic Finger Driven by Peano-HASEL Actuators," *Front. Robot. AI*, vol. 7, 2020, Accessed: Jan. 22, 2024. [Online]. Available: https://www.frontiersin.org/articles/10.3389/frobt.2020.586216

[85] T. Park, K. Kim, S.-R. Oh, and Y. Cha, "Electrohydraulic Actuator for a Soft Gripper," *Soft Robot.*, vol. 7, no. 1, pp. 68–75, Feb. 2020, doi: 10.1089/soro.2019.0009.

[86] N. Kellaris, V. Gopaluni Venkata, G. M. Smith, S. K. Mitchell, and C. Keplinger, "Peano-HASEL actuators: Muscle-mimetic, electrohydraulic transducers that linearly contract on activation," *Sci. Robot.*, vol. 3, no. 14, p. eaar3276, Jan. 2018, doi: 10.1126/scirobotics.aar3276.

[87] S. K. Chaitanya and K. Dhanalakshmi, "Design and Control of Shape Memory Alloy Actuated Grippers," *IFAC Proc. Vol.*, vol. 47, no. 1, pp. 400–407, Jan. 2014, doi: 10.3182/20140313-3-IN-3024.00166.

[88] F. Morra, R. Molfino, and F. Cepolina, "Miniature gripping device".

[89] C. Son, S. Jeong, S. Lee, P. M. Ferreira, and S. Kim, “Tunable Adhesion of Shape Memory Polymer Dry Adhesive Soft Robotic Gripper via Stiffness Control,” *Robotics*, vol. 12, no. 2, Art. no. 2, Apr. 2023, doi: 10.3390/robotics12020059.

[90] J. R. Amend, E. Brown, N. Rodenberg, H. M. Jaeger, and H. Lipson, “A Positive Pressure Universal Gripper Based on the Jamming of Granular Material,” *IEEE Trans. Robot.*, vol. 28, no. 2, pp. 341–350, Apr. 2012, doi: 10.1109/TRO.2011.2171093.

[91] L. Al Abeach, S. Nefti-Meziani, T. Theodoridis, and S. Davis, “A Variable Stiffness Soft Gripper Using Granular Jamming and Biologically Inspired Pneumatic Muscles,” *J. Bionic Eng.*, vol. 15, no. 2, pp. 236–246, Mar. 2018, doi: 10.1007/s42235-018-0018-8.

[92] T. Mitsuda and S. Otsuka, “Active Bending Mechanism Employing Granular Jamming and Vacuum-Controlled Adaptable Gripper,” *IEEE Robot. Autom. Lett.*, vol. 6, no. 2, pp. 3041–3048, Apr. 2021, doi: 10.1109/LRA.2021.3058914.

[93] S. G. Fitzgerald, G. W. Delaney, D. Howard, and F. Maire, “Evolving soft robotic jamming grippers,” in *Proceedings of the Genetic and Evolutionary Computation Conference*, in GECCO ’21. New York, NY, USA: Association for Computing Machinery, Jun. 2021, pp. 102–110. doi: 10.1145/3449639.3459331.

[94] C. Löchte *et al.*, “Form-Flexible Handling and Joining Technology (FormHand) for the Forming and Assembly of Limp Materials,” *Procedia CIRP*, vol. 23, pp. 206–211, Jan. 2014, doi: 10.1016/j.procir.2014.10.086.

[95] G. D. Howard, J. Brett, J. O’Connor, J. Letchford, and G. W. Delaney, “One-Shot 3D-Printed Multimaterial Soft Robotic Jamming Grippers,” *Soft Robot.*, vol. 9, no. 3, pp. 497–508, Jun. 2022, doi: 10.1089/soro.2020.0154.

[96] D. Howard, J. O’Connor, J. Brett, and G. W. Delaney, “Shape, Size, and Fabrication Effects in 3D Printed Granular Jamming Grippers,” in *2021 IEEE 4th International Conference on Soft Robotics (RoboSoft)*, Apr. 2021, pp. 458–464. doi: 10.1109/RoboSoft51838.2021.9479438.

[97] R. Mishra, T. Philips, G. W. Delaney, and D. Howard, “Vibration Improves Performance in Granular Jamming Grippers.” arXiv, Sep. 21, 2021. Accessed: Oct. 02, 2023. [Online]. Available: http://arxiv.org/abs/2109.10496

[98] M. Zhu, Y. Mori, T. Wakayama, A. Wada, and S. Kawamura, “A Fully Multi-Material Three-Dimensional Printed Soft Gripper with Variable Stiffness for Robust Grasping,” *Soft Robot.*, vol. 6, no. 4, pp. 507–519, Aug. 2019, doi: 10.1089/soro.2018.0112.

[99] Y. Hao *et al.*, “A eutectic-alloy-infused soft actuator with sensing, tunable degrees of freedom, and stiffness properties,” *J. Micromechanics Microengineering*, vol. 28, no. 2, p. 024004, Jan. 2018, doi: 10.1088/1361-6439/aa9d0e.

[100] J. Shintake, B. Schubert, S. Rosset, H. Shea, and D. Floreano, “Variable stiffness actuator for soft robotics using dielectric elastomer and low-melting-point alloy,” in *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Sep. 2015, pp. 1097–1102. doi: 10.1109/IROS.2015.7353507.

[101] Y.-F. Zhang *et al.*, “Fast-Response, Stiffness-Tunable Soft Actuator by Hybrid Multimaterial 3D Printing,” *Adv. Funct. Mater.*, vol. 29, no. 15, p. 1806698, 2019, doi: 10.1002/adfm.201806698.

[102] W. Wang and S.-H. Ahn, "Shape Memory Alloy-Based Soft Gripper with Variable Stiffness for Compliant and Effective Grasping," *Soft Robot.*, vol. 4, no. 4, pp. 379–389, Dec. 2017, doi: 10.1089/soro.2016.0081.

[103] J. Cramer, M. Cramer, E. Demeester, and K. Kellens, "Exploring the potential of magnetorheology in robotic grippers," *Procedia CIRP*, vol. 76, pp. 127–132, Jan. 2018, doi: 10.1016/j.procir.2018.01.038.

[104] D.-S. Choi, T.-H. Kim, S.-H. Lee, C. Pang, J. W. Bae, and S.-Y. Kim, "Beyond Human Hand: Shape-Adaptive and Reversible Magnetorheological Elastomer-Based Robot Gripper Skin," *ACS Appl. Mater. Interfaces*, vol. 12, no. 39, pp. 44147–44155, Sep. 2020, doi: 10.1021/acsami.0c11783.

[105] A. Koivikko, D.-M. Drotlef, M. Sitti, and V. Sariola, "Magnetically switchable soft suction grippers," *Extreme Mech. Lett.*, vol. 44, p. 101263, Apr. 2021, doi: 10.1016/j.eml.2021.101263.

[106] J. Cramer, M. Cramer, E. Demeester, and K. Kellens, "Simulation-driven parameter study of concentric Halbach cylinders for magnetorheological robotic grasping," *J. Magn. Magn. Mater.*, vol. 546, p. 168637, Mar. 2022, doi: 10.1016/j.jmmm.2021.168637.

[107] P. Van Nguyen, Q. K. Luu, Y. Takamura, and V. A. Ho, "Wet Adhesion of Micro-patterned Interfaces for Stable Grasping of Deformable Objects," in *2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Oct. 2020, pp. 9213–9219. doi: 10.1109/IROS45743.2020.9341095.

[108] V. Cacucciolo, J. Shintake, and H. Shea, "Delicate yet strong: Characterizing the electro-adhesion lifting force with a soft gripper," in *2019 2nd IEEE International Conference on Soft Robotics (RoboSoft)*, Apr. 2019, pp. 108–113. doi: 10.1109/ROBOSOFT.2019.8722706.

[109] V. Cacucciolo, H. Shea, and G. Carbone, "Peeling in electroadhesion soft grippers," *Extreme Mech. Lett.*, vol. 50, p. 101529, Jan. 2022, doi: 10.1016/j.eml.2021.101529.

[110] C. Xiang, W. Li, and Y. Guan, "A Variable Stiffness Electroadhesive Gripper Based on Low Melting Point Alloys," *Polymers*, vol. 14, no. 21, Art. no. 21, Jan. 2022, doi: 10.3390/polym14214469.

[111] M. Lanzetta and K. Iagnemma, "Gripping by controllable wet adhesion using a magnetorheological fluid," *CIRP Ann.*, vol. 62, no. 1, pp. 21–25, Jan. 2013, doi: 10.1016/j.cirp.2013.03.002.

[112] Kiyokawa, T., Takamatsu, J., & Koyanaka, S. (2024). Challenges for Future Robotic Sorters of Mixed Industrial Waste: A Survey. IEEE Transactions on Automation Science and Engineering, 21, 1023-1040.

[113] AMP Robotics, Accessed Feb 2024, [Online] https://ampsortation.com/

[114] ROBENSO, Accessed Feb 2024 [Online] https://www.robenso.gr/

[115] SamurAI Sorting Robot, Machinex Sorting, Accessed Feb 2024 [Online] https://www.machinexrecycling.com/sorting/equipment/samurai-sorting-robot/

[116] RecycleEye, Accessed Feb 2024 [Online] https://recycleye.com/robotics-3/

[117] Waste Robotics, Accessed Feb 2024, [Online] https://wasterobotic.com/technology/

[118] ZenRobotics, Accessed Feb 2024. [Online] https://www.terex.com/zenrobotics/robots

[119] Kounalakis, N., Raptopoulos, F., & Maniadakis, M. (2024). Robotic Recycling Workers: a low-cost alternative for autonomous material recovery, to appear in 33th International Conference on Flexible Automation and Intelligent Manufacturing – FAIM 2024.