Actuators **2014**, *3*, 205-225; doi:10.3390/act3030205

OPEN ACCESS

actuators

ISSN 2076-0825

www.mdpi.com/journal/actuators

Article

Novel Additive Manufacturing Pneumatic Actuators and Mechanisms for Food Handling Grippers

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Received: 1 March 2014; in revised form: 4 June 2014 / Accepted: 11 June 2014 / Published: 9 July 2014

Abstract: Conventional pneumatic grippers are widely used in industrial pick and place robot processes for rigid objects. They are simple, robust and fast, but their design, motion and features are limited, and they do not fulfil the final purpose. Food products have a wide variety of shapes and textures and are susceptible to damaged. Robot grippers for food handling should adapt to this wide range of dimensions and must be fast, cheap, reasonably reliable, and with cheap and reasonable maintenance costs. They should not damage the product and must meet hygienic conditions. The additive manufacturing (AM) process is able to manufacture parts without significant restrictions, and is Polyamide approved as food contact material by FDA. This paper presents that, taking the best of plastic flexibility, AM allows the implementation of novel actuators, original compliant mechanisms and practical grippers that are cheap, light, fast, small and easily adaptable to specific food products. However, if they are not carefully designed, the results can present problems, such as permanent deformations, low deformation limits, and low operation speed. We present possible solutions for the use of AM to design proper robot grippers for food handling. Some successful results, such as AM actuators based on deformable air chambers, AM compliant mechanisms, and grippers developed in a single part will be introduced and discussed.

Keywords: additive manufacturing; grippers; compliant actuators; compliant mechanisms; food handling; industrial robotics

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1. Introduction

The food sector has clear opportunities for robot automation in processes where manual operations are still used [1]. An example is primary packaging, where several workers performing manual manipulation is common. Operator's hands are fast, and can adapt to irregular shapes and manipulate softly sensitive products, but they play a critical role of potential microbial contamination of fresh products and can be implicated in the spread of foodborne diseases [2]. To automate these processes with robots, these should be easy to clean, with a hygienic design, low cost, fast in pick and place operations, and safe for work with humans [3]. Requirements for robot features can vary in different food sectors [4].

Robot grippers for food handling play a critical role in replacing operators. They should have dexterous skills for handling smoothly with high reliability, at high speed and no damage the food products. Chua [5] reviews the different kind of robot grippers used for food handling with robots and classifies them in different sectors. Pettersson [6] designs a gripper for food handling with force control, and makes a special study of hygienically conditions. In horticulture, Blanes [7] proposes different gripper technologies and reviews the methods used in this sector.

A gripper should adapt to the shape of the food to achieve an adequate gripping process. With multi-body-rigid gripper mechanisms, finger adaptation can be achieved by increasing the number of degrees of freedom in the gripper jaws. However, as every degree of freedom should be controlled, then the gripper complexity increases significantly. To simplify the grippers without reducing gripper degrees of freedom is possible to use underactuated mechanism. Grippers with underactuated mechanisms are able to handle irregular and sensitive products [8] due to passive adaptability that avoids controlling every motion individually [9]. These mechanisms have high complexity and the gripper weight increases. They require great design engineer effort to find solutions. Some industrial solutions can be found [10–12].

Gripper adaptation can be achieved in a prehensile contact gripper with compliant fingers, mechanism and actuator. Gripper fingers pressure should be limited for food handling to avoid hard contact points. Fingers contact should be as wide as possible and should adapt to irregular food shapes. Different possibilities can be found in the literature: Choi [13] uses inflatable rubber fingers, the Humboldt gripper [14] has a closed deformable air chamber with fingers to grasp the products, Brown [15] uses adaptation of granular materials, research in Pettersson [16] is based on magnetorheological fluids, and Zhong [17] presents shape-memory-alloy. Maruyama [18] uses incompressible fluid inside the deformable fingertips.

Actuator features are critical to achieve the adequate gripper force, range and speed to design a robot gripper for food handling. Compliant actuators facilitate the reduction of the complexity of the gripper mechanism avoiding intermediate connectors or joints, making easier its construction and reducing the cost. The equilibrium position of compliant actuators depends on the applied external forces and not from a predefined position and trajectories [19].

Air is the most commonly used energy to design robot grippers for food handling. Pneumatic actuators are used widely in designing robot grippers. Pneumatic artificial muscles, or McKibben muscles, are inherently compliant, do not require alignment, are low in cost, work with smooth action, are flexible and simplify mechanism construction because they can be directly coupled to gripper

mechanism without an intermediate joint. The major drawbacks for their use as actuators in robot grippers for food handling are their nonlinear behavior, the presence of hysteresis, their slow dynamics, and they can only work as contractive [20]. Some advances can be found to achieve double acting by embedding a muscle inside an external chamber [21].

Soft robotics needs compliant actuators to achieve the desired motion. Soft robotics has the deal of achieving flexible interactions with uncertain and unstructured environments and for hence are suitable for the manipulation of unknown objects or in interaction with humans [22]. Elastomeric pneumatic actuators used for soft robotics are mostly manufactured in silicone rubber that allows high strain, food contact approval, adaptive behavior and low cost. They have a high compliance and are able to handle a wide variety of products [23]. Their main challenges are the lack of high forces, the capability to replicate the functionality of muscles and their short life. These actuators can advance thanks to the new manufacturing processes that eliminate the traditional manufacturing constraints [24]. Their speed is related to the volume of gas and the configuration of the chambers. Mosadegh [25] develops high speed pneumatic deformable soft actuator able to support over a million cycles.

Most of the geometrical design limitations in manufacturing parts with standard grippers for food handling can be solved with additive manufacturing (AM) technology. This process has high functionality and low production cost. This technique has very low geometrical restrictions and models are manufactured quickly from 3D CAD and can be analyzed with a simple FEM model. Grzesiak [26] has used this technology to develop a complete pneumatic gripper with an AM actuator. This paper shows the possibilities and experiences for using AM process to produce grippers or components of grippers in polyamide PA2200. This plastic material has properties to design pneumatic actuators and deformable mechanisms for robot grippers in food handling applications. Its weight is light and is approved for foodstuff contact. This paper reviews the perspective, accomplishments and issues founded by the use of additive manufacturing to design robot grippers in food handling. It provides engineers with the possibilities of AM technology to develop robot gripper actuators, in order to replace mechanisms with flexible parts and to develop complete pneumatic grippers in a single part. It is divided into three sections dealing with pneumatic actuators, compliant mechanisms and grippers designed using AM.

2. Grippers for Handling Food: Design Requirements

Food is irregular, sensitive and has different textures, forcing robot grippers to accomplish different requirements for food handling. Grippers should be able to grasp and release the products quickly but without damaging them. Gripper fingers should adapt to a wide variety of shapes and textures, their pressure must not damage the product and they should be approved for contact with foodstuffs. Gripper mechanisms should be simple and with light components, to allow the increase of jaw accelerations and to reduce close and open time. The minimum number of movements also reduces closing times. The gripper should adapt to product shape as soon as possible to avoid effort concentration or hard contact points that could damage sensitive products. Gripper compliant mechanisms and soft fingers made with materials that adapt to the food shape reduce maximum pressure, increase contact area and decrease the potential damage during grasping process. The release operation is also important for light and sticky products. In this case, a gripper release system can be added. Low

process time for robot grasp means high robot accelerations reduce necessary time to close the gripper in order to establish product contact. It helps that low gripper inertial efforts can be accomplished by lighter gripper components. This kind of design also helps to reduce impact contact pressure. The robot grippers in this article have been developed for the primary packaging of confectioneries, small baked goods, pastries and small horticulture products.

3. Additive Manufacturing Pneumatic Actuators

Linear and angular pneumatic actuators are commonly used in the industry to design robot grippers. These actuators are based on the motion of a piston when an internal chamber has different pressures than the external pressure. The chamber must be sealed to avoid leaks and friction forces appear between piston-chamber and rod-chamber. These devices can be single or double acting. Pneumatic actuators can be created from the deformation of the chamber. Pneumatic artificial muscles are based on the deformation of an elastic membrane, their motions are lineal and can work with misalignments or displacements.

With the AM process, it is possible to create pneumatic actuators based on the deformation of elastic chambers manufactured in polyamide. The chamber shapes and operating pressure define actuator motion, stroke and force. Proposed AM actuators are made in PA2200, approved as food contact material by FDA and manufactured with an EOSint P380, a rapid prototype selective laser sintering machine. This plastic is between three to eight times lighter than the metals currently used for industrial pneumatic actuators. Their speed is defined by the volume of the chamber, the elastic module of the material and difficulties of the air to come in and to leave. If the shape of actuator is the same, AM actuators have higher return speed than elastomeric pneumatic actuators manufactured in silicone. Compared with the silicone, despite of the strain limitations of polyamide, AM actuators can be designed for a motion, range and force needed to develop robot grippers for food handling. AM actuators are made in a single part. Engineers do not need to adapt their gripper mechanisms to standard actuators and can develop an AM actuator as gripper features request. The AM actuator length is lower than the standard one because no rod is needed, only one air connection is needed and can be designed to save volume, and does not need room for the spring to return the piston. The AM actuators are compliant. They do not need elastic couplings to be connected to a gripper mechanism. The force control is complex, with the same pressure external force varies with the position of the actuator. Polyamide can suffer permanent deformations with long term stresses. The AM actuator gripper should be tested to ensure a large number of cycles for industrial purpose.

3.1. Classification of AM Actuators Based on Kind of Motion

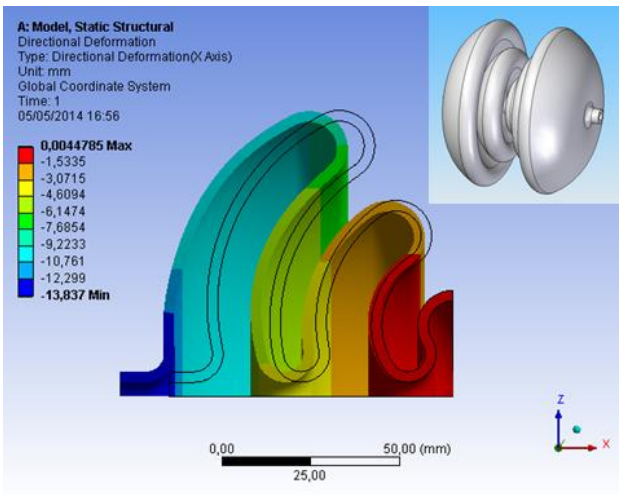
Industrial pneumatics actuators have their mechanical features defined and engineers use them to develop or adapt a mechanism able to achieve the desired motion, stroke and force of the gripper fingers. The AM actuator chamber shape and pressure will define its motion, range and force. Engineers should design AM actuators according to their requirements. These actuators are not isolated components and during the design phase can be easily integrated inside the gripper chassis mechanism with fewer restrictions, coupling bars or hardware components than a normal industrial pneumatic actuator. AM actuators can have a complex motion instead of a linear or rotational one. This feature can be used to create an actuator that works with the desired motion of the gripper finger.

The pneumatic AM actuators are compliant. They can absorb easily misalignments and displacements and no self-aligning couplers or extra bars are needed between actuator and mechanism. Colored figures (from 1 to 8) are the FEM analysis results of the CAD models.

3.1.1. AM Actuator with Linear Motion

AM actuators with linear motion can replace pneumatic cylinders function or even can work as parallel grippers. To achieve a linear motion, the chamber should have geometry and stresses with an axial symmetry (Figure 1a–c) as in the example bellows. The positive internal pressure at 0.3 MPa creates linear expansion. The maximum deformation of AM actuators manufactured in polyamide is less than 20% of the total length. The bellows can have different shapes to achieve linear motion. Without axial geometrical shapes is possible to achieve quasi linear motion (Figure 1d).

Figure 1. (**a**–**c**) Example of AM actuators with linear expansion motion with the analysis of an eighth of the part. (**d**) AM actuator with quasi linear expansion motion with the analysis of half part.



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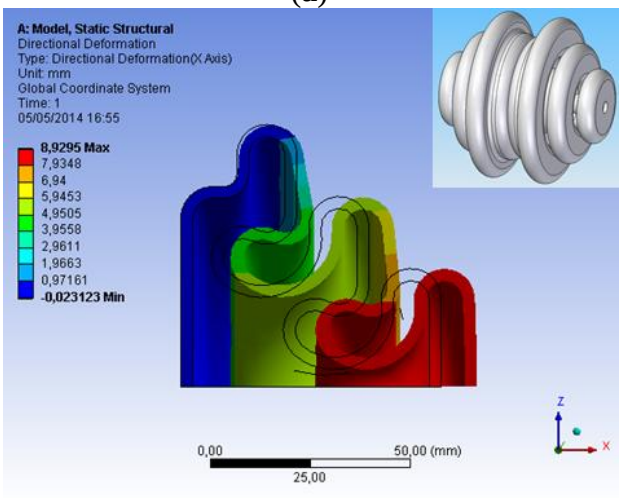

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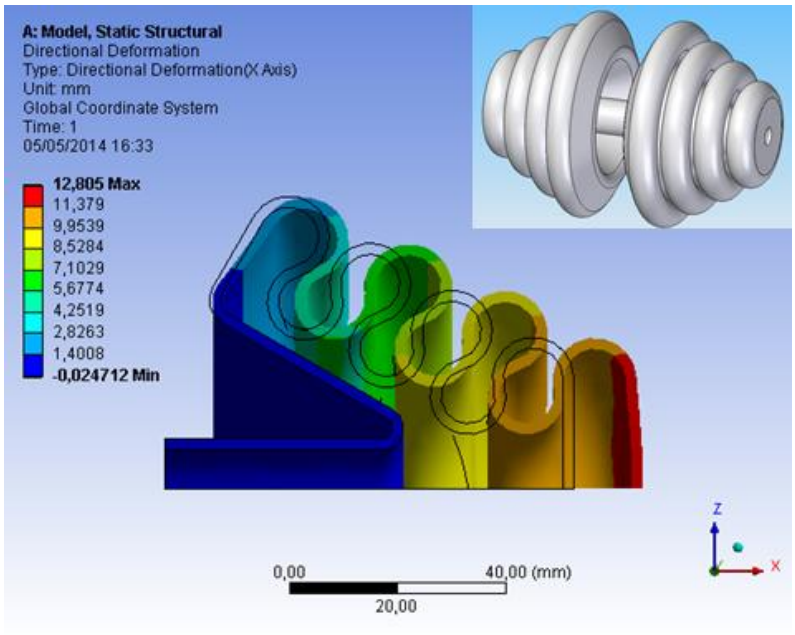
Figure 1. *Cont.*



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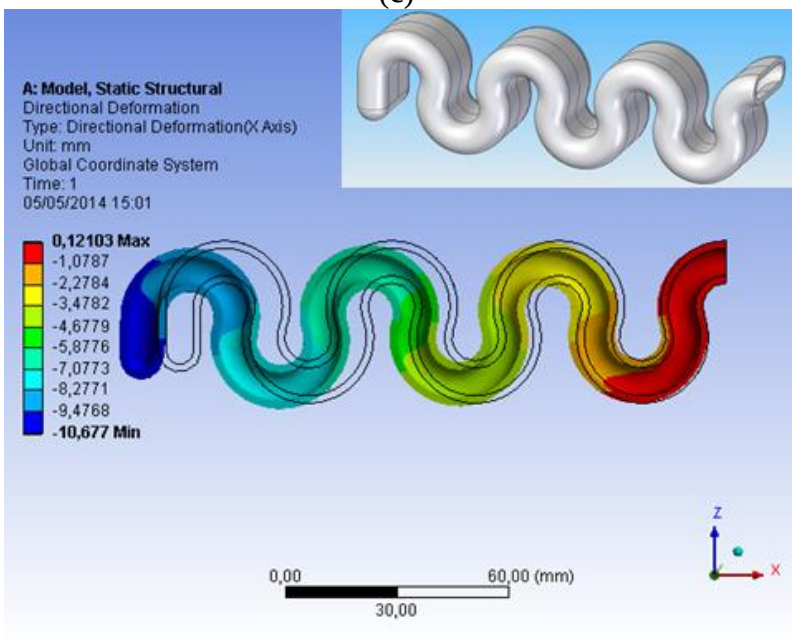

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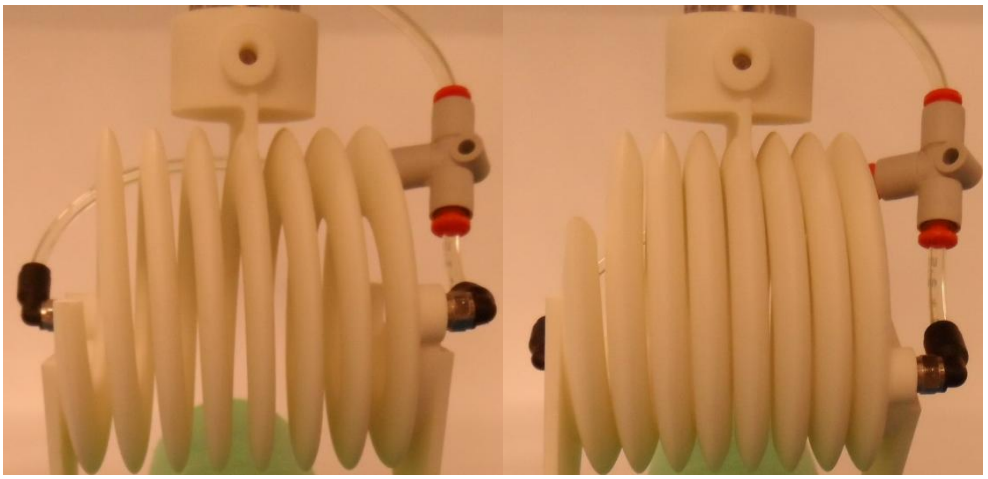
3.1.2. AM Actuator with Rotation and Linear Motion

Actuators with linear contraction motion can be used for developing parallel robot grippers that are able to grasp products from their external faces. External prehension for handling manipulation is the most commonly used grasping method in robot grippers. Figure 2 is an AM actuator with contraction and rotation motion. It is a hollow helical oval piece. The actuator contracts and rotates with positive internal pressure (Figure 2).

Figure 2. AM actuator with linear contraction motion (**a**) and rotation motion (**b**). Experiment done at 0 and 0.3 MPa.



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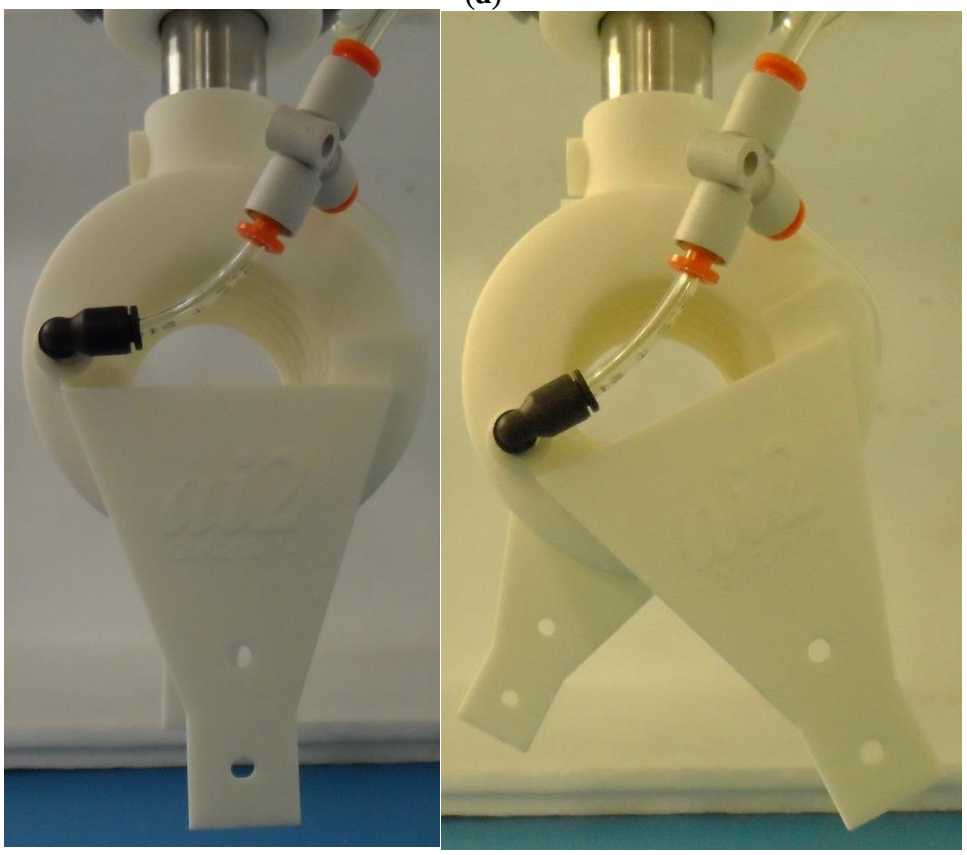
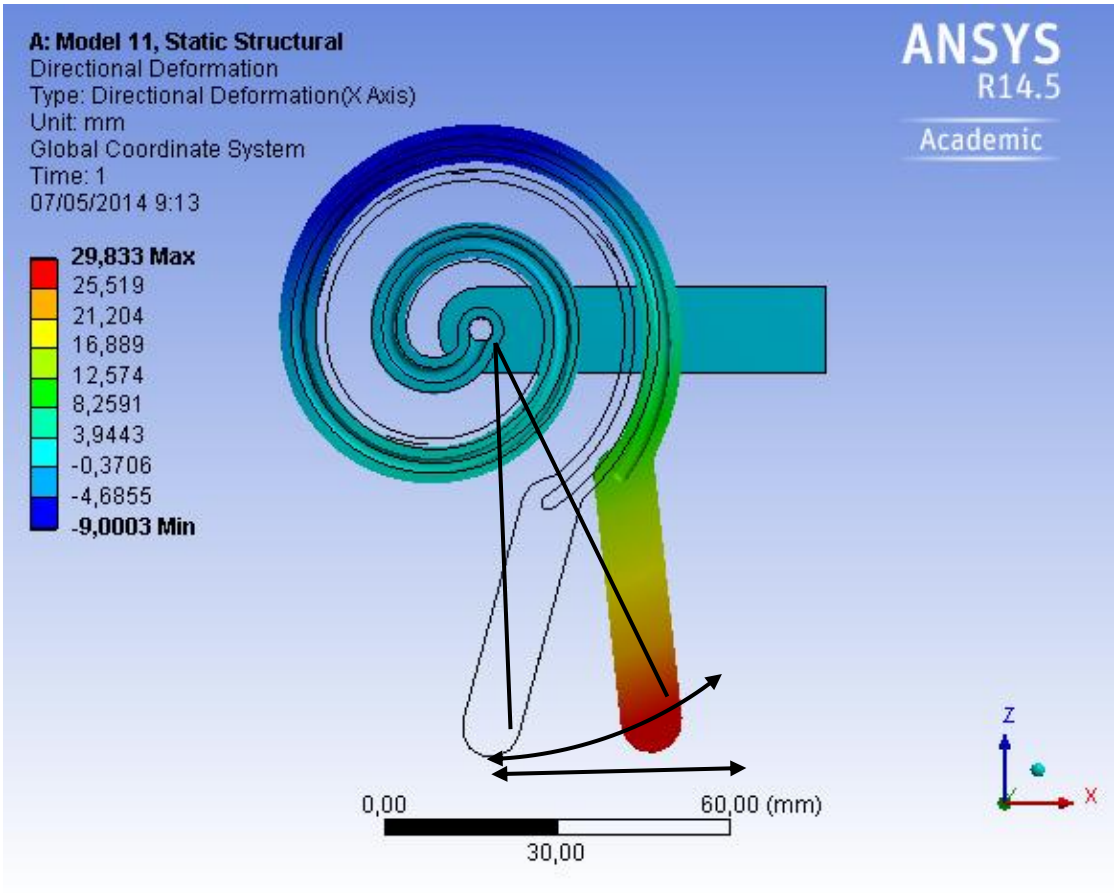


(**b**)

Taking advantage of the freedom to design any shape of a chamber, it is possible to achieve a useful motion for the fingers of a gripper. Figure 3 shows the deformation of a hollow spiral with an internal pressure. The bottom of the finger displaces mostly in horizontal way while finger rotates a small angle in such a way that the product is scooped up. This design reduces the vertical dimension of the gripper and its fingers achieve the necessary motion without any transmission bar. Grippers can be smaller and lighter.

Figure 3. AM actuators with two degrees of freedom, rotation represented in the figure and small horizontal translation.



3.1.3. AM Actuator with Double Effect

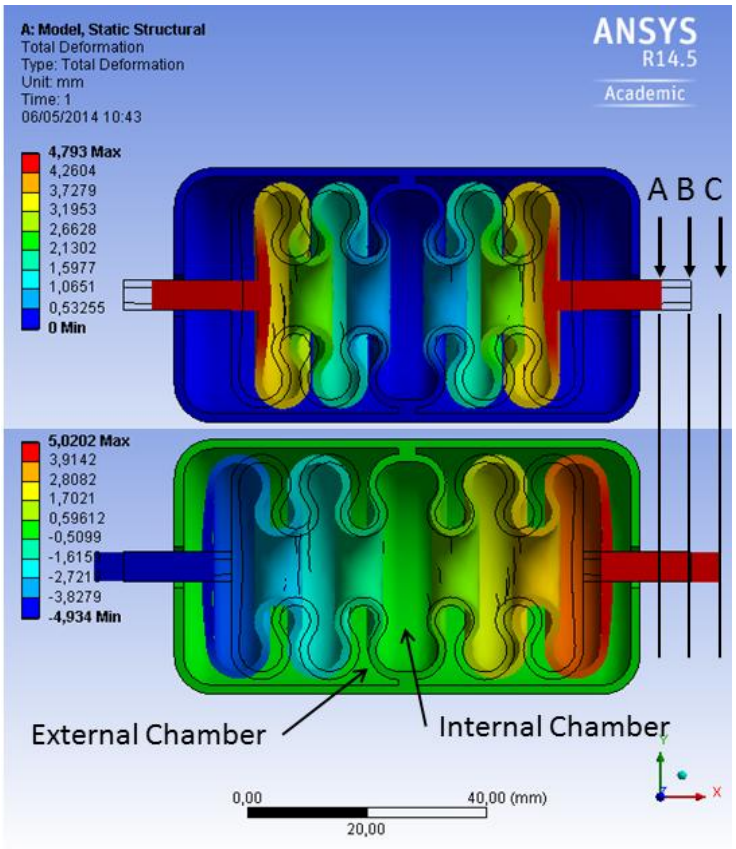
Previous actuators have single acting. The elastic material properties are the spring to return the gripper fingers to their original position. Actuator return speed is limited by the volume of the chamber, elastic module of the material and difficulties of the air to go out. The speed of industrial pneumatic grippers increases with double acting actuators.

The motion of AM actuators is generated when the internal pressure of the chamber is higher than the external one and usually the external pressure is the atmosphere. However, if the external pressure of the chamber is controlled, then it is possible to design a double effect AM actuator. The Figure 4 shows a double effect AM actuator. Note that with controlling the pressure on the air chambers, different displacement can be obtained, as listed in Table 1. This solution increases the complexity because is necessary a sealing between the rod and the external chamber but, improves the actuator displacement and provides three different positions.

Table 1. Relation between chamber pressures and position.

Internal Chamber Pressure	External Chamber Pressure	Displacement
Atmospheric	0.4 MPa	A
Atmospheric	Atmospheric	B
0.4 MPa	Atmospheric	C

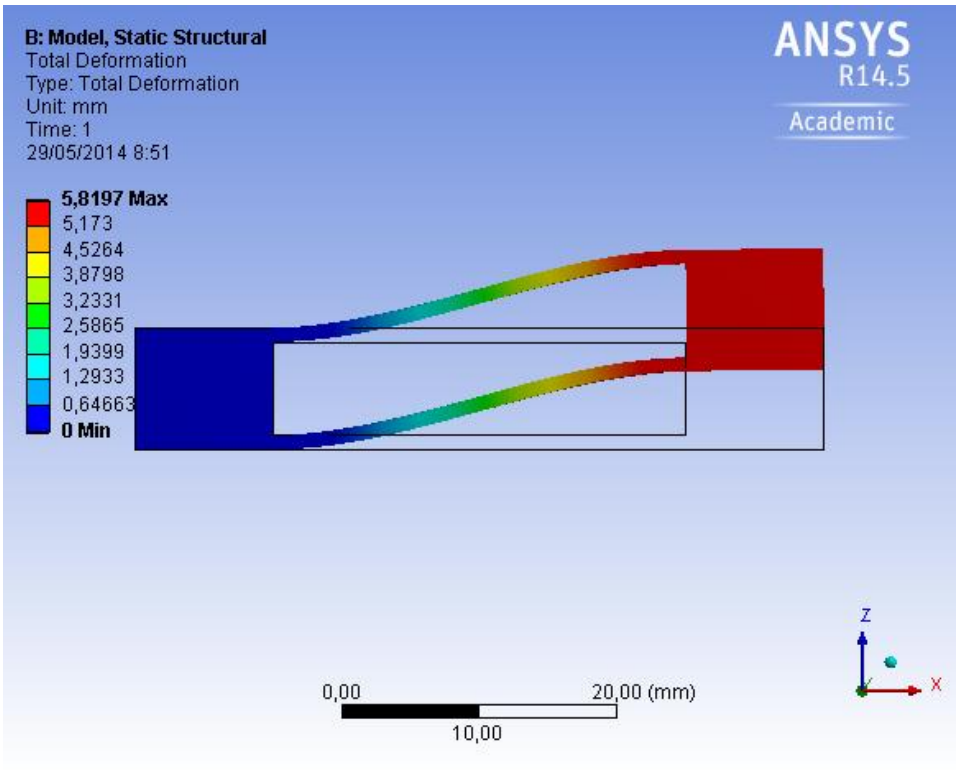
Figure 4. Pneumatic AM actuator with double effect. The picture at the top shows the result when the internal chamber is at atmospheric pressure and the external is with 0.4 MPa. In the second picture, the internal chamber is with 0.4 MPa and the external with atmosphere pressure.



3.2. AM for Compliant Mechanisms

A multi-body rigid gripper mechanism can be replaced by a pseudo-rigid body mechanism with the use of the AM process. The joints of the mechanism are replaced by elastic parts. Lineal sliders or rotational joints are the most common motions in gripper mechanisms. With AM process the joints can be replaced by deformable structures, which can be integrated in a single part. The maximum stress that polyamide is capable to support before permanent deformation limits the degree of freedom of the joint. Figure 5a shows how to achieve a parallel joint with a double parallelogram. When large strokes are needed the deformation of the coupling increases, this can be achieved with longer or thinner bars. Rotational joints for small angular rotation can be made with a thin bar (Figure 5b) or with a section reduction or crossing different bars (Figure 5c) or for larger rotations with spirals (Figure 5d). By studying the thickness and length of the bars or the spirals is possible to achieve more rotation angle with the same stress of the material.

Figure 5. (**a**) Joint to replace sliders, (**b**–**d**) to replace shafts.



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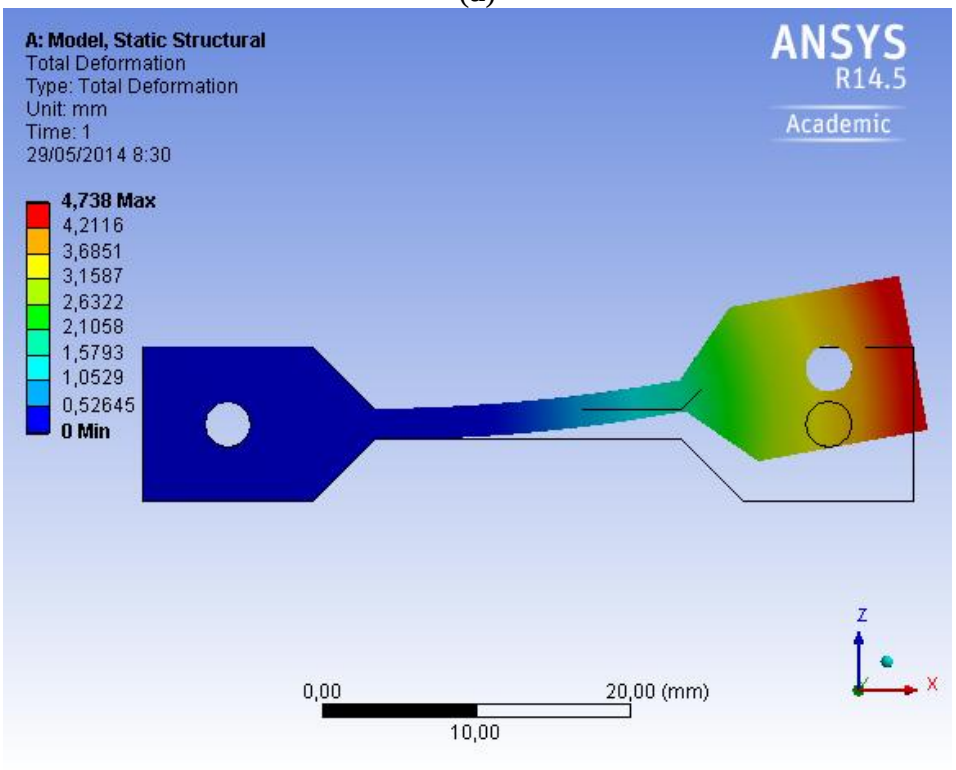

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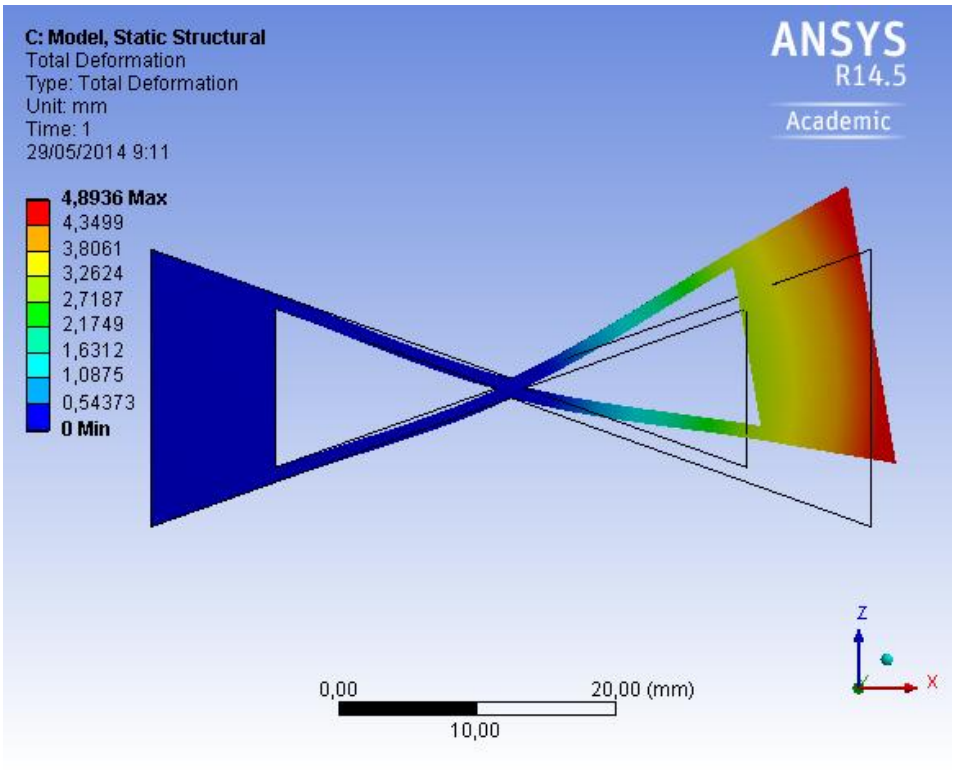

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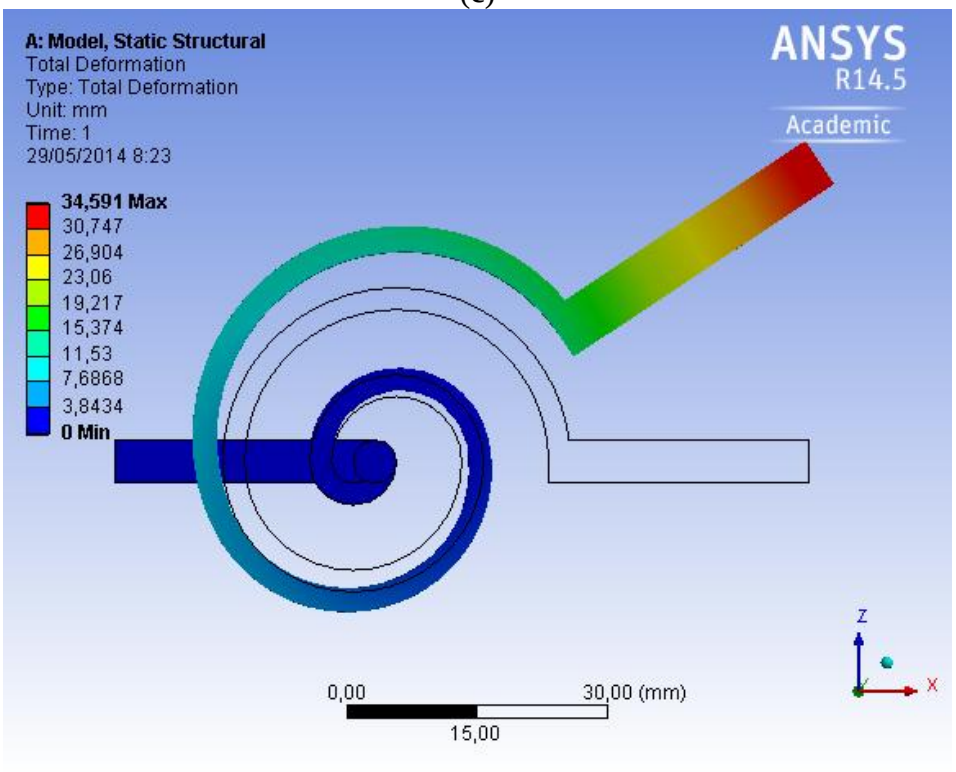


(**d**)

3.3. AM for the Design of Pneumatic Robot Grippers

Food handling with robots can damage the products when the pressure against products is high. Fast robot motions are necessary for profitable robotic cells. A robot gripper for food handling should work

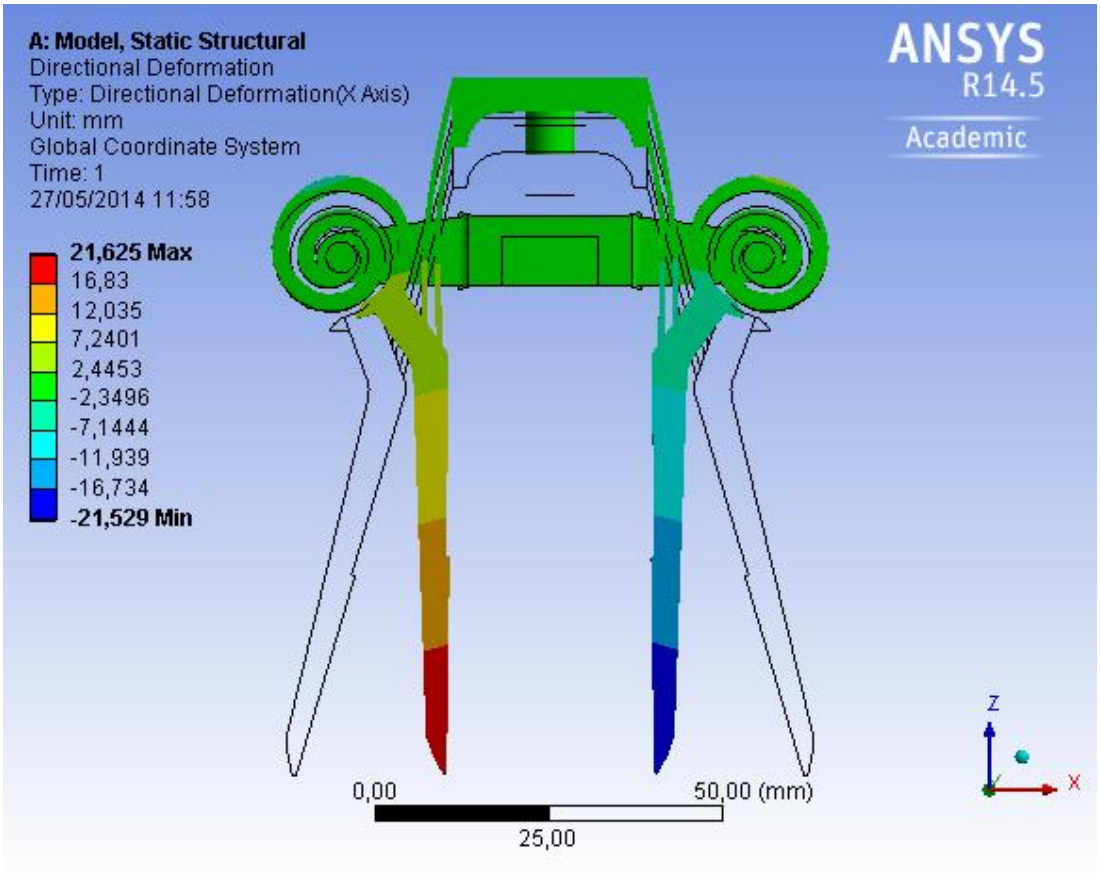
at high speed, and the mass of fingers and gripper mechanism should be low to reduce impact on the product.

Pneumatic standard grippers can fulfil the requirements for food handling with robots, usually with parallel or angular motion. Parallel grippers ensure constant grasp force during all the gripper fingers movement avoiding squeezing forces and are used when the dimensions of the parts have a wide variability. Angular grippers give larger grasping capability for heavy loads and are preferred when high forces are needed. For food handling with robots in most of the cases the standard pneumatic grippers do not fulfil the requirements and engineers need to develop their own mechanism to achieve the desired stroke, type of motion and force. To achieve these requirements engineers need to adapt their gripper mechanism to the features of pneumatic standard cylinders. The kinematics of gripper mechanism defines the fingers stroke, kind of motion and the relation between actuator force-speed and fingers force-speed-position. Mechanism components are made or designed to be rigid bodies and they are joined with shafts and sliders. The joints of gripper mechanism need adequate accuracy to work soft. The join of the pneumatic cylinder rod and gripper mechanism sometimes needs self-aligning couplers to absorb misalignments or displacements. If components and joints are not within tolerances the mechanism can block. If the gripper is made with hard and heavy components without elastic couplings, food products will absorb the energy of the mechanism when grasped and hard contact points can be produced.

A robot gripper developed with elastic components (chassis, actuators, joints and fingers), can adapt easier to the irregular shapes of food products, produces a softer contact, increases the contact area between fingers and product, increases the reliability, and reduces hard contacts points. The use of AM process with polyamide and the lack of geometrical restrictions of this technology make easier to achieve these features. Pneumatic actuators, components, joints and fingers can be designed to be flexible during gripper grasping process. Gripper designs can be simplified as all the gripper components can be manufactured quickly in a single part and gripper reduces its total weight. AM pneumatic actuator displacement is short due to elastic properties of polyamide. For food handling in most cases, AM pneumatic actuators cannot achieve by themselves the necessary finger gripper stroke, motion and force. They need a mechanism to achieve these requirements. The join of AM actuators with gripper mechanisms can have misalignments and displacements. Gripper fingers can be designed to be elastic and with shapes similar to the food. They can deform during grasping process. These features increase the contact area and reduce the pressure against the product. Mechanical joints developed in plastic with AM work inside its elastic limit. If the mechanism joints are not rigid and their deformations are under control, gripper has a compliant motion that will adapt to the products. Food shapes are irregular and grippers can adapt to them. With AM joints are integrated in a single part reducing the number of components.

Figure 6a shows an angular robot gripper where the main finger shaft is replaced with spirals and the transmission bars between cylinder rod and finger are replaced by two parallel and deformable thin bars. This gripper is actuated by a double acting standard pneumatic cylinder SMC CUJB-10-10D. Fingers are elastically joined to the chassis, facilitating the adaptation to the product shape during grasping action. Figure 6b is the equivalent mechanism designed with rigid bodies and shafts. It needs six axes and at least five rigid bodies: chassis, two intermediate transmission bars and two fingers. In this case, fingers are elastically joined with cylinder rod and chassis.

Figure 6. (**a**) Angular gripper mechanism, fingers and chassis all made in a single plastic piece, without shafts and actuated with a double effect pneumatic cylinder. (**b**) Equivalent gripper designed with rigid bodies.



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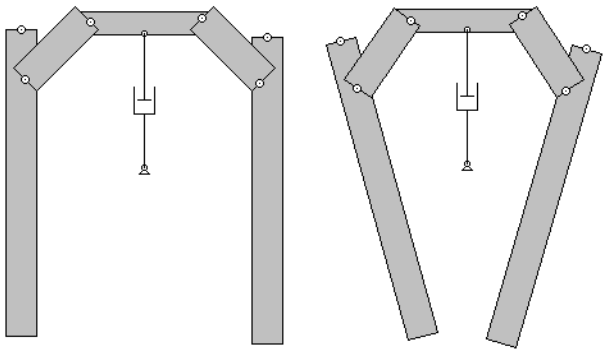
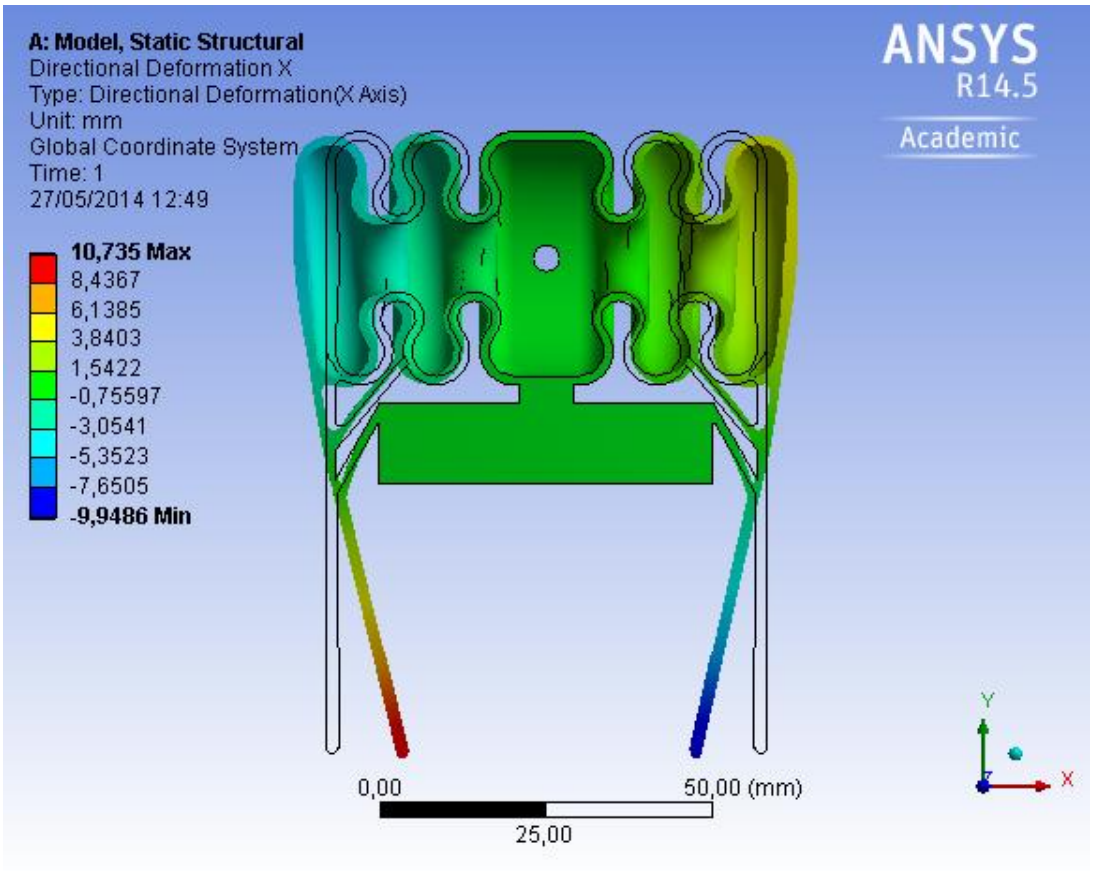


(**b**)

Figure 7a shows a complete gripper developed in a single plastic piece with two AM pneumatic actuators. The equivalent gripper needs a chassis, two connector bars, two fingers and four shafts for each finger (Figure 7b). This gripper is very light, simple and compact because all is contained in a single plastic part. No intermediate bars are needed to connect pneumatic actuator with the fingers, reducing the gripper length, in the direction of the actuator motion, and obtaining a more compact gripper. Two deformable bars connect actuator with finger, each one from different positions of the actuator. With this configuration the fingers move parallel and angular at the same time. The AM

actuator motion is linear but it also moves vertically and rotates to follow the motion of the mechanism.

Figure 7. (**a**) A complete gripper made in a single piece of polyamide. Pneumatic actuators are bellows at 0.4 MPa and shafts are replaced by deformable bars. (**b**) Equivalent design with rigid bodies.



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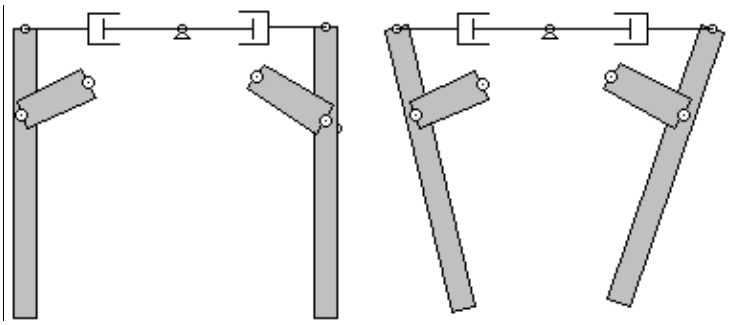
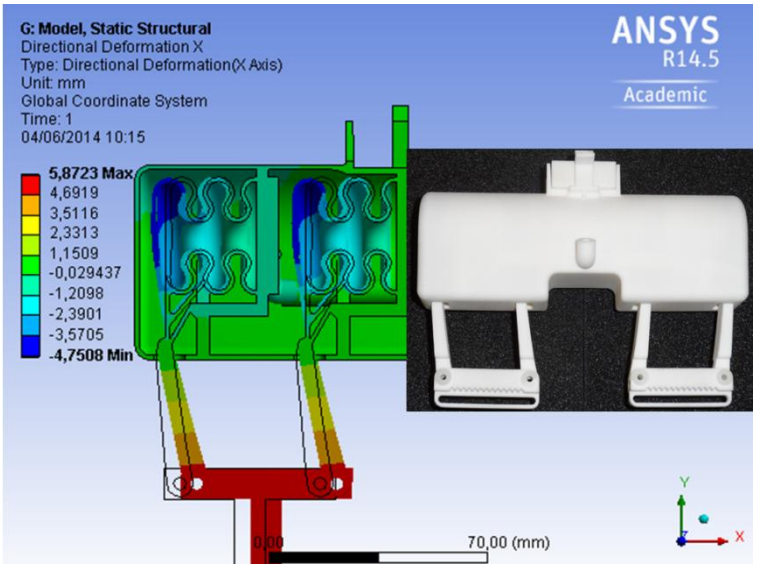


(**b**)

From the analysis of the vertical motion of the fingers of the gripper in Figure 7a, it is noted that there are areas where vertical motion is close to zero. Tacking advantage of this feature a new gripper is developed with two internal chambers per finger (Figure 8a). The Figure 8b is the directional deformation of the Y axis of this gripper. The dotted line is formed by points with close to zero deformations in the Y axis direction. No point in this line will move vertically. This feature can be used to introduce shafts with centers located in this line so that these shafts move parallel to X axis.

The positions of the shafts are experimentally defined by the analysis of a FEM model. Figure 8b shows the parallel motion of one finger of this gripper. This gripper needs at least three plastic parts and four shafts. Therefore, this design increases the size of the gripper and the number of components.

Figure 8. (**a**) The gripper, with two internal chambers per finger and analysis of the horizontal displacement of one finger at 0.4 MPa. (**b**) Analysis of the vertical displacement. The dotted line represents points where shaft centers can be located to get only horizontal motion in finger.



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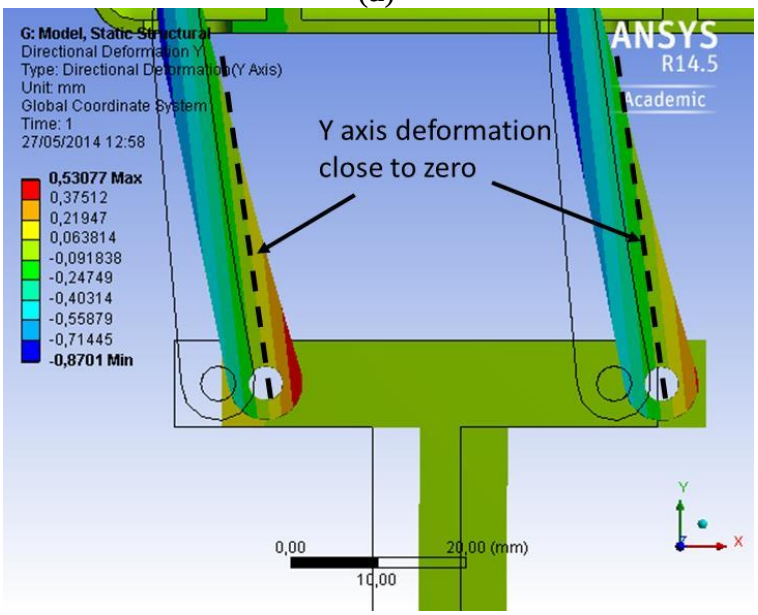
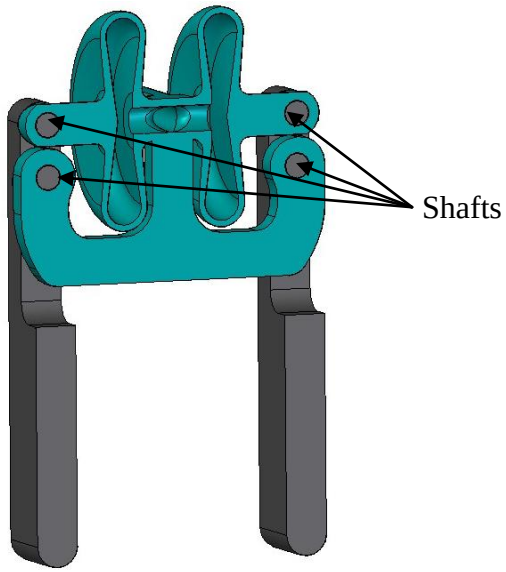


(**b**)

To achieve a fast pneumatic AM, the actuator is necessary to reduce the volume of the chamber. Small chambers have small motion and to use them as actuators for grippers is necessary a mechanism to achieve enough motion of the fingers. Figure 9 has two small AM pneumatic actuators with only one lobe. Every finger is moved by one pneumatic AM actuator. The fingers are rigid and they are joined to the gripper and chassis with two shafts per finger (shafts in Figure 9a). An equivalent gripper

mechanism can be solved with multi-body rigid mechanism (Figure 9b) with two simple effect pneumatic standard cylinders, joined to the fingers with sliders or intermediate bars (these elements are necessary because fingers rotate around Shafts and a small vertical displacement happened). With AM actuators the length of the gripper decreases and grippers can be designed for the requested force by modifying the dimensions of the pneumatic chambers. Figure 9c shows the result of a fatigue test of the gripper represented in the Figure 9a. With 0 cycles gripper opens 81 mm and after 20,000 cycles it only opens 69 mm.

Figure 9. (**a**) A gripper mechanism with AM pneumatic actuators. (**b**) 2 different possibilities of equivalent designs with standard simple effect pneumatic cylinders. (**c**) Fatigue test with 0 cycles and after 20,000 cycles.



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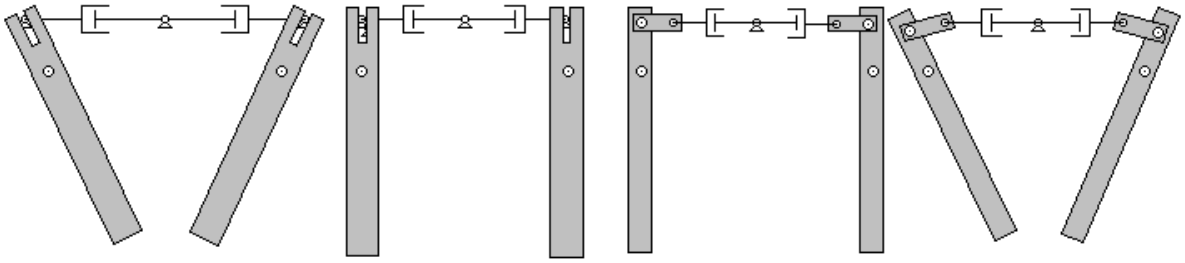
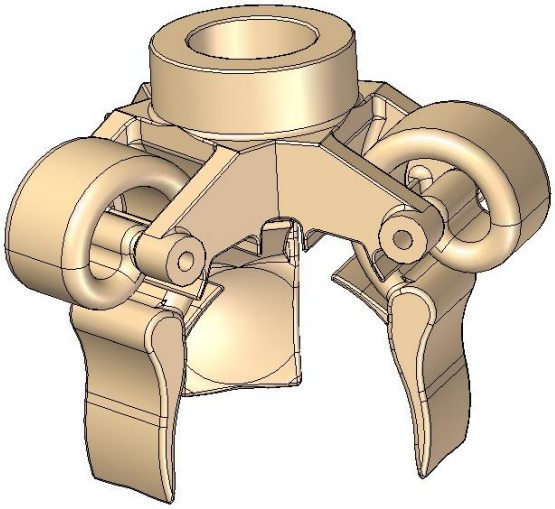


(**b**)

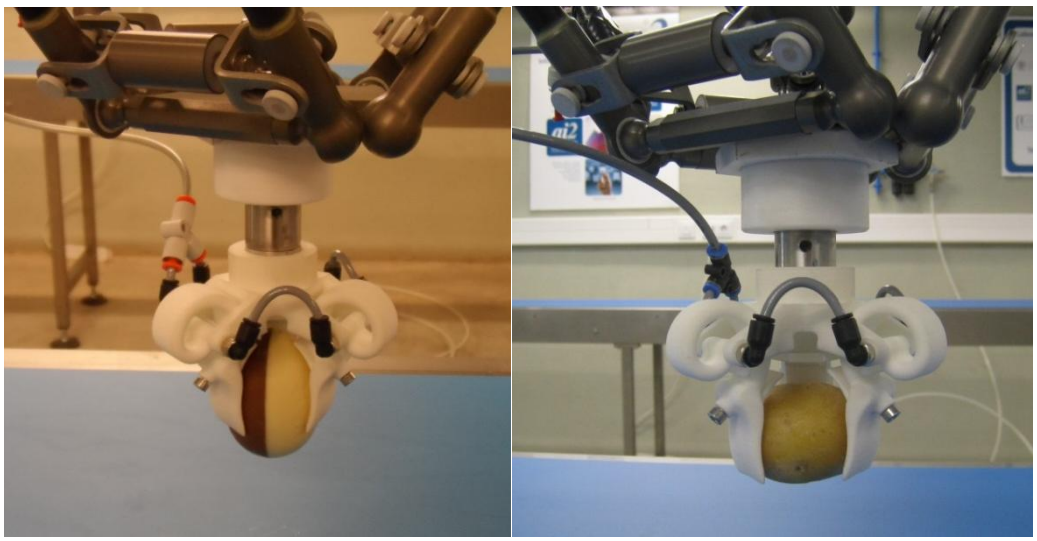
(**c**)

To design a multi-finger gripper with a multi-body rigid mechanism, it is necessary to reproduce the transmission mechanism for every finger. With multi-body rigid components, grippers increase significantly their complexity, weight, cost, number of components and weight. The design of the gripper should consider assembly difficulties and whether volume increases significantly. AM process has no geometrical restrictions to develop complex parts as far as thickness is higher than 0.6 mm for the current available AM machines. When a finger with its actuator is designed, it can be easily duplicated with CAD functions to design a multi-finger gripper in a single part. The production cost of the gripper with three fingers in Figure 10 and the gripper with two fingers in Figure 8 are both around 100 euros. Multi-finger grippers are easier to design and produce with AM process. Figure 10 is a concentric gripper with three fingers. A hollow chamber with spiral shape achieves the necessary finger motion. This gripper can be used for handling spherical products like chocolate eggs and has also been tested with horticulture products like mandarin oranges or potatoes (Figure 10b).

Figure 10. (**a**) Concentric gripper with three fingers designed and manufactured with AM process. (**b**) The gripper grasping a chocolate egg and a small potato.



(**a**)



(**b**)

4. Results and Discussion

Different possibilities have been presented in this paper for using the AM process for the development of robot grippers for food handling. Robot grippers for this purpose can be done in a single part and in polyamide with AM technology. With AM, it is possible to manufacture pneumatic actuators, compliant mechanisms, specific flexible fingers to adapt to the irregular shapes of the products, and chassis with complex shapes. The proposed pneumatic AM actuators are simple acting but a double action possibility is shown in the paper. The flexibility of this polyamide helps to simplify the connection between parts, and AM joints are compliant mechanisms able to adapt to different product shapes. This aspect is critical for handling bakery products as high forces cannot be applied and it is necessary the adaptation to the products before grasping them.

Major drawbacks in AM actuators are the permanent deformations due to the creep effect when stresses are high, and the limitations of the polyamide to achieve large displacements. After approximately 20,000 cycles grasping hard cylinders with the gripper in the Figure 9, its AM actuator suffered permanent deformations. A possible solution is showed in the Figure 4, where tension stresses in the shell of the chambers can be compensated with compression stresses for reducing the creep effect. This solution additionally increases the gripper range and the possibility to control three reachable positions. AM joints can be more reliable, as for example, the joints in Figure 6 had no permanent deformation after more than five million cycles grasping hard cylinders. However, the flexibility of AM joints can affect the gripper motion at high speed and can create harmonic oscillations of the fingers with low damping lower than critical damping. That increases the time of stabilization of the product while is grasped at high speed and also the gripper open time is higher. Fortunately, this issue can be solved if the rigidity of the joints is increased. AM actuators are manufactured from fine powder that is accumulated inside of the chambers. This powder is difficult to remove from the inner face of the chamber and can contaminate pneumatic pipes and electro-valves. Therefore, a pneumatic filter should be added. AM parts have a rough surface finishing where leftovers can be accumulated during the manipulation of products. Consequently, surfaces should be polished or properly painted to allow food contact.

The flexibility of AM process allows the improvement of the hygienic design of grippers. Parts can have smooth shapes where leftovers cannot be accumulated. AM actuators have no seals, do not need grease and cannot be damaged during water jet washing processes. Gripper finger movements can combine angular and parallel motion, facilitating the manipulation of the products. Complex geometrical parts can be manufactured without increasing prices. Traditional machining methods to manufacture parts are more expensive and have clear geometrical restrictions. Parts do not need to be designed to be machined and the time necessary to design the parts is lower. All the grippers showed in this paper have been manufactured with a polyamide that is approved for food contact. Moreover, the weight, cost and friction of this polyamide is low and it can work as bearings. Fingers designed with AM can suffer deformation during the grasp process, making easier the adaptation to the products, increasing the contact area and reducing hard contact points. Fingers can also have complex shapes similar to the products.

5. Conclusions

This paper has reviewed the possibilities, benefits and risks of developing grippers for food handling using AM technology. When AM is used with flexible materials, such as Polyamide plastic, the possibilities increase considerably, because it is possible to take advantage of the flexibility of the plastic to generate motion, to compensate deviations or to modify the shape in order to adapt to external surfaces. Therefore, the gripper components such as actuators, compliant mechanisms and fingers can be easily designed with this technology. Different solutions using AM for pneumatic actuator design have been shown, based on air chambers. A classification has been presented according to the chamber shape (sine wave, helical, spiral, *etc.*) obtaining different motion types (linear, rotational and mixed motion). Compliant mechanisms also take the best of the flexibility of plastic materials that can transmit motion and at the same time, compensate for deviations and displacements. Last but not least, flexibility in fingers provides the adaptation to product shape and their manipulation with enough care and tact to avoid any damage in the product. Some examples of grippers have demonstrated the results of applying AM in the design process for actuators, compliant mechanisms and finger shapes.

The authors conclude that AM is a good candidate for developing robot grippers for food handling, to reduce the time of the design and manufacturing, and to accomplish in an easier way most of the application requirements. AM opens new possibilities in robot grippers reducing the complexity of their mechanisms, allowing new concepts and ideas to develop flexible grippers, and avoiding the imposed limitations of the design for manufacturing that were not possible some time ago. AM can be applied to design proper and useful grippers, as they can be cheap, light and small, flexible and adaptable to the product, hygienic and cleanable, and reliable and profitable for industrial applications. These features fit with usual requirements in many food pick and place processes, for example, in packaging lines for fruits, vegetables, cakes, and chocolates.

Acknowledgments

This research is partially founded by the Spanish Government (MINECO-INIA) and FEDER funding under the MANI-DACSA project (ref. RTA2012-00062-C04-02).

Author Contributions

The research and development of the prototypes were done by Carlos Blanes in collaboration with Pablo Beltran. Martin Mellado is leading this research line and was involved in conceptual designs and responsible for founds and supervising.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Wilson, M. Developments in Robot Applications for Food Manufacturing. *Ind. Robot* **2010**, *37*, 498–502.
2. Todd, E.C.; Michaels, B.S.; Smith, D.; Greig, J.D.; Bartleson, C.A. Outbreaks Where Food Workers have been Implicated in the Spread of Foodborne Disease. Part 9. Washing and Drying of Hands to Reduce Microbial Contamination. *J. Food Prot.* **2010**, *73*, 1937–1955.
3. Masey, R.J.M. Guidelines for the Design of Low-Cost Robots for the Food Industry. *Ind. Robot* **2010**, *37*, 509–517.
4. Holmes, J.F. Guidelines for Designing Washdown Robots for Meat Packaging Applications. *Trends Food Sci. Technol.* **2010**, *21*, 158–163.
5. Chua, P.; Ilschner, T.; Caldwell, D. Robotic Manipulation of Food products—A Review. *Ind. Robot* **2003**, *30*, 345–354.
6. Pettersson, A.; Ohlsson, T.; Davis, S.; Gray, J.O.; Dodd, T.J. A Hygienically Designed Force Gripper for Flexible Handling of Variable and Easily Damaged Natural Food Products. *Innov. Food Sci. Emerg. Technol.* **2011**, *12*, 344–351.
7. Blanes, C.; Mellado, M.; Ortiz, C.; Valera, A. Technologies for Robot Grippers in Pick and Place Operations for Fresh Fruits and Vegetables. *Span. J. Agric. Res.* **2011**, *9*, 1130–1141.
8. Laliberte, T.; Gosselin, C.M. Simulation and Design of Underactuated Mechanical Hands. *Mech. Mach. Theory* **1998**, *33*, 39–57.
9. Laliberte, T.; Birglen, L.; Gosselin, C. Underactuation in Robotic Grasping Hands. *Mach. Intell. Robot. Control* **2002**, *4*, 1–11.
10. Meijneke, C.; Kragten, G.; Wisse, M. Design and Performance Assessment of an Underactuated Hand for Industrial Applications. *Mech. Sci.* **2011**, *2*, 9–15.
11. Van der Linde, R.Q. http://food.lacquey.nl/ (accessed on 30 June 2014).
12. http://robotiq.com/en/ (accessed on 30 June 2014).
13. Choi, H.; Koē, M. Design and Feasibility Tests of a Flexible Gripper Based on Inflatable Rubber Pockets. *Int. J. Mach. Tools Manuf.* **2006**, *46*, 1350–1361.
14. http://www.adept.com/products/grippers (accessed on 30 June 2014).
15. Brown, E.; Rodenberg, N.; Amend, J.; Mozeika, A.; Steltz, E.; Zakin, M.R.; Lipson, H.; Jaeger, H.M. From the Cover: Universal Robotic Gripper Based on the Jamming of Granular Material. *Proc. Natl. Acad. Sci. USA* **2010**, *107*, 18809–18814.
16. Pettersson, A.; Davis, S.; Gray, J.; Dodd, T.; Ohlsson, T. Design of a Magnetorheological Robot Gripper for Handling of Delicate Food Products with Varying Shapes. *J. Food Eng.* **2010**, *98*, 332–338.
17. Zhong, Z.; Yeong, C. Development of a Gripper using SMA Wire. *Sens. Actuators A Phys.* **2006**, *126*, 375–381.
18. Maruyama, R.; Watanabe, T.; Uchida, M. Delicate Grasping by Robotic Gripper with Incompressible Fluid-Based Deformable Fingertips. In Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Tokyo, Japan, 3–8 November 2013; pp. 5469–5474.

19. Van Ham, R.; Sugar, T.G.; Vanderborght, B.; Hollander, K.W.; Lefeber, D. Compliant Actuator Designs Review of Actuators with Passive Adjustable Compliance/Controllable Stiffness for Robotic Applications. *Robot. Autom. Mag.* **2009**, *16*, 81–94.
20. Vanderborght, B.; Albu-Schaeffer, A.; Bicchi, A.; Burdet, E.; Caldwell, D.G.; Carloni, R.; Catalano, M.; Eiberger, O.; Friedl, W.; Ganesh, G.; *et al.* Variable Impedance Actuators: A Review. *Robot. Auton. Syst.* **2013**, *61*, 1601–1614.
21. Zheng, H.; Shen, X. Double-Acting Sleeve Muscle Actuator for Bio-Robotic Systems. *Actuators* **2013**, *2*, 129–144.
22. Kim, S.; Laschi, C.; Trimmer, B. Soft Robotics: A Bioinspired Evolution in Robotics. *Trends Biotechnol*. **2013**, *31*, 287–294.
23. Deimel, R.; Brock, O. A Compliant Hand Based on a Novel Pneumatic Actuator. In Proceedings of the IEEE International Conference on Robotics and Automation (ICRA), Karlsruhe, Germany, 6–10 May 2013; pp. 2039–2045.
24. Lipson, H. Challenges and Opportunities for Design, Simulation, and Fabrication of Soft Robots. *Soft Robot.* **2013**, *1*, 21–27.
25. Mosadegh, B.; Polygerinos, P.; Keplinger, C.; Wennstedt, S.; Shepherd, R.F.; Gupta, U.; Shim, J.; Bertoldi, K.; Walsh, C.J.; Whitesides, G.M. Pneumatic Networks for Soft Robotics that Actuate Rapidly. *Adv. Funct. Mater.* **2014**, *24*, 2163–2170.
26. Grzesiak, A.; Becker, R.; Verl, A. The Bionic Handling Assistant: A Success Story of Additive Manufacturing. *Assem. Autom.* **2011**, *31*, 329–333.