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Towards designing a robot gripper for efficient strawberry harvesting

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Abstract. Strawberry is a very delicate fruit that requires special treatment during harvesting. It this paper, a strawberry gripper is developed for picking by investigating the hand motion of a skilled worker. It is demonstrated that the hand motion for detaching the fruit from the stem has a significant role in the process because it can reduce the required force and consequently the damage to the fruit. Experiments are conducted using a robot arm and force sensors to measure the maximum gripping force and the required detachment force under a variety of detachment ways and gripping materials. By analysing those results a prototype of a simple and economic gripper is developed that demonstrates an efficiency comparable to the human hand for this task.

Keywords. gripper design, strawberry picking, robotic harvesting

1. Introduction

The strawberry is a fruit that is difficult to harvest because of its soft material that requires gently manipulation. In Greece, strawberry is cultivated mostly in greenhouses (estimated annual production of 15.000 tons) and is produced both for fresh consumption and mashing. Particularly for fresh consumption, a special treatment of the crop is required from harvesting to packing in order to be delivered undamaged. So far, harvesting has been conducted by skilled workers, who can easily handle this delicate product without damaging it. To minimise the damage, the fruit is harvested early in the morning, when it is still cold. The total amount of time spent for harvesting, the working conditions and the effort required to identify, collect and carry the crops demand the automation of the harvesting process.

The benefits of robot automation have yet to be widely utilised because of the high cost of current robotic systems and the complexity of the task (Chua et al., 2003; Burks et al., 2005). The developed robotic grippers for food handling cover a wide range of operating principles that use pneumatical and electromechanical systems (Monta et al., 1998; Tanigaki et al., 2008; Davis et al., 2008; Berdetto et al., 2010). To achieve the gentle handling that is required for a strawberry, force feedback during gripping is a solution that is complicated and expensive (Allotta et al., 1990). A suction gripper that was designed for gently strawberry handling (Hayashi et al., 2011), only involves the post processing of the crop and cannot be implemented for harvesting as the required gripping forces to detach the strawberry from the plant would damage the fruit. Pettersson et al. (Pettersson et al., 2010) developed a universal robot gripper for fruit picking based on magneto-rheological fluid. Even though this gripper can provide the required compliance of the gripping surface, it is very complex and has not been evaluated in harvesting.

A simple and effective solution for strawberry harvesting involves a scissor-like tool that cuts the stem of the strawberry, while the crop is restrained either with a suction cup (Hayashi et al., 2010) or with a mechanical gripper (Qingchun et al., 2012). This method minimises the damage to the fruit, since it does not apply high forces for the detachment, although it leaves a small stem to the fruit. This stem has to be removed before the strawberry is packed, which requires a post-processing stage, increasing the cost and affecting the fruit quality. Another technique is the encapsulation of the strawberry with a container and its detachment from the stem, while the gripper moves away from the plant (Agrobot, 2011). However, this method can easily damage the strawberry and this makes it insufficient for fresh consumption.

It this paper, an efficient strawberry gripper is developed that is inspired from the way that a skilled worker follows to pick the fruit. This technique of the human is analysed in order to investigate the mechanisms of a suitable strawberry picking according to the minimization of the detachment force and consequently, to the damage to the fruit. Experiments are conducted using a KUKA LWR robot arm and two force sensors to measure the maximum gripping force and the required detachment force respectively, under a variety of techniques and cover materials. The results are used for the mechanical design of a simple and low cost gripper that demonstrates the efficiency of the human hand for this task.

2. Requirements of the harvesting process

In order to analyse the requirements and set the specifications for the gripper, a thorough analysis of the used harvesting technique is conducted. A number of skilled workers is observed picking strawberries in a greenhouse, their technique is analysed and the results of this analysis are used on the laboratory to quantify the observations.

2.1. Harvesting Technique

A number of skilled workers is observed harvesting various sizes of strawberries from an elevated greenhouse hydroponic cultivation. Those fruits are intended for fresh consumption and they have to be treated gently. In a successfully harvested fruit, the sepal without any stem must remain on the fruit (1st requirement). The sepal is needed because it decreases the rate of degradation of the fruit. The stem must be removed since it can wound other fruits during packaging. In addition, the selected for harvesting fruit must be unwounded before and after harvesting (2nd requirement). It is assumed that the selected for harvesting fruit has the correct color, as well as it is free from diseases (3rd requirement). The worker is able to distinguish the fruit among entangled stems (4th requirement). The fruit should be placed in a plastic box in a specific orientation according to the final vendor's specifications (5th requirement) and finally, the gripper should be able to distinguish and grasp fruits that are in contact (6th requirement).

The third requirement will be satisfied by a vision system, incorporated in the harvesting robot and by the gripper itself. Assuming that the vision system is able to detect unwounded strawberries the second requirement can be mapped to a design constraint concerning the force that the gripper should apply to the fruit. The remaining requirements are used to evaluate the gripper design concepts.

Concerning the 1st requirement, from the in-site observations two different grasping techniques that share some common characteristics are recognised. In Fig. 1a, the worker uses three fingers (thumb, index and middle) to grasp the fruit. The worker rotates it's wrist (around pitch axis) in order to bend the stem of the fruit approximately until reaching the sepal. Finally, the worker retracts its hand and the fruit with the sepal is separated from the stem in point **a** (see Fig. 2).

(a) (b)

Fig. 1: Gripping techniques of a skilled worker

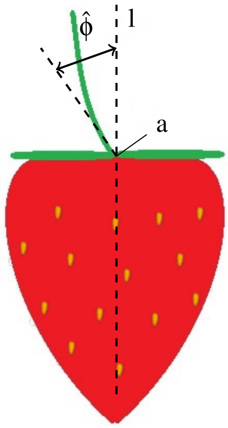


Fig. 2: Strawberry illustration. $\hat{\phi}$ determines the angle between the tangent axis of the stem on point a and the axis of the strawberry.

In Fig. 1b the worker encloses the fruit using the palm, while the thumb grasps the fruit from above in order to secure the grasping. The wrist of the worker rotates (around roll axis) in order to bend the stem and then retracts the hand in order to pick it. Both techniques share the same principles: (a) only one hand is used, (b) the worker bends the stem, (c) the hand is retracted in order to remove the fruit from the stem. They differ only in the grasping since the gripping force in the latter is relatively lower because the fruit is encapsulated by the fingers. The latex gloves apart from protecting the hand, prevent the damage and contamination of the fruit. The latter grip is preferred when the fruit has a large stem diameter because the the required force is higher and the thumb restrains the sepal on the fruit.

Assuming that the human brain has the ability to find the optimal way to accomplish a task though a series of iterations, an experienced worker in strawberry harvesting should be able to find the optimal technique to detach strawberries in terms of effort and productivity. The effort is related directly to the force required for detaching the fruit. By implementing this technique on a robot gripper, this optimality is inherited in the automation and the fruit is easily detached without any damage.

2.2. Measurements

In order to quantify the applied forces of the observed techniques, a series of experiments is conducted, as it is shown in Fig. 3, where the detachment force is measured. A number of fresh strawberries (9) of the same variety are used that were specially harvested with their stem attached using a knife to minimise the effect on the fruit and the stem itself (see Fig. 2). For the experiment, the stem of the strawberry is attached to a portable force sensor instrument using duct tape and the maximum detachment force is measured. After the weight of the fruit is compensated, the operator grabs the fruit and detaches it from its stem using two different ways. In Tab. 1 the average diameter of the stems is shown as well as the maximum detachment force that is measured. In the first three measurements a tensile force is applied (technique A) while in the last six measurements a combination of bending and tensile is applied (technique B).

It is observed that the rotational motion used by the operator during the detachment of the fruit is around the vertical axis perpendicular to the axis **l** that passes through the point **a**. The direction of the rotation in the example of Fig. 2 is anti-clockwise. This rotation imposes the stem to bend towards the axis **l** and create strain concentration to point **a**. It has to be noted that the maximum strain is achieved when the stem is bended along a certain direction. This direction is expressed as a horizontal vector that begins from a point to the stem and passes through axis **l**.

For the first picking way a mean force of 13.94 N is needed to detach fruits of mean stem diameter of 2.17 mm. With the second technique for a mean diameter of 1.78 mm a detaching force of 3.17 N is needed. From the measurements it can be concluded that the technique used by the workers (technique B) requires much less effort in order to detach the fruit. A simple tensile force (technique A) needs excessive force to detach the fruit from the stem which can result separation of the sepal (which occurred on sample 1).

The required gripping force to achieve a sufficient grip without slip or damage of the fruit is measured with the help of a manipulator (see Fig. 4). A force sensor is attached to the end of the robot arm and is coated with 1cm of polyurethane foam. Another part of polyurethane foam is glued on a table and the robot presses a strawberry that is positioned between the two parts of the foam. The stiffness of the foam is estimated with a simple experiment by measuring the curve of the compression force-compression distance

	Avg. diameter [mm]	Technique	F [N]
1	2.69	A	22.00
2	1.95	A	10.00
3	1.87	A	9.81
4	1.77	B	2.78
5	1.79	B	3.76
6	1.68	B	2.31
7	2.19	B	1.57
8	1.76	B	5.10
9	1.53	B	3.53

Tab. 1: Stem diameter and required force for detachment using two different techniques (A & B)

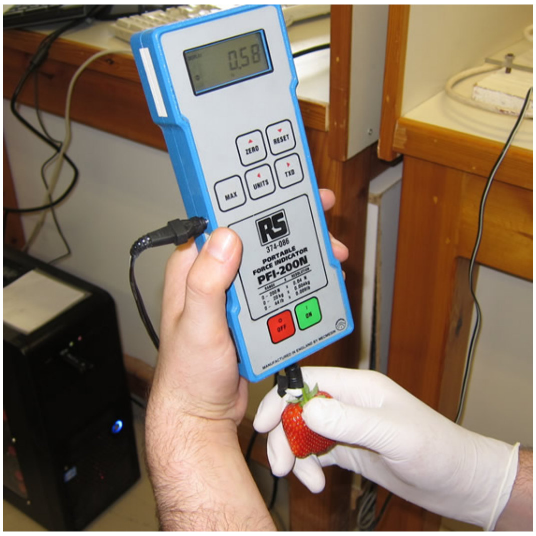


Fig. 3: Measuring detachment force with a portable force sensor

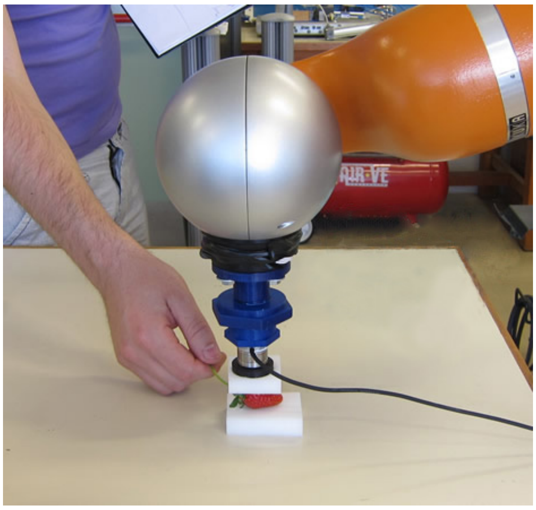


Fig. 4: Measuring required gripping force with a KUKA LWR robot and a force sensor

chart to be linear and equal to 1N/mm. The purpose of the robot is to maintain the force sensor to a steady position in order to measure the required gripping force and analyse these results for the design of the gripper.

An initial compressive force equal to 1N is applied to a number of strawberries by moving the robot arm vertically towards the table. An operator tries to remove the stem from the fruit using the technique B as it is described above. If the operator notices that the strawberry is not retained sufficiently, commands the robot to close the grip by 1mm and apply greater force until the stem can be removed or the strawberry is damaged. When the stem is removed, the gripping force is recorded and the fruit is visually inspected for damage or deformation.

After a preliminary series of tests that is conducted, the visual inspection showed small deformations and wounds in the surface of the fruit. Since two main parallel surfaces of contact are used, the strawberry suffers from high concentrated compressive force. In order to distribute this force, taking into account the variation in size and shape of the strawberry the contact surfaces must be increased. The wounds are caused by the slipping of the strawberry along the rough surface of the foam. By coating the polyurethane foam with latex, the fruit does not slip and the contact surface becomes very smooth.

A set of experiments is conducted with the latex coating of the foam and the measurements are illustrated in Tab. 2. As it is demonstrated, the required gripping force is related to the stem diameter. However, the purpose of this analysis is to determine the maximum force so that the fruit is not damaged or at least to minimise the deformation to an acceptable level. Consequently, it is concluded that if the total gripping force is below 10N, then there is no obvious damage to the fruit and is eligible for fresh consumption. Above this value the latex injures the strawberry and the deformation of the fruit surface is significant, something which happens mainly due to the duration that the force is applied.

dm [mm]	F [N]	Damage
2.73	6.00	None
2.46	6.00	None
2.81	10.00	Deformation
1.75	5.00	None
2.10	12.00	Visible
1.70	8.50	None
2.54	6.70	None

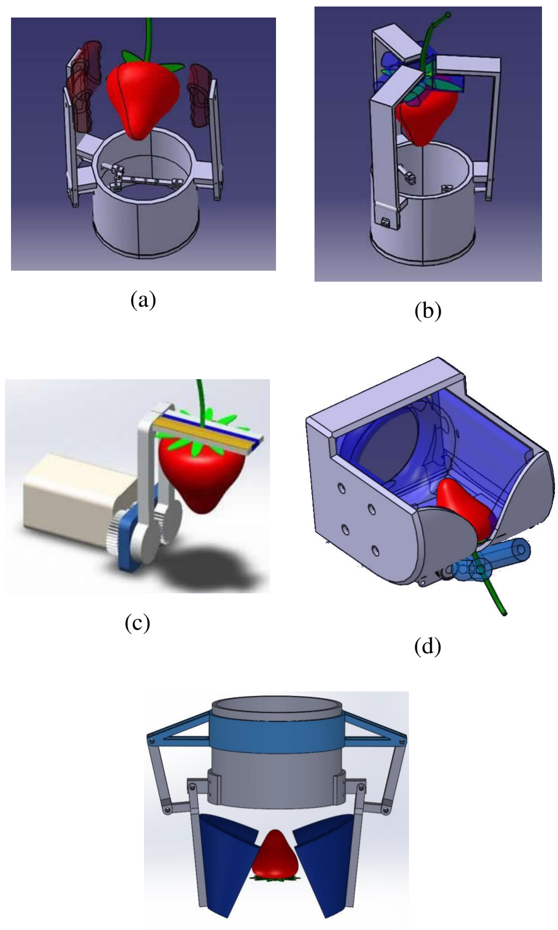
Tab. 2: Measurements of the required gripping force and the corresponding stem diameter

3. The Proposed Concept

Five concepts are developed based on the state of the art grippers as well as the original ideas which are shown in Fig. 5. The first concept (Fig. 5a) has three fingers with a soft material in the contact areas in order to grasp the strawberry from below or sideways. The fingers are mechanically coupled and the mechanism has one degree of freedom. This gripper can lay easily the fruit in a box. The second concept (Fig. 5b) also has three fingers and the grasping of the fruit is performed from above. In this case, the placement of the fruit is much more difficult. Both concepts need a rotational degree of freedom in the arm in order to perform the detachment process.

The third and fourth concept (Fig. 5c,d) are inspired by the proposed grippers in (Hayashi et al., 2010) and (Agrobot, 2011) respectively. Finally, the fifth concept (Fig. 5d) nests the fruits in a clamping gripper, by approaching it from below. It has similar design to the first concept, however, the 2nd requirement is very difficult to be achieved due to the different shape and size of the fruit.

All grippers have the same performance regarding



(a) (b) (c) (d) (e)

Fig. 5: Developed concepts

the third requirement except the third concept that needs the stem to be identified by the visual system. This disadvantage is also mapped in the fourth requirement. In addition, all concepts except the fourth one, can distinguish and grasp easily strawberries that are entangled or in contact with each ohter (see Fig. 6 for the first concept).

In Tab. 3, the five concepts are evaluated relative to the four requirements. From this evaluation, the first concept appears to be the most promising and is selected for further design and prototyping. By comparing the first concept with the rest, it has the most similarities with the gripping technique of a skilled worker which confirms the selection.

Concept	R1	R2	R4	R5	R6
1	+2	+1	+2	+2	+2
2	+2	+1	+2	-1	+2
3	-1	+2	-1	+2	+2
4	-1	+1	+2	-1	-1
5	+2	-1	+2	-1	+2

Tab. 3: Evaluation of concepts against the requirements. (+2: very good, +1: good, -1: bad).

4. The Prototype

The experiments that were conducted in section 2.2 led to the selection of a concept in section 3, which is subjected here to further analysis and development. The selected gripper consists of three fingers in order to distribute the contact forces evenly and to minimise the stress in the fruit. The 3D model of the gripper is illustrated in Fig. 7a. Every finger is a part of a four-bar mechanism (slider-crank) with three rotational joints and one driving translational joint as it is illustrated in Fig. 7b. All fingers are connected in the same translational joint and move simultaneously with a ball-screw system. Since they are identical, the analysis is conducted for a single finger.

4.1. Kinematic Analysis

The purpose of this analysis is to determine the position of the tip of the finger E as a function of the rotation of the actuator motor ϕ. Then the position E can derive relative to the base coordinate system of the gripper O. The four-bar mechanism that is illustrated in Fig. 7c consists of three rotational joints (A,C,D), one linear joint in A and rigid links. The dimensions of the mechanism are determined heuristically to achieve manipulability and compact size but in the expense of the mechanical advantage.

The position of the point E, that comes in contact with the strawberry, is described in the local coordinate system xOy of each finger as a function of θ_3 according to the equation:

$$\bar{E} = -Lcos\theta_3\bar{i} + Lsin\theta_3\bar{j} \quad (1)$$

The kinematics of the four-bar mechanism derived

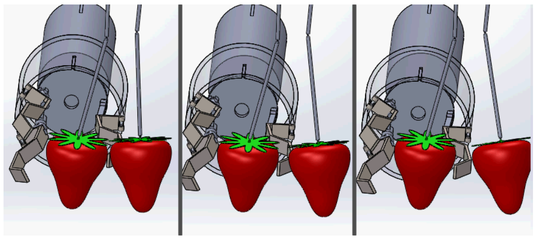
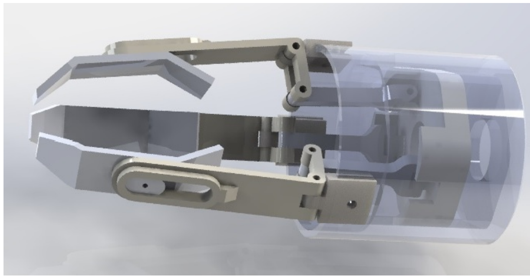
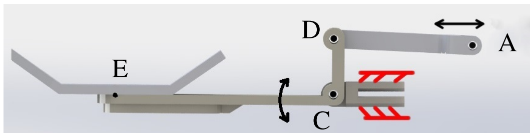


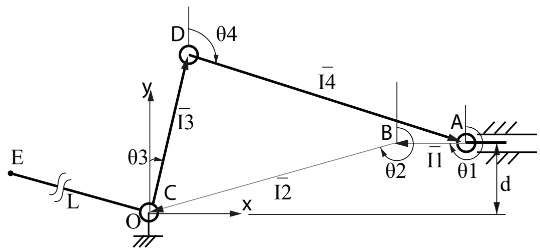
Fig. 6: Separation of entangled strawberries



(a)



(b)



(c)

Fig. 7: (a) The 3D model of the gripper, (b) the mechanism of a finger and (c) the kinematic sketch

from the planar analysis of the closed chain that consists of the vectors $\vec{I}_1\vec{I}_2\vec{I}_3\vec{I}_4$. The angles θ_i, $i = 1,2,3,4$ correspond to the direction of each vector and I_i are the corresponding lengths. Point B demonstrates the upper limit of the linear joint and as a result, $\vec{I}_2$ is a constant. The equation of the closed chain vectors is:

$$\vec{I}_1 + \vec{I}_2 + \vec{I}_3 + \vec{I}_4 = \vec{0} \quad (2)$$

In complex number form, Eq. (2) can be rewritten in the following form:

$$I_1e^{j\theta_1} + I_2e^{j\theta_2} + I_3e^{j\theta_3} + I_4e^{j\theta_4} = 0 \quad (3)$$

where θ_3, θ_4, I_1 are the unknown parameters. The trigonometric equations from the Euler's formula are (with $\theta_1 = 270°, \theta_2 = 250.55°$):

$$-I_1 + I_2 sin\theta_2 + I_3 sin\theta_3 + I_4 sin\theta_4 = 0, \quad (4a)$$

$$I_2 cos\theta_2 + I_3 cos\theta_3 + I_4 cos\theta_4 = 0 \quad (4b)$$

By summing the squares of (4a)(4b) the following equation derives:

$$2c_1 I_3 sin\theta_3 + 2c_2 I_3 cos\theta_3 = I_4{}^2 - I_3{}^2 - c_1{}^2 - c_2{}^2 \quad (5)$$

where $c_1 = I_1 + I_2 sin\theta_2$ and $c_2 = I_2 cos\theta_2$. Eq. (5) is a *transcendental* equation (Craig, 2004) of the type:

$$acos\theta + bsin\theta = c \quad (6)$$

which can be solved by:

$$\theta = Atan2(b,a) \pm Atan2(\sqrt{a^2 + b^2 - c^2}, c) \quad (7)$$

Therefore, (5) is solved by θ_3 according to (7):

$$\theta_3 = f(I_1) = Atan2(2c_1 I_3, 2c_2 I_3) + Atan2(\sqrt{(2c_2 I_3)^2 + (2c_1 I_3)^2 - c_3{}^2}, c_3) \quad (8)$$

where $c_3 = I_4{}^2 - c_1{}^2 - c_2{}^2 - I_3{}^2$.

Finally, the translation I_1 can be easily calculated as a function of the rotation of the motor shaft ϕ:

$$I_1 = \frac{n}{2\pi}\phi \quad (9)$$

where n is the step of the ball-screw system.

The inverse kinematic of each finger are derived from (5) and (9) by calculating the rotation ϕ as a function of the angle θ_3. As a result, by substituting the parameters from Tab. 4 and with n=1.2mm, a grip of e.g. $\theta_3 = 20 degrees$ requires a rotation of the motor shaft equal to 32rad (see Fig. 8), which can be quickly achieved with a stepper DC motor.

Label	Value
I2	47.67 mm
I3	18 mm
I4	45 mm
d	15.87 mm
L	55 (45÷ 65mm)
θ_1	270 deg
θ_2	250.55 deg

Tab. 4: Parameters of the gripper

4.2. Discussion

The proposed design is based on low cost and efficiency. The motion of the fingers can be achieved with a single actuator (stepper DC motor), which can drive all of the fingers accurately to the required grip force with a ball screw system. The use of only one actuator lowers the weight, the complexity and the cost of the gripper. Moreover, since the gripping force has

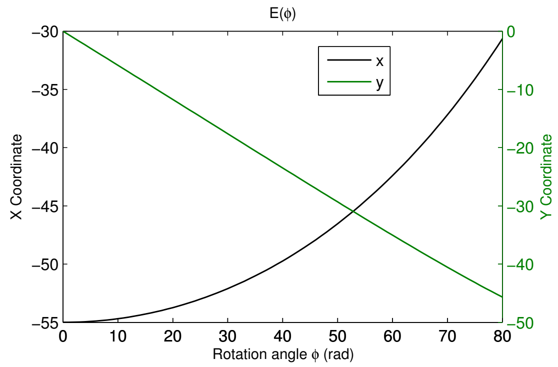


Fig. 8: Graphic relationship between the rotation ϕ of the motor (for n=1.2mm) and the coordinates of point E.

been minimised by finding an efficient harvesting technique, there is no need for high strength materials. The fingers provide a wide surface to attach polyurethane foam and their formation enables the grasping with many contact points to distribute the force and prevent damage of the fruit.

To demonstrate the constructibility of the design, an experimental prototype is produced on a domestic 3D printer with fused deposition modelling (FDM) and by using polylactic acid (PLA) thermoplastic material. The contact surfaces are coated with polyurethane foam and are overlaid with latex as in the experiments. Figure 9a,b illustrates the prototype, without the electrical components, grasping a strawberry from different views. The cost of the materials and the mechanical components, including the 3D print process, is as much as 5€.

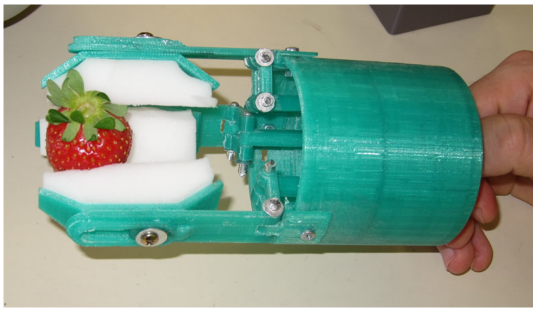
The position control of the proposed gripper can be performed with a stepper motor. The gripping force can be measured either with strain sensors on the finger extensions or with pressure sensors between the finger surface and the foam coat. Both methods can provide accurate measurements since the mechanical properties of the components (e.g. elastic module of the finger or stiffness of the foam) are known or can be calculated.

5. Conclusions

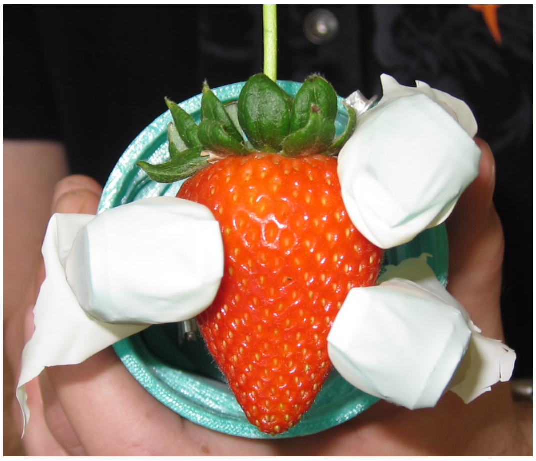
In this paper, the conceptual design and the prototype of a new gripper for harvesting strawberries is presented that is inspired from the handling and manipulation of a skilled field worker. It is assumed that the human through his obtained experience has identified the ”optimal” way on harvesting strawberries regarding fatigue and productivity.

In an effort to propagate this ”optimal” solution to harvesting automation, an analysis is conducted of the technique for detaching the fruit from the stem using a force sensor. In addition experiments are conducted using a robot arm and force sensors to measure the maximum gripping force without damaging the fruit and the required detachment force under a variety of picking techniques. The contact material that is used in the gripper is selected by visual inspection of the strawberries after the experiments as the one which causes the less slipping and damage to the fruit.

Taking into account the analysis of the measurements, a gripper is developed and an experimental prototype is manufactured in a 3D printer with very low cost. As future work, a static and dynamic analysis is needed in order to specify critical dimensions and select the actuator. Moreover, the requirements for sensors have to be defined in order to be able to control the gripping process in a way that the fruit is not damaged. A grasping control scheme will be developed that is based on fuzzy logic grasping of fragile objects (Glossas and Aspragathos, 2010). In addition, the gripper will be integrated with a robot arm and the harvesting technique will be programmed and tested.



(a)



(b)

Fig. 9: 3D printed experimental prototype of the gripper (a) without and (b) with latex overlay

6. Acknowledgement

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