A novel pneumatic gripper for in-hand manipulation and feeding of lightweight complex parts—a consumer goods case study

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Received: 9 November 2017 / Accepted: 21 May 2018 / Published online: 30 May 2018
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Abstract

This paper discusses the design and implementation of a robotic gripper that uses compressed air to (a) orient the parts in the desired grasping position, (b) guide the parts inside a grasping mechanism and (c) feed the parts to a track conveyor with sufficient accuracy. The novelty of the approach lays in the ability to perform in-hand manipulation of the object by the gripper allowing to pick randomly placed objects that have a complex geometry. Unlike existing ‘pick and place’ operations which are mainly focused on flat objects that require minimal manipulation (rotation around vertical axis), the gripper can re-orient the parts itself, minimizing the robot’s motion. The major components of the gripper are 3D printed, allowing fast customization for different products. The manipulation and gripping mechanisms have been inspired by an application in the consumer goods industry involving the feeding of shaver handles to an assembly machine. The findings indicate that the proposed solution can be an alternative to part-dedicated, high-cost feeding equipment that is currently used.

Keywords Robotics · Pneumatic gripper · Manufacturing · Automation · In-hand manipulation

1 Introduction

Mass production of small-sized, lightweight parts is one of the most common activities encountered in different production sectors around the globe [1]. Consumer goods, plastics, medical and healthcare products and small metallic parts are some indicative examples (Fig. 1). In most cases, hard automation has provided an efficient but very costly and inflexible solution [2, 3].

The increased demand for higher product variety as well as the evolution of manufacturing processes and control systems [4] has favoured the development of robotic applications that can undertake several tasks in the manufacturing chain either as standalone or as cooperating units [5, 6]. The sorting and feeding of the parts are indicative examples. Up to now, the need for loading parts from bulk has been covered by devices such as vibratory feeding bowls and conveyors as well as manual labour. With the advancement in robot sensing and

manipulation capabilities, it has become possible to partially or fully automate these activities. In such applications, the main development focus is on issues as follows:

1. Development and deployment of advanced vision systems that are able to identify multiple moving parts that are either in bulk or moving on a conveyor surface [7].
2. Introduction of algorithms and communication frameworks [8] for the synchronized, collision-free and efficient operations of multiple robots [9] in the same workspace. This involves tools for the determination of the optimum sequence of operations (e.g. pick, place) [10, 11] as well as the real-time motion planning [12] and operational reconfiguration [13] of each robotic arm towards minimizing the cycle time.
3. Development of dexterous and flexible grippers that allow the simple and efficient pick and place operations emphasizing on hardware and software complexity minimization to achieve robust operation. A vast range of grippers have been proposed and classified so far and are also discussed in the following paragraphs [14].

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An example of the most typical setups for robotized sorting and feeding is presented in Fig. 2. The parallel kinematic robot on the right side is driven by a control logic to pick randomly

Fig. 1 Lightweight non-symmetrical parts from multiple industrial sectors

placed parts and form groups of four. The decision is driven by the output of a high-speed vision system. The coordination software ensures that the batteries are picked in a sequence that optimizes the pick and place operation and also drives the second robot (on the left) to pick the group of parts without colliding.

In the specific system, although the robot provides the speed of motion, it is the gripper that provides the ability to carry out the entire application. What is more important though is the fact that the problem at hand is somehow simplified due to the following conditions:

1. The identification by the vision system is a 2D problem and is solved rather easily by detecting the outlines of each battery and the side with the battery poles (orientation). There is therefore no need to identify the pose of the item.
2. The parts are flat objects that lay rigidly and do not move with small forces due to the friction between them and the conveyor surface.
3. The batteries always provide an area on their surface that is flat and large enough to allow picking using vacuum. Picking is always performed on the part without the need to ensure that it is in a correct orientation.

4. The required re-orientation of the parts only takes place along the vertical axis rotation and thus, fast motions can be achieved by the parallel robot on the expense of constrained/2D manipulation. No further dexterity is needed to manipulate the battery.

However, observing the items of Fig. 1, it is obvious that these parts do not allow for most of the aforementioned simplifications. The main reason is that they have a complex 3D geometry (not flat) that requires a more dexterous manipulation. Towards this direction, this paper presents the design of a novel gripper that can handle such parts. To efficiently present the design approach, the presented gripper is customized for handling plastic shaver handles that are not symmetrical along all axes. The ability of the gripper to overcome these limitations comes from the fact that it is designed to carry out in-hand manipulation of the part and correctly orienting them before grasping. The generalization of the proposed gripper relies on the ability to use 3D printed components to meet the geometry of the objects to be handled (see also Section 3.1: Operating principle) and also the positioning of the compressed air nozzles to ensure that the required force vectors for manipulating the object are achieved.

1.1 Literature review

The wide variety of objects manipulated in industrial process has resulted in an extensive development of new robot grippers and robotic hands, based on different geometries and working principles [16]. The same work identifies 12 grasping principles namely friction, jaws, magnetic, suction, needle, electrostatic, Van der Waals, ice, acoustic, laser, Bernoulli and adhesive. In terms of actuation principle, air-driven grippers are in their majority, based on the Bernoulli and vacuum effects. However, they have been primarily applied in the case of planar products [17, 18 and 33] and in some limited cases in more complex 3D parts but without any manipulation capability [20].

An additional characteristic of few grippers is the ability of in-hand manipulation of parts. The grippers of [21, 22] use

Fig. 2 High-speed sorting and pick and place operations [15]

two interlinked belts as active surfaces allowing the grasped object to be rotated in-hand. In-hand manipulation can also be achieved with the use of omnidirectional driving gears allowing the translation and rotation of the part [23].

The above-mentioned working principles as well as gripping devices either are dedicated for manipulating simple geometrical components or consist of complex devices that would require difficult and intricate control. Since the targeted application poses requirements (please see Section 2) for fast manipulation and accurate placement of components, the proposed gripper cannot be classified in the above categories as it differs from these examples in the following areas:

1. It uses two different hardware modules to achieve in-hand manipulation and grasping. In this sense, it is closer to the Bernoulli or vacuum grippers (although no negative pressure forces/suction are used) in the sense that it uses air flow. No category in the literature uses compressed air to directly manipulate the part. The final grasping is done by two parallel components and would otherwise classify it as a jaw gripper.
2. The manipulation is done using compressed air nozzles allowing the part to move freely before it is grasped. Up to now, the non-contact manipulation can be partially achieved by using magnetic actuation which is nonetheless applicable in a reduced set of metal parts [24]. The in-hand manipulation is not performed by the gripper fingers/gears allowing a more simplified control approach. No real-time sensing and correction is needed.

In the past, a somehow similar approach has been used in vortex levitation grippers where the handling is performed by blowing air into a vortex cup through a tangential nozzle. This results in a swirling air flow which causes negative pressure due to the developed centrifugal forces. The workpiece can be picked up and held at an equilibrium position [25]. Similar swirl-based handling effect has been replicated by means of electrical actuation [26]. In both cases however, only picking is possible and not direct manipulation can be achieved.

In terms of the manipulation capabilities, the gripper developed in [27] as part of the EU project AUTORECON is the most relevant. It belongs to the jaw gripper categories and incorporates linear actuators at the fingertips that allow the rotation of the part. This gripper seems to perform very well in the case of parts that are balanced and have a circular circumference. The shaver handles required very good accuracy in the positioning of the device before grasping and this was affected by the accumulated errors by the robot and the conveyor tracking or vision systems. Another fact is that the structure is heavy and very complex and thus inefficient for handling small lightweight parts as the handles. Vibrations during the acceleration/deceleration motion of the robot also affect the performance.

The advantages of the discussed gripper, compared with other grippers and robotic hands (e.g. [28]), are that with the use of four nozzles, it can achieve rotation and positioning in short period of time and it is lightweight as very few actuators are needed to perform the grasping and consists of parts that can be 3D printed, reducing the cost between product changes.

The paper is organized as follows: Section 2 presents the problem definition stemming from the analysis of requirements of the particular consumer goods industrial case. Section 3 is dedicated to presenting the operating principle of the gripper as well as the design of the constituting models. The results of a fluid dynamics simulation analysis that was performed to validate the feasibility of the approach are also presented in this section. Section 4 is dedicated to presenting the implementation of the actual gripper hardware and control systems and Section 5 outlines the outcome of experiments conducted in laboratory. Finally, Section 6 draws the conclusions of this work and outlines areas of future research.

2 Problem definition

The origins of this research work come from the consumer goods industry and more specifically the production and assembly of shavers. The presentation of the designed gripper is therefore coupled to the specific application for simplicity of explanation, but a generalized method to transfer the operation principles in gripper designs for different part types is also provided in Section 3. Shavers are assembled by two components: the shaver handle and the razor head. The handle is a plastic moulded part weighing around 20 grams and its geometry varies depending on the model. Its main characteristics however is that it is not symmetrical along all its axes. On the opposite, it has a rather complex geometry as shown in Fig. 3.

As most of the parts that are created by injection moulding, it is produced in the orders of millions per day and has to be allowed time for curing which is about 24 h. Given the large number of parts and its production method, the produced handles are stored in bulk in large containers and need to be fed into production after the plastic settling period. More specifically, the handles have to be fed in an automated machine that assembles the handle with the razor head. For this purpose, vibratory feeding bowls such as the one shown in Fig. 4 are used to sort and feed the parts. The box with the bulk handles are emptied inside the bowl and the vibrations drive the parts against the surfaces of the bowl, making them to climb from the bottom to the top. During this process, the parts either obtain a correct orientation that allows them to finish their travel to the exit (left of the image) or fall inside the bowl and repeat the process until they are successfully oriented. At the exit of the bowl, a track conveyor is attached, driving the handles to the entrance of the assembly machine by securing the

front path of the handle inside an aluminium rail of a proper profile (Fig. 5). At the end of the conveyor, special opening slots are used to release the handle which is picked by means of an automated suction system.

Feeding bowls have been very efficient in terms of production rates and robustness; however, they have the following critical drawbacks:

1. *High investment costs.* Each one starts in the order of tenths of thousands and may well surpass the hundreds of thousands.
2. *Long development time.* These devices are built by experience people only and usually following a trial and error approach that leads to months before the equipment can be delivered. All surfaces are created manually and it is almost certain that combines have to outsource its production than manufacture it in-house.
3. *Product dedicated.* These bowls are made for a specific product only. Even the slightest changes in the product material, surface, weight or geometry will result in becoming it unusable. A new bowl has to be built every time a new product is introduced or an old one is modified.
4. *Very high noise levels.* Due to the vibratory motion, the generated sound levels are such that do not allow operators to safely work around these devices without using ear protection. Especially in the case where multiple bowls operate inside the same room, the conditions become unbearable for the operators.

As a result, the consumer goods industry has initiated research to identify other means of performing the feeding operation to the track conveyor. The H2020 VERSATILE Project which has funded this research has allowed to analyse the requirements towards the robotization of the process. However, the investigation of ‘off the shelf’ solutions has led to the conclusion that the case is much more complex than the simple ‘pick and place’ operations that have been presented in Section 1. The

Fig. 3 Shaver handle resting poses on flat surface

Fig. 4 Vibratory feeding bowl [19]

reason is the fact that the handle and the production process requirements presents almost none of the features that would allow it to be manipulated by standard gripping solutions:

1. The handle can rest in many different poses, making it impossible to use a standard approach for grasping (as in the case of flat objects).
2. It does not have large enough flat surfaces that could allow it to be picked using small suction caps. Even if for one of the poses it could be possible to use suction caps, the process requirement for fast motion (acceleration) would not allow the part to be firmly grasped.
3. The geometry is variable along almost all axes, thus requiring a very compliant grasping means (e.g. not rigid/metal fingers). This however signifies very low grasping accuracy. The placement in the track conveyor on the other hand requires good positional accuracy to be successfully achieved.

The use of parallel, angular or suction grippers to pick and orient the part using direct contact is only possible in the case where the handle already has a correct pose allowing to grasp

Fig. 5 Track conveyor

it directly. In the cases where the handle is laying on its side, the grasping will result in the position of the gripper being next to the handle and the fingers being on the top and bottom side of it. As a result, this will not allow its release when the handle is correctly oriented. Considering to grasp it from the rear end would fail as the centre of gravity is such that would require high clamping forces that may damage the outer surface of the part. Even if this was resolved, the high acceleration of the robot may result in forces that affect the certainty of the grasping position (slipping, sliding, rotating at the grasping points), eventually leading in the part not being successfully loaded to the machine. In addition, conventional gripping devices, or grippers similar to the one proposed in [27], result in deflections in the orientation of the manipulated handle once it has been grasped, leading to an inaccurate placement of the handle in the track conveyor.

Summarizing the above, it is evident that a more efficient gripper design is required for performing the feeding process. The main criteria are the ability to successfully pick the parts regardless of their orientation and the accurate positioning so that they can be fed to the track conveyor. The following section describes the design of the proposed gripper in terms of operating principle as well as its detailed design.

3 Approach

To address the challenges that were described in the previous paragraph, this section describes the design of a pneumatic gripper that is able to pick randomly placed (in terms of position and 3D orientation) parts from a flat surface or conveyor and feed them to a predefined location. The shaver handles will be used as the basic example to explain the operation of the device; however, it will be demonstrated in the next sections that the same design can be used to derive grippers for a range of similar products. Considering the analysis of the previous section, an efficient gripper design will need to lead to the following:

1. A gripper that is able to correctly orient the part on its own, eliminating the need of deploying and controlling robots of multiple degrees of freedom (DoF), such as 6-

DoF robots. Simple Cartesian mechanisms or SCARA type robots seem more preferable for high-speed manipulation.

2. Increased accuracy during the grasping, leading to accurate placement of the parts.
3. Small weight of the device removing the need for large motors or mechanical structures to manipulate the object. The parts of interest are lightweight (several grams) and therefore using a heavy device that has to be moved continuously in the 3D space is considered a waste of energy and efficiency.
4. Use of easily replaceable parts (3D printed) to accommodate different product types.

3.1 Operating principle

Given the fact that the parts to be manipulated are lightweight, they can be displaced or rotated by small forces exerted on their surface. As a result, the concept of manipulation by means of compressed air which is directed through small nozzles in carefully selected locations was selected. Unlike the case of grasping/clamping devices, the part is manipulated without coming in contact with a moving object such as the fingers of a parallel gripper. In fact, the use of parallel or angular grippers is not advisable considering that the geometry of the handle along its longitudinal axis is constantly changing. As a result, the grasping with the use of rigid fixture would result in uncertainties of the final position when the part is grasped due to local sliding in the contact area. Even if the fingers are shaped to match the object surface locally, the positioning accuracy (vision system, robot accuracy and conveyor motion) could lead to a premature contact between the gripper and the part, altering the calculated position between it and the gripper fingers.

Figure 6 depicts the overview of the methodology for the design and implementation of a pneumatic gripping device able to manipulate and accurately place small complex shaped parts. The geometrical analysis of the handling surface will indicate the key features for the air stream impact points to rotate the part, while the analysis of the airflow will reveal the precise placement of the nozzles as well as the required

Fig. 6 General methodology

geometry/surfaces of the gripping device. Based on the requirements of each application in terms of grasping and releasing the manipulated component, the final design of the gripper will be generated. The last step of the method deals with the validation of the proposed concept by conducting a fluid dynamics analysis for validating the orientation capabilities of the gripper, while the experimentation phase provides the feedback to the design phase for verifying and optimizing the device for each application (orientation, grasp, release/place). The aforementioned methodology as well as its general applicability is described in the following sections.

3.1.1 Geometrical analysis

The analysis of the handling surface has indicated some key features of the surface that may be used to control the motion of the part under the exertion of air bursts on it. More specifically as illustrated in Fig. 7 (views of handles), the areas marked with A and B provide possible points where force can be exerted to create a rotation moment around the longitudinal axis (forces in points A are vertical to the image and directed inwards while points B and C signify outwards forces, see also Fig. 8). In each case, the identified areas are at the same height (h) from the flat surface, ensuring that the force is applied in the same areas regardless of the handle's pose. In this sense, if the rotation around the other two axes is physically constrained, a manipulation of the part in a desired position is achievable.

As it can be observed, the geometry of the handle is such that allows identifying similar areas in every possible pose that it may be resting on the flat surface. This ensures

Fig. 7 Side view of possible handle poses and candidate points for force application

Fig. 8 Selected nozzle arrangement

that the handle can be forced to rotate regardless of the position that it is laid upon the surface. Based on this analysis and the examination of the different part poses, the best configuration to achieve the rotation of the part is to have two nozzles pointed at the upper front and upper rear parts of the handle and one nozzle pointing at the bottom part of the middle section (Fig. 8).

However, a critical question arises that is how to ensure that the rotation of the handle is controllable and can be stopped at the desired orientation. The solution is found at the part geometry itself. As it can be observed in Fig. 7, pose 1 is the only one where empty space is observable at the bottom part of the middle section (area marked with C). By using the arrangement of nozzles that was described above, a single nozzle is directed to this area on one side of the handle. As a result, when the handle is found in this, and only this orientation, the air passes through this space, exerting no force and thus cancelling the force couple that creates the rotation. In other words, the arrangement of the nozzles in combination with the part geometry creates a locking effect that does not allow the part to further rotate. The inequality of the lateral forces results in the part being pushed against one of the side walls; however, this has no effect to the whole process as long as the desired orientation is achieved. The aforementioned analysis has led to the design of the manipulation module that is presented in Section 3.2.1.

3.1.2 Orientation principle

In addition to the above-mentioned geometrical analysis of the handle, and as soon as the points of interest on the surface of the component have been identified, an analysis on the airflow angle will ensure the efficient placement of the nozzles. As presented in Fig. 7, there are three possible areas where the air nozzles can be installed (namely upper front nozzle, upper rear nozzle and bottom middle nozzle) and there are six possible equilibrium positions of the shaver handle. As it is required to constrain the irregular movement of the shaver handle, once air streams are applied on its surface a concave design of the side walls of the gripper was selected. The geometrical analysis of the object as described in the previous section allows to

Fig. 9 Upper front nozzle

design the side walls of the gripper according to the individual geometry of the parts to be manipulated.

The analysis of the angle of incidence coupled with the location of each air nozzle follows. Considering the height of placement for the upper front and the rear nozzle as was described in Fig. 7, a placement of these nozzles parallel to the flat surface would result in no significant rotational effect to the handle. Taking also into account all the six possible equilibrium poses of the handle, the air-flow angle was extracted by identifying the minimum and maximum points of incidence to the manipulated component. Figure 9 shows that the selection of the upper front nozzle placement at an angle between 35° and 55° from the flat surface will result in the same rotational effect. Similarly, the extraction of the angle of incidence was accomplished for the upper rear and the bottom middle nozzles and their results are presented in Table 1.

The previous concept is able to perform the in-hand manipulation/orientation of the part; however, it provides no means of accurately positioning of the part which is still free to move within the concave surface. If the part is to be assembled

or fed to specific slots in a conveyor, a way to accurately position it and grasp it is required.

The main challenge is that no equipment can be added in the interior of the concave surface as it would disrupt the free motion of the part or the air flow from the nozzles. To overcome this issue, it was decided to add an additional module which can actively grasp the part after it has been properly oriented. Since the front and rear sides of the handle are not needed for the orientation process, they were selected for the removal of the part from the gripper. The addition of one extra nozzle in the front part allows for driving the part towards the rear end of the gripper. The selection of the front part for applying the air stream was due to the fact that:

1. The front part is more complex and thus would require more effort to constrain.
2. The rear part involves a smooth geometry that can be also used to fine tune the position of the handle upon grasping.

The designed grasping module to achieve this operation is presented in detail in Section 3.2.2.

Table 1 Angle of incidence for the upper rear and bottom middle nozzles

Point	Pose 1	Pose 2	Pose 3	Pose 4	Pose 5	Pose 6	Common area
Upper rear nozzle							
A	$\varphi_A = 8^\circ$	$\varphi_A = 10^\circ$	$\varphi_A = 30^\circ$	$\varphi_A = 25^\circ$	$\varphi_A = 20^\circ$	$\varphi_A = 20^\circ$	$30^\circ \leq \varphi \leq 60^\circ$
B	$\varphi_B = 65^\circ$	$\varphi_B = 60^\circ$	$\varphi_B = 65^\circ$	$\varphi_B = 80^\circ$	$\varphi_B = 75^\circ$	$\varphi_B = 75^\circ$	
Bottom middle nozzle							
A	$\varphi_A = 0^\circ$	$\varphi_A = 5^\circ$	$\varphi_A = 35^\circ$	$\varphi_A = 40^\circ$	$\varphi_A = 25^\circ$	$\varphi_A = 22^\circ$	$-10^\circ \leq \varphi \leq 5^\circ$
B	$\varphi_B = -50^\circ$	$\varphi_B = -45^\circ$	$\varphi_B = -25^\circ$	$\varphi_B = -15^\circ$	$\varphi_B = -10^\circ$	$\varphi_B = -15^\circ$	

One might argue that once the correct orientation of the part is achieved a more conventional gripper can be used to pick up the part. However, this would mean that the robot will need to exchange the tools for every part that it handles (increasing drastically the cycle time) or more than one robots need to be used (essentially doubling the investment cost). For this purpose, the design was defined as a single device with two modules implementing the manipulation and grasping functionalities as described in the following section.

3.2 Design

Based on the analysis of the operating principle in the previous section the operation of the gripper was assigned to two separate but cooperating modules, namely the manipulation and the grasping module.

3.2.1 Manipulation module

In order to limit and not fully constrain the motion of the part, a concave form was selected which is large enough to allow a complete rotation of the part within it as shown in Fig. 10. The handle is able to perform a full rotation along the longitudinal axis and some small translation along all three axes. The rotations around the lateral and vertical axes are constrained by the module walls.

As already mentioned, the inner design of the manipulation module is concave in order to meet the geometrical requirements posed by the manipulated object.

Following the investigation of the previous section an arrangement of three nozzles on the side of the surface has been designed. The exact position of each nozzle has been determined through the geometrical and orientation analysis, while their feasibility was validated through the use of computational fluid dynamics simulation (please see Section 3.3). As will be explained in the following sections, a pivot mechanism has been added to allow the

Fig. 10 Manipulation module CAD model

Fig. 11 Medical parts

assembly of the manipulation module with the module that is responsible for the grasping of the part. In addition, a fourth nozzle in front of the manipulation module has been designed and integrated. This nozzle is responsible for transferring the well-oriented component from the manipulation to the grasping module and it is described in the following section. The outer surface of the module has been designed to be flat in order to minimize the 3D printing time and to provide space for the installation of components such as the valves for controlling air flow and the servomotors.

The manipulation module can be easily redesigned (e.g. semi-circular, orthogonal) to meet a wider applicability on similar products (lightweight with complex geometries). Some indicative examples of possible areas of applicability of the proposed solution can be found in the medical, mold and consumer goods sectors. Small and lightweight parts are being extensively used in the medical sector (as the dosage spoon presented in Fig. 11). In this case and as the dosage spoon has a simple orthogonal geometry, the manipulation module could follow a semi-circular concave geometry for achieving the rotation of the component.

A more complex geometry of a component can be found in the mold industry and more specifically, the plastic component is depicted in Fig. 12. As the plastic part along its longitudinal axis has a wider front part, the manipulation module could be split into two chambers (front and rear). The front chamber of the manipulation module could follow a wider

Fig. 12 Plastic mold parts

Fig. 13 Consumer goods parts

semi-circular geometry in order to provide enough space for the component to rotate, while the rear chamber has more narrow side walls that will allow a more controlled rotation of the part while streams of air are applied on its surface. Several lightweight components with complex geometries can be found in the consumer goods industry.

The water scraper (depicted in Fig. 13) is an indicative example of a complex lightweight part. In order to achieve the rotation of the scraper, the front part of the manipulation module could follow a wider geometry for allowing the component to rotate, while the rear part of the module could have a more constrained geometry. The guiding surfaces inside the manipulation module could help the part to be transferred away from the module. At this point, it should be mentioned that the flexibility and reconfigurability of the manipulation module derives from the ability of using 3D printed components. The applicability of the proposed solution under the above-mentioned industrial sectors should be further investigated to meet the individual requirements per case.

3.2.2 Grasping module

The operation principle of the grasping involves the handle being pushed by an air stream against a mechanical stop at the end of the gripper. This ensures that its rear end is always located against a known surface. Another nozzle has therefore been added at the front of the manipulation module (see also

Fig. 14 Air stream of the front nozzle

Fig. 15 Parts of grasping module

Fig. 18) that is able to transfer the well-oriented component towards the grasping module (Fig. 14). The geometry of the part that slides against the surface upon which it lays, in combination with the guiding surfaces within the manipulation module, helps in the smooth transition from the manipulation to the grasping module.

Following, a double-acting clamping mechanism is added to clamp the part from its sides. A servomotor is directly mounted on a rotating element which acts as a spacer between the two clamping parts. As presented in Fig. 15, the servomotor is placed on the top of the main body of the grasping module and with the help of two pairs of small linear guides, the open/close motion of the clamping parts is achieved. The assembled grasping module is presented in Fig. 16 while the open/close functionality of the module is presented in Fig. 17.

The clamping elements that come in contact with the part are 3D printed to form a cavity that matches the shape of the handle. As a result, the closing action guides the handle in this cavity and ensures that a known position is eventually assumed by it. Again the design of this cavity can be easily

Fig. 16 Assembled grasping module

Fig. 17 Open/close functionality of the grasping module

redesigned and 3D printed in order to meet the geometrical characteristics of different components based on the several different applications.

Last but not least, it needs to be observed that the handle needs to be somehow removed from the clamping mechanism which is however aligned with the body of the gripper. To accommodate this functionality, a pivot mechanism has been adopted allowing the grasping module to rotate along the lateral axis and thus reveal the front end of the razor by lowering it. The arrangement is convenient as the front end is currently used to introduce the part in the machines that assemble the shaver handles with the razor heads. To ensure that the inclination angle is adjustable, a servomotor has been added in the design connected in a ‘piston-rod’ configuration with the grasping module. However, it can be easily converted to a pneumatic rotary joint in order to achieve higher speed and control simplicity. The assembled gripper CAD model is shown in the following figure including the configuration for picking the part (grasping module aligned with the orientation module) and for releasing it (grasping module rotated) (Fig. 18).

The adaptability/reconfigurability of the grasping module derives from the ability of using 3D printed components. Similar to Section 3.2.1, the following figures depict the

modifications in the design of the inner geometries of the clamping parts (left and right) to meet the geometrical characteristics from the parts of the medical, mold and consumer goods sectors in order to be graspable (Figs. 19, 20 and 21).

3.3 Fluid dynamics analysis

Following the design of the gripper and in order to validate the assumptions of the operating principle and the feasibility of the design, a computational fluid dynamics analysis was performed. Since an analytic computation of the applied forces on the complex geometry is a very complex task to model and calculate, simulation software was used to estimate and visualize the air flow inside the gripper. Moreover, it was possible to validate the motion of the handle when air burst is applied.

The initial analysis indicated that the generated forces are big enough to initiate the rotation of the handle; however, not all poses could be accommodated. For this reason, multiple positions and inclination angles of the nozzles were tested in a ‘try and error’ approach which eventually led to identifying several placements that are suitable for the task. A similar analysis was also performed for the front nozzle which is responsible to drive the handle towards the grasping module. This activity has allowed to prove that the assumptions of

Fig. 18 Assembled gripper CAD model

Fig. 19 Medical sector

Section 3.1 are valid and that the gripper concept is technologically viable.

Multiple runs confirmed the ability of the manipulation module to rotate the handle from every possible resting pose. Figure 22 presents a screenshot of the analysis.

With the use of the simulation experiment, the forces and moments around the X , Y and Z axes of the part have been calculated in the surfaces that are found opposite to each nozzle. The following table summarizes these values (Table 2).

4 Implementation

4.1 Gripper structure and hardware components

Following the design of the previous section, the prototype in Fig. 23 was developed.

The manipulation module was printed as a single piece using a BfB 3000 3D printer and standard PLA plastic as the build material. The grasping module was created by three printed parts of the same material. The linear guides and the servomotors were assembled with the use of small screws. An elastic band was attached at the back of the two moving parts in order to provide the grasping/closing force.

An aluminium shaft was created providing a flange for attaching the gripper to the robot on the one side and a flat surface for attaching the manipulation module and the peripheral components. More specifically, two electric valves operated by 24 V DC were installed and connected to the two sets of nozzles. The rear valve (black) regulates the air

Fig. 20 Mold sector

Fig. 21 Consumer goods sector

flow to the nozzles that are installed on the sides of the manipulation module while the front one (blue) is used to activate the nozzle responsible for driving the handle towards the grasping module.

A similar servomotor as the one that was used for the grasping module was installed on the gripper body and attached to the grasping module through a revolute joint in a ‘piston-rod’ configuration as explained above. The rotation of the motor leads to the rotation of the grasping module and thus the lowering of the grasped part’s front end (Fig. 24) to achieve a configuration that allows the collision-free release of the handle.

The total weight of the gripper prototype is 1.293 kg including all the components shown in Fig. 18. Further reduction of the weight and the resulting inertias that have to be handled can be achieved by more effective design of the aluminium flange reducing drastically its size and mass (from 340 to 250 grams) as well as by transferring the electrical valves (total 360 grams) on the robot arm or even at the robot base. It is estimated that the reduction due to such changes will be in the order of 0.75 kg.

Fig. 22 CFD analysis model

Table 2 Calculated forces and moments by the CFD simulation

Nozzle	1	2	3
Total area (cm ²)	8.77	2.91	5.32
F _x (N)	5.31×10^{-3}	20.61×10^{-3}	70.4×10^{-3}
F _y (N)	92.10×10^{-3}	95.79×10^{-3}	228.92×10^{-3}
F _z (N)	17.77×10^{-3}	0.259489×10^{-3}	0.497239
M _x (N-m)	1.40×10^{-3}	8.1×10^{-3}	13.71×10^{-3}
M _y (N-m)	-1.32×10^{-3}	-24.51×10^{-3}	-18.80×10^{-3}
M _z (N-m)	6.45×10^{-3}	7.80×10^{-3}	11.94×10^{-3}

4.2 Control system

In order to control the device an ARM-based embedded PC (IGEP v2 with TI OMAP Cortex A8 CPU @ 1 GHz, 512 MB NAND Flash memory and 512 MB RAM) was used running the UBUNTU 12.04 LTS distribution. A USB hub was attached allowing to connect a Denkov 4 channel USB relay that was used to control the two electrical valves that open and close air supply to the different nozzle sets (rotation and final positioning). The relay is equipped with an FTDI chip supporting bitbang operation, thus allowing direct read/write access to each relay on an 8-bit bi-directional. The open source library libFTDI [29] was used as the driver to interface the relay module through Linux. Moreover, two Phidget Advanced Servo 1 controllers were attached to control the open/close and inclination functionalities of the grasping module. A simple c program was used to implement the sequencing between the electric valves and the motors. Thanks to the small size of the components, it was possible to fit them in a small-sized casing that can be attached on the robot arm while the power requirements are kept very low (5 V DC for the PC and the USB hub and 24 V for the electric valves). Figures 25 and 26 depict the control structure and actual implementation of the system respectively.

Fig. 23 Gripper implementation (left side) **Fig. 24** Gripper at part placement configuration (right side view)

The integration between the gripper controller and the robot controller was implemented using a standard TCP/IP connection. A server was implemented on the embedded PC and through the wired connection the robot controller was able to send string messages ('pick' and 'place') to the gripper. These commands were programmed in the native PDL2 language of the robot so that they are executed once the robot moves to each relevant position. The receipt of each message by the PC resulted in executing the relevant function for actuating the gripper modules. The following table summarizes the activities performed by each function (Table 3).

The parametrization of the overall mechatronic system derives from the ability to control the individual degrees of freedom for the gripper, which in our case are the two sets of nozzles (rotation and positioning) controlled through the electric air valves and the rotation of two servomotors controlled by the Phidget Advanced Servo controllers. Directly connected to the robot controller through the embedded system (IGEP v2), the mechatronic system is a simple synchronization of I/O's that control the air valves and the rotation of the servomotors.

5 Experiments

In order to evaluate the performance of the developed gripper, it was installed on a COMAU Smart 6 robot with an OpenC4G controller. In front of the robot, several handles were placed on a flat surface with different random orientations. For the testing, ten different positions for handles to be picked were manually programmed to the robot in a sequential manner. However, in each test run, the handles were placed by hand in each pre-programmed position but in a random orientation and pose (see Table 4). This allowed to evaluate the

Fig. 25 Control system structure

effectiveness under a small positional uncertainty. The setup is shown in Fig. 27.

One might argue that the use of a vision system for identifying the location and the pose of the shaver handle could be also implemented. The current work though focuses on the manipulation and placement of the components. Such relevant research studies have been conducted under [7, 30] and their

implementation under a common development is proposed in Section 6.

After the first runs for fine tuning, ten experiments involving the manipulation of 100 handles were carried out. The results of the experiment are shown in the following table (Table 4, the numbers in italic indicate the part that failed to be picked correctly).

Out of the 100 handles, 90 were correctly oriented and successfully placed in the feeding track conveyor. The inability to orient the remaining ten parts is traced to the geometry of the manipulation module and the positioning of the nozzles against the handle. It seems that there is a sensitivity for poses 5 and 6 which means that the rotation is not always stable. The behaviour is also attributed to the fact that the air from the

Fig. 26 Control hardware implementation

Table 3 Control functions of the gripper

Function	Description
Pick	<ol style="list-style-type: none"> 1. Ensure that grasping module is in open position—set servo value to 130° 2. Enable valve for rotation nozzles and disable after 150 ms 3. Close valves for 100 ms 4. Enable again rotation nozzles for 400 ms 5. Enable valve for front nozzle and disable after 400 ms 6. Close grasping module by setting servo value to 30°
Set	<ol style="list-style-type: none"> 7. Rotate the inclination servo at place position (45°) so that part can be inserted in the track
Place	<ol style="list-style-type: none"> 8. Open grasping module—setting servo value to 130 degrees
Retract	<ol style="list-style-type: none"> 9. Rotate the inclination servo at pick position (30°) so that next part can be grasped

Table 4 Experimental results

Experiment ID	Handle pose in each position (1–6 as in Fig. 3)										Correctly oriented handles
	1	2	3	4	5	6	7	8	9	10	
1	2	2	5	3	5	4	6	4	2	5	8
2	4	2	4	6	1	1	2	3	3	1	10
3	6	4	1	6	1	2	3	4	3	4	9
4	4	1	4	4	4	6	3	2	4	6	10
5	5	4	6	6	2	5	3	5	3	5	9
6	3	3	4	6	5	5	6	2	4	5	8
7	2	5	6	1	5	1	4	3	3	1	9
8	4	4	5	6	1	1	2	1	6	4	10
9	2	1	2	5	3	4	6	6	5	5	8
10	3	1	5	2	6	5	4	3	6	6	9
Total											90

nozzles does not impact the razor surface only due to its dispersion. As a result, swirl effects also take place in the gripper, leading to a more stochastic behaviour. Further research in the positioning of the nozzles is required to achieve 100% repeatability. All parts that were correctly oriented have been fed to the conveyor, thus ensuring that the grasping module is very efficient. The total time for executing each experiment was around 3.5 min and is mainly attributed to the non-optimized picking positions (lower than the conveyor) and the robot trajectory. The gripper operating time is about 1 s for rotating and grasping the part but it expected that with further analysis, this time can be further reduced. The actual productions requirements (around 100 parts per minute) may be reached with the use of two robots but more work needs to be carried out on this topic in the coming years.

6 Conclusions and future work

In this paper, a novel gripper concept which uses compressed air streams to manipulate complex non-symmetrical parts has been presented. The simulation experiments as well as the application in a case study stemming from the consumer goods case has validated the ability of the gripper to perform reliable in-hand manipulation and accurate positioning of the part. The design was carried out so that the part can be picked from any resting pose, thus reducing the need for further manipulation by the robot arm. The gripper is of very low weight and can be easily integrated in any robot or feeding machine. The use of 3D printed parts signifies low cost for maintenance and low downtime as well as modifiability in case of product changes.

Fig. 27 Experimental setup

The presented results indicate that the proposed solution is a step towards achieving flexible production in the consumer goods industry and can be easily extended to meet the requirements that derive from similar applications in different industrial sectors. Coupled with the identified enhancements that are proposed hereafter, an industrialization phase is required in order to ensure the technical reliability of the proposed gripper, which at the moment presents a 90% of production efficiency. Once the reliability of the gripper (as two cooperating modules) is ensured, then it is a matter of wear of the main hardware components, namely nozzles, servomotors and electric valves.

There are several aspects that need to be considered for future research in order to allow introduction in actual production environments. These involve the following:

1. Further optimization of the manipulation module to achieve 100% successful rotation of the handles.
2. Integration with vision system/depth sensors, as the one suggested in [30], so that different nozzles can be activated based on the actual pose of the part and minimize the manipulation time.
3. Creation of more robust/metallic 3D parts of the gripper that are suitable for mass production conditions. Less wear and higher accuracy are needed.
4. Application with a moving conveyor to evaluate accuracy under more dynamic conditions.
5. Elaboration of the grasping module so that the parts can be released in open space to accommodate not only feeding but also packaging scenarios.
6. Optimization of compressed air consumption techniques such as the ones suggested in [31] for further improving gripper design and efficiency.
7. Replacement of the grasping module actuation with pneumatic rotary/linear joints so that a single power source is needed, simplifying the control at the same time.
8. Development of a HMI for easily modifying the input parameters of the mechatronic system, such as the degrees of rotation of the servomotors.

Acknowledgements The authors would also like to express their gratitude to Mrs. Evita Bougiouri, Mr. Nikos Skounakis and Mr. Vasilis Davos for the valuable information and assistance they have provided.

Funding information This research has been financially supported by the research project ‘VERSATILE – Innovative robotic applications for highly reconfigurable production lines’ (Grant Agreement 731330) [32], funded by the European Commission.

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