Research Article

Underactuated embedded constraints gripper for grasping in toxic environments

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Received: 29 June 2022 / Accepted: 3 January 2023

Abstract
In this paper a soft gripper is proposed and designed to achieve some of the 17 Sustainable Development Goals (SDG) described by United Nations (UN) and in particular SDG3, SDG8, SDG 9 and SDG 12. In fact, the presented gripper is conceived for application in the waste industry for helping or partially replacing human operations which could lead to risks or hazards for human health. The device can artificially reproduce the action of human hands allowing a more sustainable work, focusing the attention on worker's health. Also the design characteristics are oriented to sustainability by using eco-friendly materials. Furthermore, the device is an underactuated soft gripper with modular elements and without sensors. There are no electronic components, and the damageable and non-recyclable parts are minimized. After the description of gripper and mechanical analysis, three different configurations (wearable, with extension and mounted on a cobot) are presented where it is possible to notice that the ends of the gripper (the fingers) are far from the most delicate and less recyclable components such as the motor. Thus, thanks to the modularity of the fingers, it is easy to replace damaged fingers: they have a lower environmental impact than electronic components. In this way, the presented project falls in "the circular design for sustainability" in robotics.

Article Highlights

- An eco-friendly underactuated soft gripper is presented and described for application in the waste industry, to help or partially replace humans in harmful works.
- Its design oriented to sustainability is described and the mechanical characteristics are analyzed by Finite Element Modelling (FEM).
- Results and different application strategies for the waste industry are presented and discussed.

Keywords SDG3 · SDG8 · SDG 9 · SDG 12 · Soft robotics · Collaborative robotics

1 Introduction

Worldwide waste production has been increasing in the last decade. Both municipal solid waste [1] and special waste [2] are growing in landfills. The overall goal for sustainability is to reduce the waste generation, as well as to improve waste lifecycle by reuse and end-of-life through recycling [3, 4] (Fig. 1).

For this purpose, it is crucial to sort waste according to materials and applications. In many developing countries,

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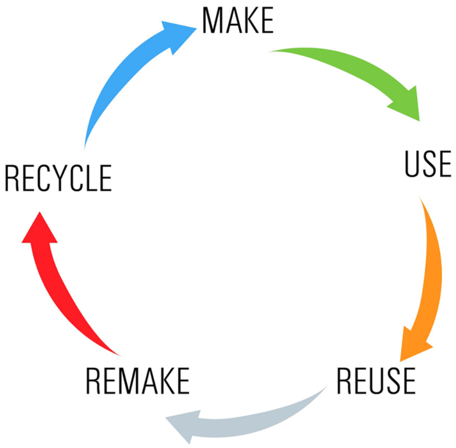


Fig. 1 Waste lifecycle

large open-air dumps are used as workplaces where workers still manually sort waste before it goes into recycling processes [1, 5, 6], and the legal regulation of this occupation is in progress [7–9].

The management of solid waste disposal is a great challenge mainly in the cities where it is fundamental to find a valid method to gathering solid waste material from recycling ones [10, 11]. For this purpose, automated waste sorting systems can be used [12–14], but the manual action performed by human operators is still necessary for the separation of solid waste [15]. Figure 2 shows a typical industrial sorting and disposal workflow for non-organic waste, where all the manual sorting phases are highlighted. According to this workflow, after the drum, the medium elements, having a dimension between 70 and 300 mm are subjected to manual separation. These materials are mainly rubber products, glass, paper and cardboard, packaging plastics such as polyethylene terephthalate (PET) and films. Next, large items with dimension larger than 250 mm are fed to the manual sorting posts. These elements are polypropylene (PP) products, plastic containers, plastic pallets and spools, stretch film packaging, pressed or non-pressed low-density polyethylene (LDPE) packaging, stale films. Furthermore, also non-standard elements are manually separated, e,g.: gate runners, stretch wrap films, textiles, garbage bags, polyethylene (PE) wastes, small construction waste such as stones, wood, concrete fragments and glass. The remaining waste is relocated to the main sorting conveyor where there are posts for the sorting of useful types of raw materials. An operator for each post is in charge to separate manually the fraction of recycled materials. In particular, the recyclable materials are plastic, glass, metal, and paper.

In addition to municipal solid waste, the management of medical waste is also carried out by operators [16], both before and after automated separation machinery [17].

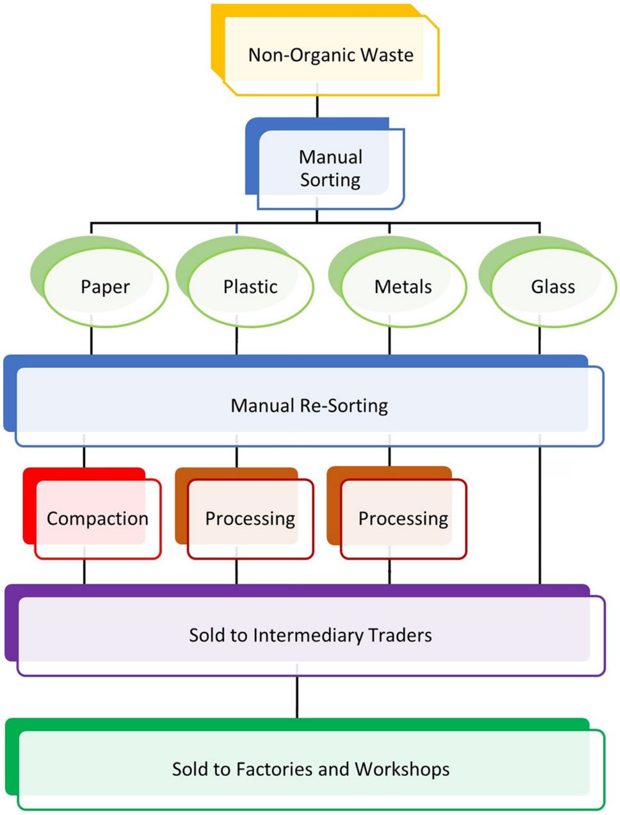


Fig. 2 Waste sorting and disposal

When medical waste is manually sorted, the risk for the workers' health is high due both to toxicity and to numerous accidents and injuries [18], and the presence of waste sorting machines is not enough to enhance safeguard of pickers. As manual sorting leads to high health risks for workers, the Sustainable Development Goals (SDGs) described by United Nations (UN) [19] are also focused on improving the status of the pickers, in addition to obtaining protection of the environment and global resources. From this perspective, the introduction of technologies leading to human–robot collaboration in the waste industry is a topic of great significance to protect humans, considering also that the increased prevalence of robots in the work processes is not a risk to overall employment [20].

Medina et al. [1] describe a protocol for the safe handling of waste in an environment where robots and operators coexist [21]. Although technologies are being developed to improve the accuracy of the machines and of grasping strategies [13, 14, 22, 23], some studies report the limitations of waste sorting using only robots for these tasks, due to the technological limitations of the sensors, the difficulty of separating waste layered on top of each other, and the slowness in performing these tasks correctly [24–28].

All these aspects highlight the current dependence on the presence of humans. The main purpose of this work is to provide pickers with a versatile tool that allows them to safely handle waste manually or in collaboration with robots. Innovative underactuated grasping devices are recently under study and development as they provide simple, manageable, and economic solutions to help humans in manipulating operations [29–31]. Other key features to consider in the design of new grippers to reduce the complexity of the hand by maintaining a suitable level of performance are modularity [32] and effective transmission systems [33]. Underactuated mechanisms are characterized by having fewer actuators than the degrees of freedom (DoFs) [34]. This characteristic could reduce the manipulation abilities, but it has been demonstrated that underactuated compliant grippers are promising self-adapting grasping devices [35–37]. In fact, underactuated devices have the ability to facilitate a human-like adaptive grasping [38–42].

Underactuation is often realized by tendon-driven modular robotic fingers which have been widely discussed in literature, with particular attention to joint stiffness adjustability and tendon redundancy [43] to obtain specific grasping trajectories [44, 45]. Underactuation has the advantage to allow a simpler mechanical structure of robotic hands, reducing mass and improving robustness even in mechanisms with many (DoFs) [46, 47].

This manuscript presents the design and development of an articulated soft robot. This device is an underactuated, tendon-driven system-based gripper [48], composed of rigid parts and deformable soft joints. In addition, the underactuated structure of the robot makes it possible to reduce the number of actuators due to the presence of a differential transmission system [49]. The main parts of the gripper are a pair of soft fingers and a modular deformable surface. This modular and flexible surface is alike an embedded constraint, which reduces grasp uncertainty and allows safe grasping of heavier objects. The adaptability to objects with complex shapes is also a relevant characteristic [50]. In fact, the widespread use of underactuated grippers stems from the need to grasp objects even of unknown shapes: the joints connecting the links are flexible and do not require beforehand knowledge of the object structure, and both the fingers and the scoop adapt themselves to the surface without requiring special control systems [51]. The entire gripper is made by additive manufacturing technique. A wide range of polymeric materials with good mechanical properties can be used with this technology. In addition, joints with different stiffness can be made in additive manufacturing by varying the infill density of the component and other properties related to the manufacturing technology.

The material chosen for the rigid parts of the device presented in this manuscript is polylactic acid (PLA), which is a biobased polymer that is derived from renewable sources and can be biodegradable [52]. The software analysis presented in [53] shows that the environmental impact of PLA is lower than other polymers such as acrylonitrile butadiene styrene (ABS) or acrylonitrile styrene acrylate (ASA), with similar mechanical properties. The choice of environmentally sustainable materials is important for the SDGs, as reported by many studies in literature [54]. Moreover, flanking the design with a simulation tool makes it possible to reduce prototyping waste and have a more real-world estimation of the behavior of the gripper components before fabrication [55]. Flexible parts are realized in polycaprolactone (PCL) which is a biodegradable plastic [56] with a better environmental impact than thermoplastic polyurethane (TPU) [57, 58]. Its mechanical properties are similar to TPU with a higher elongation at break, and it is more elastic, with a slightly lower tensile strength [59].

In this paper, some possible strategies for integrating the developed gripper in the waste sorting line were identified. In this context, the gripper presented and proposed in this paper can be a valid help to human operators [60] and it can be used according to three different applications that are described at the end of the paper in a working environment where the human-robots collaboration can be achieved. Within a waste industry line, the operator can use the device manually, to safely pick the waste up and take advantage of the presence of the scoop to sort the surrounding waste and pick up only the waste of interest. The gripper can also be attached to a robotic arm positioned in the working space, to work in cooperation with the picker who can guide it manually or through a control system. This solution preserves the accuracy of the human detection of waste but protecting the worker from exposure to health hazards. In addition, a third integration can be conceived by combining the gripper with a third wearable-arm [61, 62]. This allows for greater user mobility, leaving both hands free to perform other tasks, limiting the risk management of interaction with the autonomous robotic arm, and ensuring a high level of safety. Among the proposed solutions, the first one was analyzed in this manuscript. An extension of the current gripper allows safe tasks, avoiding direct contact with the conveyor belt where the waste is located. The components in contact with the waste are only the fingers and the scoop: the electronics and motors are placed away from the belt conveyor, reducing the risk of damage. Moreover, by placing the most delicate and valuable components away, in conjunction with the modularity of the chosen system, a more rapid replacement of parts, that may be damaged during the grasp stages, is possible. These components, made of sustainable polymeric materials, also have a lower environmental impact for replacement.

The paper is organized as follows. In Sect. 2 there is the description of the new gripper design, considering the structure of a previous version and including the position analysis of two different typical grasping cases. Section 3 shows the use of new eco-friendly materials for the gripper and the FEM analysis whose results are presented in Sect. 4. Three different integration strategies of the gripper in the waste industry are described in Sect. 5 for helping or partially replacing human operations, which could lead to risks or hazards for human health. Conclusion and future developments are reported in Sect. 6.

2 New design of gripper

2.1 Previous version

In soft robotic manipulation, robotic gripper is compliant to adapt itself to the shape of the object to grasp [63–65]. The developed idea in this work is a gripper with embedded constraints for soft manipulation in the management of solid waste disposal. The previous version is represented by a robotic hand with two soft fingers and a flat surface working as a scoop having tendon drive system. The flat surface is quite rigid with only one actuated degree of freedom at its base and the bending is very limited on its base. Therefore, the limits of this gripper in this previous configuration are the insufficient adaptability to the object shapes, the risk of damage for the grasped objects and low mobility of the scoop.

2.2 Design modification and improvement

A modular reconfigurable soft gripper working with a tendon driven system and a differential mechanism is proposed as a modification of the previous version. The redesign of the gripper was aimed at improving the capability to adapt to the freeform objects. This aspect is very important for those operations that require manual separation of waste. The introduction of some phalanges as joints for the scoop and the use of a soft material instead of a rigid one for the flat scoop is a novelty that generates an improvement in mobility for the gripper in its entirety. Thus, the new design is versatile and easily reconfigurable. The reconfigurability is very useful in case of gripper damages during waste separation operations even in the presence of liquids.

This type of gripper has the motor and the power supply away from the components used for grasping, and this allows to protect the delicate parts and an easy replacement and reconfiguration is possible also in the case of damages to the fingers and paddle. The flexible joints connect rigid modules to build a deformable structure that can fit the shape of the grasped object. The introduction of two fingers at the base of the scoop converts it into an actuated scoop improving the mobility and the adaptability. The flexible flat modules turn fingers into scoop. Figure 3 shows the designed modules: (a) and (b) are flexible components, while (c) is a rigid module.

The main structure of the scoop is composed of two rigid parts and a flexible component which is inserted into the slots, created on rigid modules (Fig. 4a). Redesigned rigid modules allow to convert two fingers in an actuated scoop assembly, as represented in Fig. 4b.

This new design generates the capability of the gripper to adapt itself to non-flat rigid surfaces and to avoid damage of grabbed objects. Therefore, it generates enough adaptability to the shape of objects and a good mobility, versatility and reconfigurability.

2.3 Differential mechanisms

In the new design configuration, the soft robotic hand is composed of two modular fingers and the gripper is actuated by a single tendon with a differential system. Figure 5 shows the typical scheme of a differential mechanism with pulleys and cables, which is the configuration used in the proposed underactuated gripper to transmit the motion to all the fingers with a single actuator and a system of tendons [65]. In this configuration a pulley transmits the actuation to a seesaw component which splits the actuation between two outputs. The same result can be obtained by using a 2 Dofs movable pulley instead of the seesaw component. The differential mechanism was realized by 3D printing.

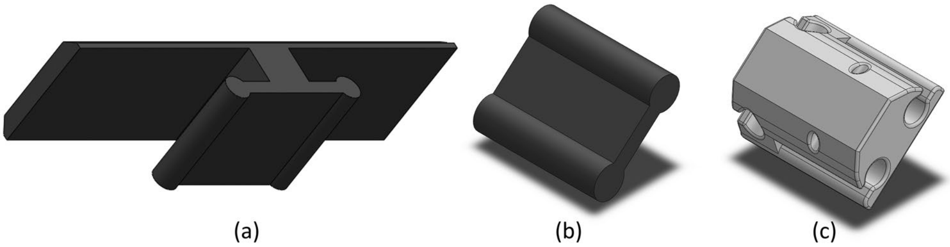


Fig. 3 Designed modules: **a** flexible scoop joint; **b** flexible finger joint; **c** rigid phalange

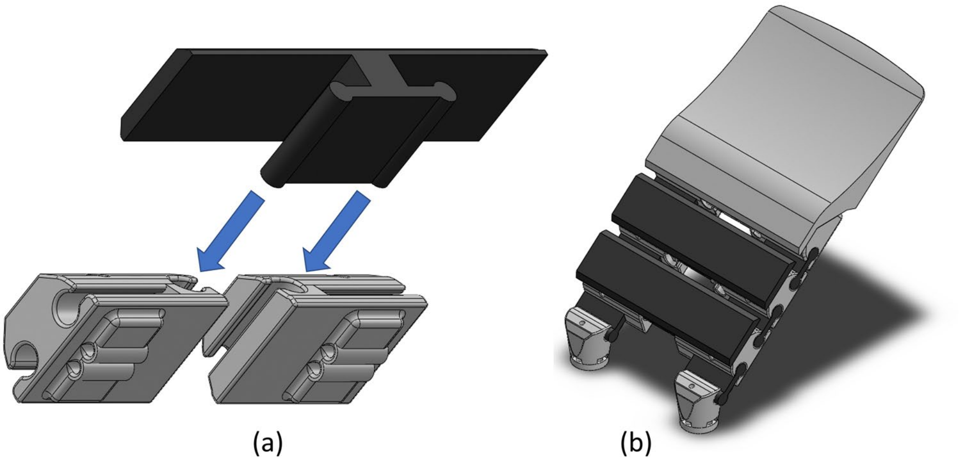


Fig. 4 Actuated scoop: **a** flexible component inserted into the slots of rigid modules; **b** scoop assembly

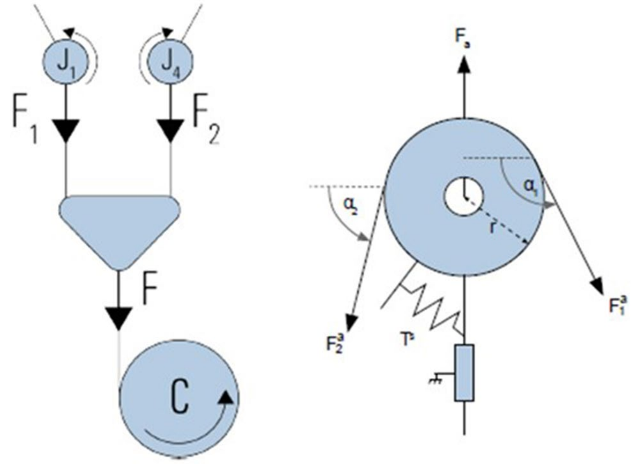


Fig. 5 Differential mechanism with pulleys and cables

2.4 Simulations of position analysis

The position analysis of two different grasping cases was performed by simulation using a dedicated tool in Simulink through Simscape Multibody as described in [66]. The proposed gripper was simulated during the grasping of two different objects. In the first simulation there the grasping of a symmetrical object as for instance a sphere was considered. The trajectories of the two fingertips of the gripper were simulated and, as on can observe from Fig. 6, in this case they follow the same trajectory. The grasping of an asymmetrical prism was performed in the second simulation and results are shown in Figs. 7 and 8, where one can notice the different trajectory of the fingertip when it comes in contact with the object before the other one.

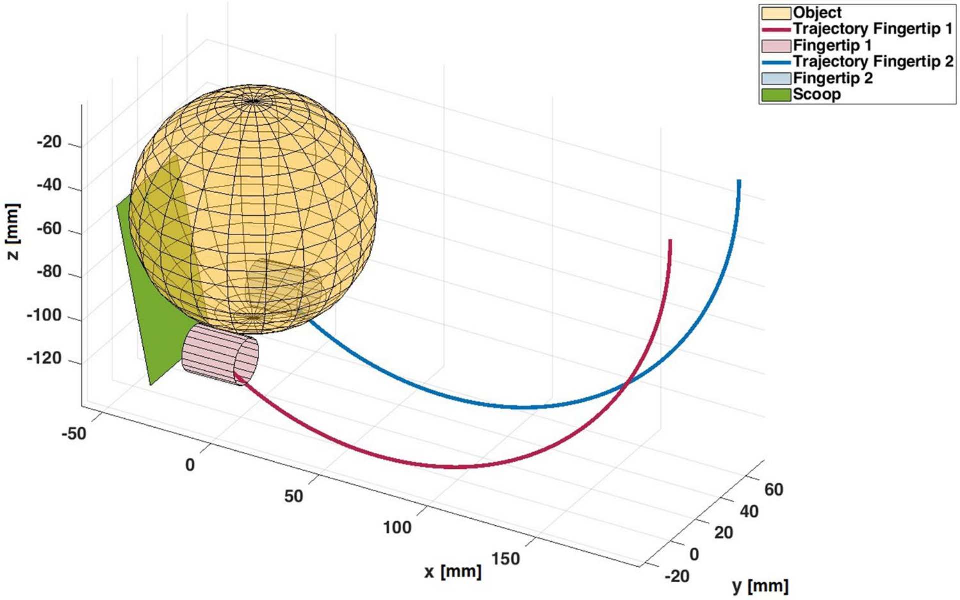
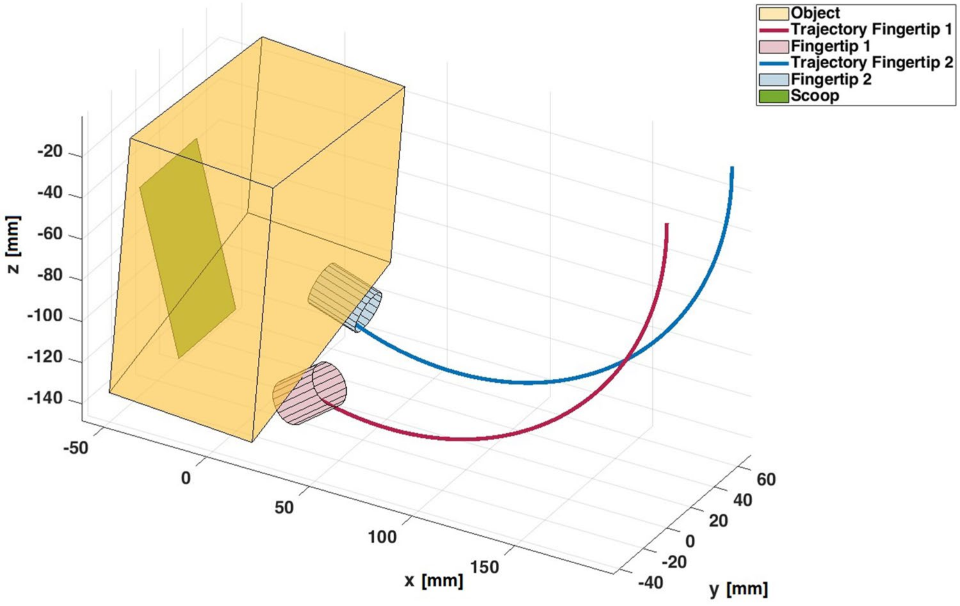


Fig. 6 Position analysis during grasping of a spherical object

Fig. 7 Position analysis during grasping of an asymmetrical prism



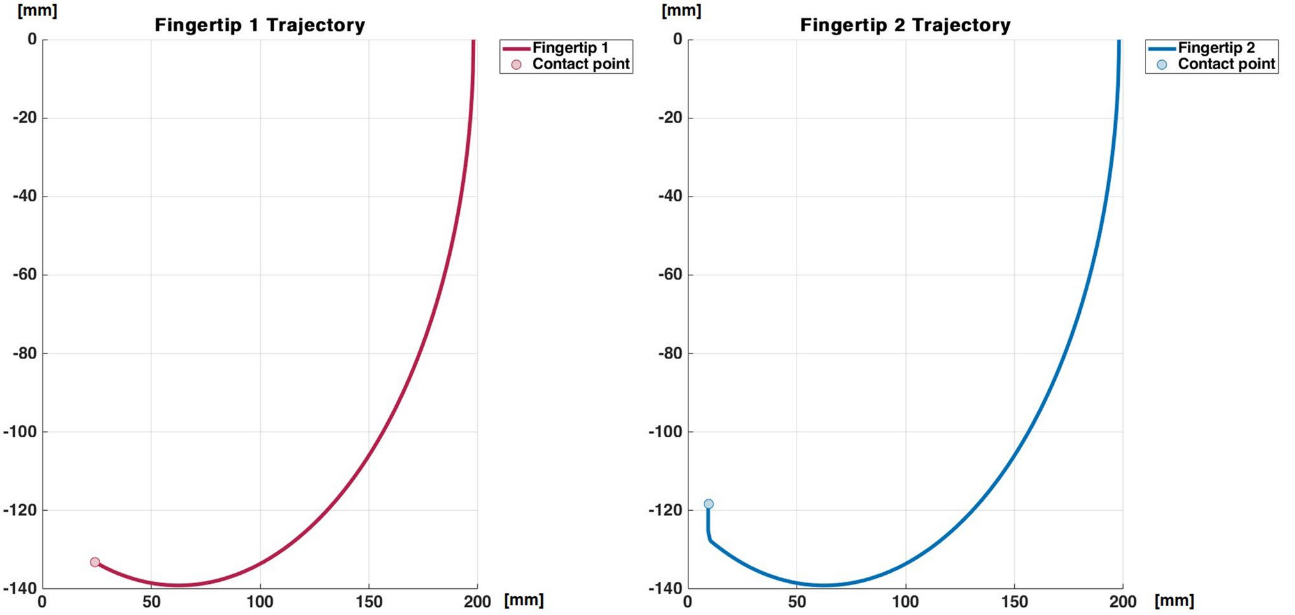


Fig. 8 2D trajectories during grasping of an asymmetrical prism

3 New ecofriendly materials

As it is known, plastic is an artificial organic substance produced primarily using fossil materials, such as oil and gas. Considering the example of Europe that is the second world's largest producer of plastics after China, the production of plastics is from fossil materials for a 90% and it uses 4–6% of the whole oil and gas used in Europe. In 2016, the Europe produced 60 million tons of plastic that generated 27 million tons of waste. Then, just the 31% of the produced waste was used for recycling, the 27% ended up in landfills and the rest was used for energy recovery. The 40% of European plastic is destined for packaging and is transformed into 16.7 million tons of waste [67]. Although the major production of plastic has fossil origin, it can be also made from cellulose and corn starch, generating bio-based and biodegradable plastics, so that to reduce the environmental impact and the load on the landfills. The bio-based plastics are derived from biomasses obtained from plants and their origin is biological without fossil components. Biodegradable plastics, on the other hand, can be both bio-based and non-bio-based.

To produce the gripper prototypes, two different types of material must be considered: a rigid material and a flexible one. In the previous version, the two materials were ASA for the main part of the device and TPU for the deformable joints. In the new gripper the use of bio-based materials was considered: PLA was chosen for rigid components, and PCL (polycaprolactone) for flexible joints. PLA is a polymer with mechanical characteristic that are compatible with ASA in terms of tensile strength even if it is more fragile. PCL is a petrochemical plastic but biodegradable and even if it has a fossil origin, its environmental impact is lower than TPU. It has a higher elongation at break with respect to TPU, and it is more elastic, with a slightly lower tensile strength. These characteristics make PCL a suitable material for the realization of flexible joints.

3.1 Renewal with ecofriendly materials and FEM analysis

The goal of this study was to propose a renewed gripper with ecofriendly materials and for this purpose the gripper was made with different materials and mechanical properties by combining different rigid and flexible materials, creating three combinations to be studied by FEM analysis. The aim of the FEM analysis was to evaluate the behavior of the device, and in particular of the scoop, for different material combinations, in order to assess the effectiveness of the new considered ecofriendly materials with respect to the previous ones.

The geometry was simplified to improve calculation time. Simplifications were made both on the geometry and shape properties of the parts, and on the constraints and forces used for kinematic analysis. The extremity of the prototype was examined and for the evaluation of the tendon-driven actuation behavior, the two fingers were constrained and fixed and then a prismatic constraint was applied to the back edges of the scoop.

Two different forces in two different directions were applied. In the first configuration the force was normal to the scoop to simulate the behavior of the gripper during the power grasping and when an object is grasped in a horizontal configuration (Fig. 9a), while the second one is a payload configuration with a lateral force (Fig. 9b). The study was performed by analyzing both the areas where the gripper is more stressed and the displacements of the scoop.

The analysis was performed with an applied force of 19.61 N. This value is due to the weight of a standard object with a mass of 2 kg. This choice is due to consider gripping of standard YCB objects. The force was applied to evaluate the device behavior for different positions of the object during the grasping and the analysis was carried out with different materials for the rigid parts (PLA and ASA) and for the flexible parts (TPU and PCL). FEM analysis was performed with a mesh of 165,677 elements with the hypothesis of large displacement. The mechanical characteristics of the considered materials are reported in Table 1. The three analyzed material combinations were PCL-PLA, TPU-ASA, TPU-PLA.

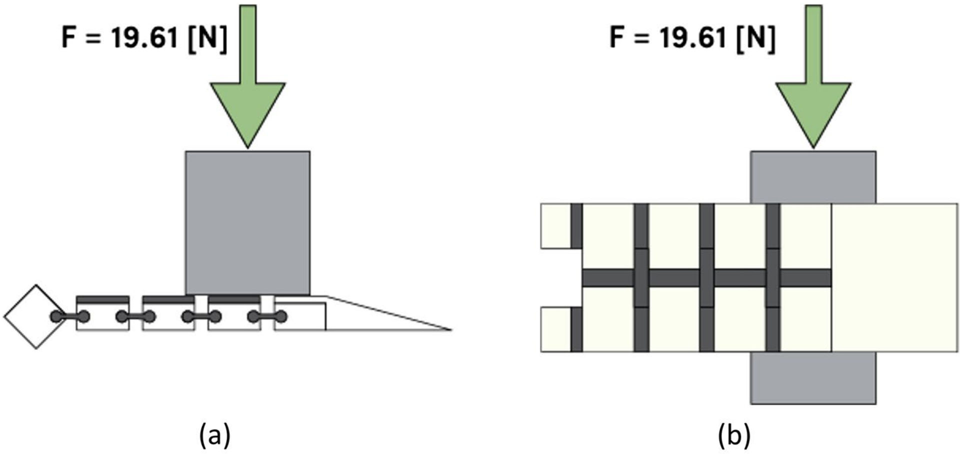
4 Numerical results

Numerical results obtained by FEM analysis are reported in Figs. 10, 11 and 12 in terms of displacement and von Mises stress for all the three considered material

Table 1 Material properties

Material	Density (kg/m^3)	Elastic modulus (MPa)	Poisson's ratio
ASA	1030	2097	0.371
TPU	1135	15.6	0.495
PLA	1024	3149	0.360
PCL	1200	24.9	0.495

Fig. 9 FEM configurations: **a** first configuration; **b** second configuration



combinations. One can observe that the behavior of the device for all the configurations is similar considering the different analyzed materials. Tables 2 and 3 show numerical results in terms of maximum static displacement and maximum static nodal stress for both the configurations.

The most ecofriendly material combination (PCL-PLA) shows a different behavior with respect to the other ones: the displacement is lesser than the other cases. This is due to a higher stiffness of the flexible material which makes the deformation of the joint more difficult. To compensate this higher stiffness, the joint density can be reduced during the 3D printing prototyping to enhance the joint flexibility.

5 Integration strategies for waste industry

The proposed soft gripper works in the context of human–robot collaboration and three different integration strategies in the waste industry were conceived with the aim of helping and protecting humans in manual sorting operations. The first strategy is represented in Fig. 13 and it concerns the integration of the gripper as a grasping device handled and controlled by the operator. To realize this kind of integration, the proposed gripper was equipped with a handle which contains the control interface and allows the operator to avoid a direct interaction with the waste material. A specific button allows the operator to control the flexion and extension of the modular finger and another button controls

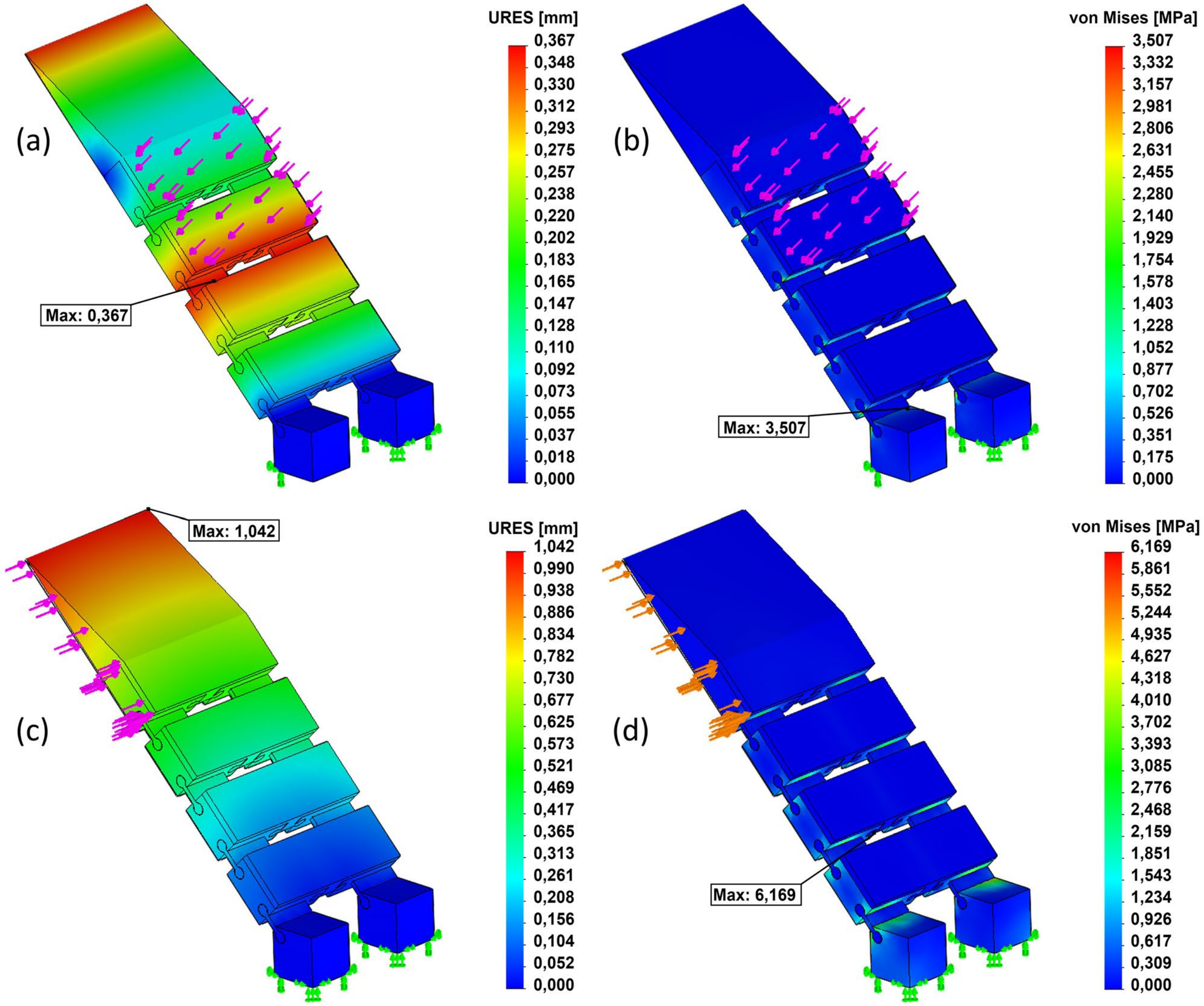


Fig. 10 PCL-PLA **a** displacement first configuration; **b** von Mises stress first configuration; **c** displacement second configuration; **d** von Mises stress second configuration

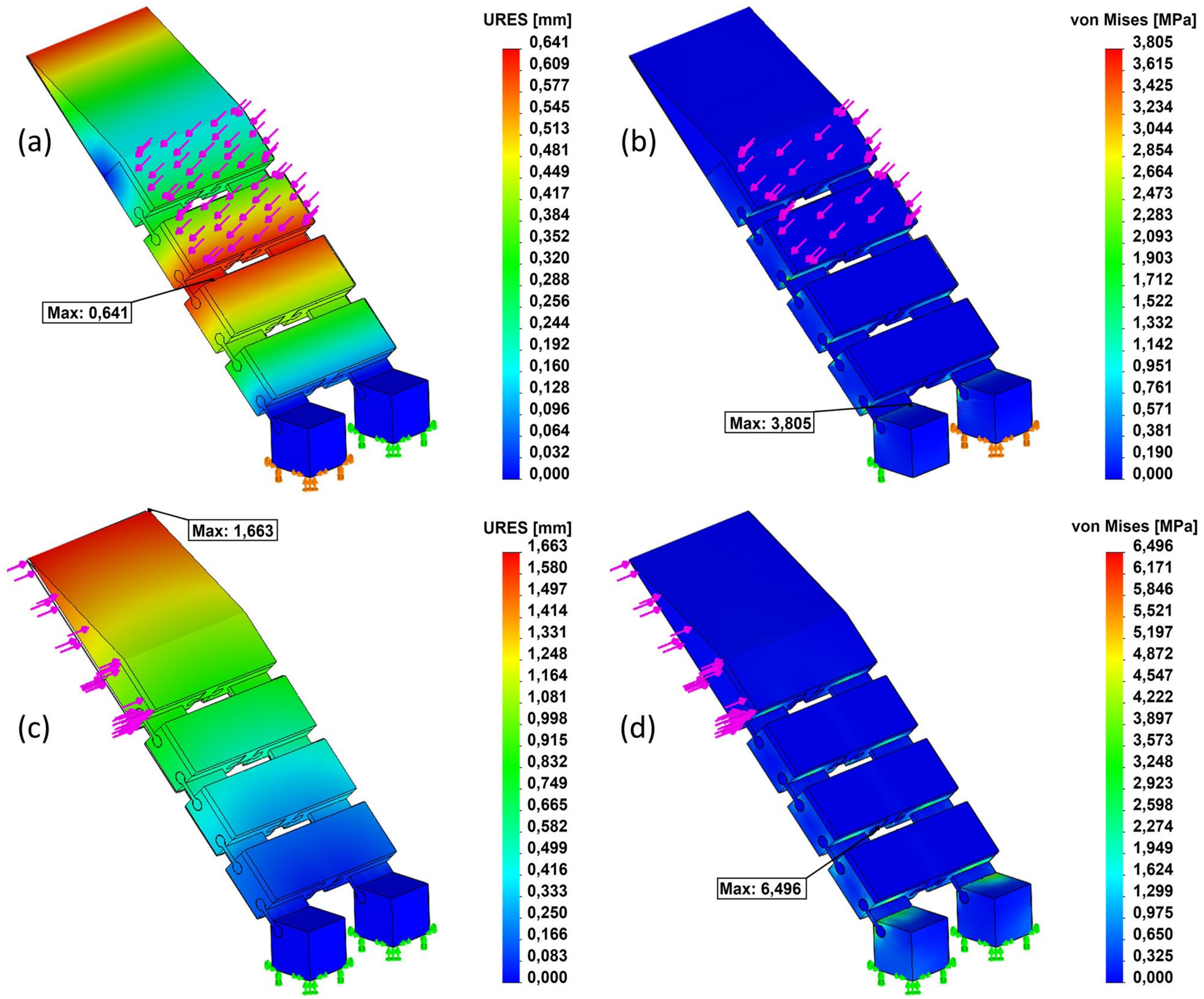


Fig. 11 TPU-ASA **a** displacement first configuration; **b** von Mises stress first configuration; **c** displacement second configuration; **d** von Mises stress second configuration

the movements of the scoop. The control scheme of the device is based on the finite state machine (FSM) model. When the finger flexion is activated, the fingers continue to flex until they come into contact with the object to be grasped. From this moment, a further pressure on the button increases the motor torque to make the grasping more stable until the complete flexion configuration is reached, based on the object shape. The fingers and the scoop can be extended with a double activation of the button in any of their state. The extension can be interrupted with a single button activation.

The second integration strategy can be performed by using the designed gripper as the end-effector of a cobot, as represented in Fig. 14. In this case, the gripper can be controlled by the operator throughout the cobot control system or it can be programmed to cooperate with humans substituting them in the most harmful operations.

The third integration strategy is performed by equipping the gripper with a wearable handle which allows the operator to manage the gripper as a third auxiliary arm, as represented in Fig. 15. In this case, the same considerations about the control system reported for the first integration strategy can be applied to this solution.

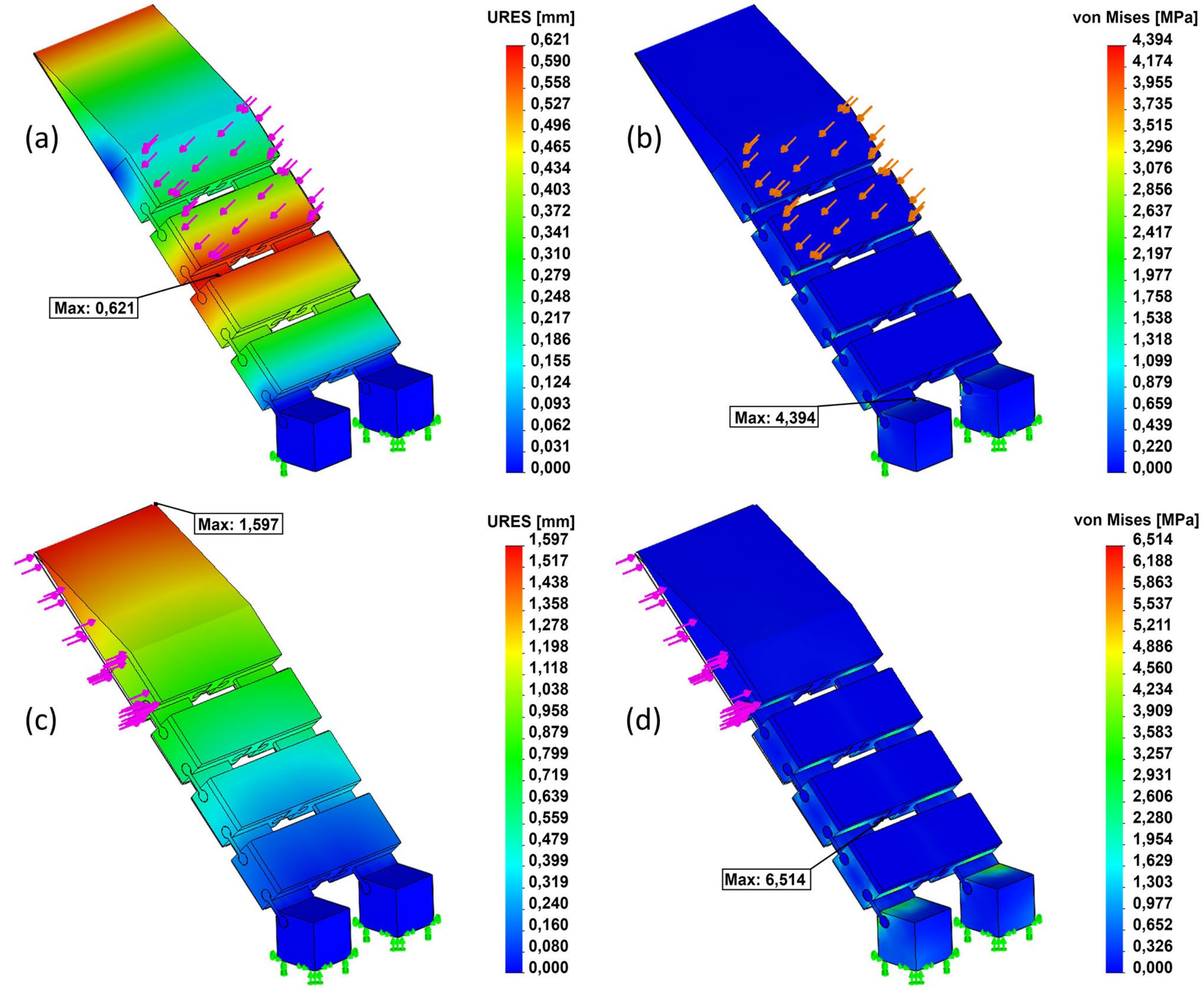


Fig. 12 TPU-PLA **a** displacement first configuration; **b** von Mises stress first configuration; **c** displacement second configuration; **d** von Mises stress second configuration

Table 2 Power grasp (first configuration)

Configuration (rigid-flexible)	Static displacement (mm)	Static nodal stress (N/mm^2)
TPU-ASA	0.641	3.805
TPU-PLA	0.621	4.394
PCL-PLA	0.367	3.507

Table 3 Payload (second configuration)

Configuration (rigid-flexible)	Static displacement (mm)	Static nodal stress (N/mm^2)
TPU-ASA	1.663	6.496
TPU-PLA	1.597	6.514
PCL-PLA	1.042	6.169

6 Conclusion and future developments

The proposed robotic gripper can help to meet the UN's 17 Sustainable Development Goals (SDG) in industry for achieving a healthier planet [19]. One of the consequences, in many industrial fields, is the quality of life of workers that will be improved together with their health, thanks to the use of this kind of grippers that fall within a context of collaborative robotics. The use of the presented gripper is particularly advantageous in the specific context of the recycling and waste

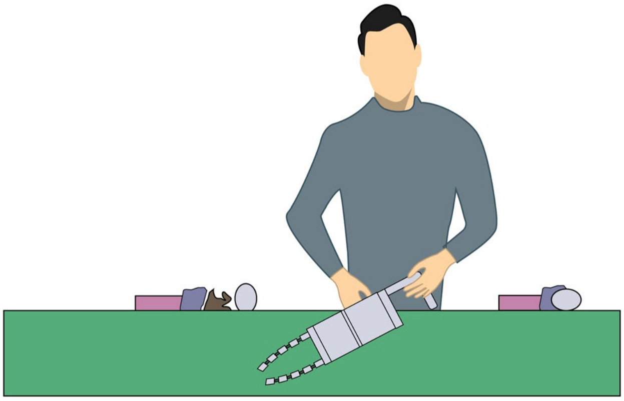


Fig. 13 First integration strategy: handling

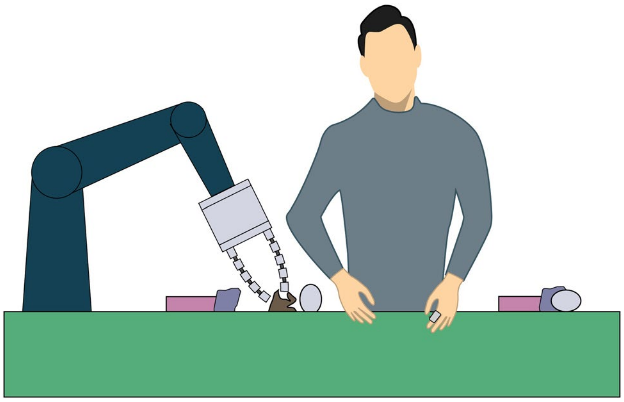


Fig. 14 Second integration strategy: cobot

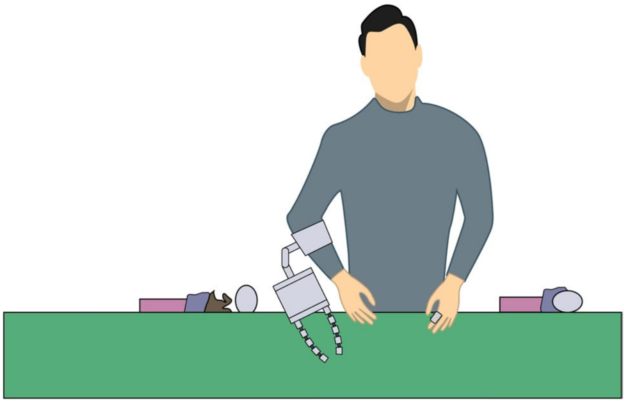


Fig. 15 Third integration strategy: auxiliary arm

disposal chain, where the processing of waste and the separate collection process are sometimes dangerous for the health of workers, which must manipulate the waste. The three proposed strategies for the integration of the gripper contribute at satisfying the SDG3 in terms of decent work and the SDG8 in ensuring healthy lives.

In particular, in the paper the design and analysis of an underactuated gripper for helping humans in manual operations in the waste industry was presented. The described gripper is a combination of modular elements which lend high versatility and reconfigurability to the whole device, especially for application in manual waste sorting. In this application the probability of damage mainly regards the extremities of device (such as fingers) that are easily replaceable. Therefore, it is precisely the modularity of the extreme parts of the gripper that allows an easy recycle of the material with a reduction of waste and eliminating the obsolescence linked to the development of new devices. Furthermore, all the modules were conceived to be realized in ecofriendly and biodegradable materials such as PCL and PLA, maintaining good mechanical properties and device effectiveness, as demonstrated by the FEM analysis. Therefore, the proposed device can find applications in a prospective of circular economy, for its intrinsic characteristics of modularity and simple substitution of eventual damaged components. Moreover, the use of "eco-friendly" materials for the realization of the gripper improves a sustainable industrialzation, according to SDG9, with responsible production and consumption, according to SDG12). All these considerations are also reinforced if one considers that the gripper is an underactuated system with high versatility and cost-effectiveness due to the use of fewer actuators which allows to create lighter mechanisms.

Limitations of this study can be overcome by planning future developments focused on the evaluation of the device life in terms of fatigue under the effect of cyclic bending moments. This task will be addressed experimentally considering different materials, but for a theoretical evaluation there will be a limitation related to the knowledge of the characteristics of 3D printed materials. In addition, future experimental tests could be performed considering the methodology proposed in [68] to evaluate the grip force, that is a crucial parameter to investigate for using this kind of grippers in industrial operations.

Funding The authors have not disclosed any funding.

Declarations

Competing Interests The authors have not disclosed any competing interests.

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