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Design and fuzzy control of a robotic gripper for efficient strawberry harvesting

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SUMMARY

Strawberry is a very delicate fruit that requires special treatment during harvesting. A hierarchical control scheme is proposed based on a fuzzy controller for the force regulation of the gripper and proper grasping criteria, that can detect misplaced strawberries on the gripper or uneven distribution of forces. The design of the gripper and the controller are based on conducted experiments to measure the maximum gripping force and the required detachment force under a variety of detachment techniques. 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. By analysing those results a robotic gripper with pressure profile sensors is developed that demonstrates an efficiency comparable to the human hand for strawberry grasping. The designed gripper and fuzzy controller performance is tested with a considerable number of fresh fruits to demonstrate the effectiveness to the uncertainties of strawberry grasping.

KEYWORDS: Gripper design; Strawberry picking; Hierarchical control; Fuzzy force control.

1. Introduction

The strawberry is a fruit that requires gentle manipulation during harvesting because of its soft material. 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 is being 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 automation of the harvesting process usually requires a combination of three fields. Computer vision for mature strawberry identification and localisation, path planning of the manipulator, and the design of an end-effector for gripping, detachment, and deposition of the fruit. The developed robotic grippers for food handling cover a wide range of operating principles that use pneumatic and electromechanical systems.[1–4] To achieve the gentle handling that is required for a strawberry, an indication of the actual applied force is necessary, however, until now the proposed solutions are complicated and expensive.[5] A suction gripper that was designed for strawberry handling[6] has been used only in the post processing of the crop and cannot be applied for harvesting as the required gripping forces to detach the strawberry from the plant would damage the fruit. Pettersson *et al.*[7] developed a universal robot gripper for fruit picking based on magneto-rheological fluid. Even though

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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[8] or with a mechanical gripper.[9] Although this method minimises the damage, since it does not apply high forces for the detachment, 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.[10] However, this method can easily damage the strawberry and this makes it insufficient for fresh consumption.

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.[11,12] To the authors' best knowledge, on the existing agricultural systems the accuracy of the grip and consequently the quality of the harvested crop depends on the accuracy of the vision system. For that purpose, a gripper with simple operating principles and low-cost mechanical design, that also includes tactile sensing, would increase the efficiency and would benefit the adoption of robotic harvesting. Romano *et al.*[13] have proposed the use of pressure array sensors for grasping unknown fragile objects, inspired by the tactile function of the human. Glossas and Aspragathos[14] have proposed a control scheme based on fuzzy logic and tactile sensors, that applies the minimal required force for grasp without slip. It has been demonstrated that intelligent methods for the control of grippers with pressure array sensors that interact with unknown or uncertain objects can reduce the computational cost and the complexity of the overall control scheme.[15]

It this paper, a mechatronic gripper and its hierarchical control for strawberry harvesting is developed. The technique of the human is analysed in order to investigate the grasp affordance of the fruit and minimise the detachment force. Experiments are conducted using force sensors to measure the maximum gripping force and the required detachment force, under the observed techniques. The results are used for the design of a three-finger, single actuation gripper inspired from a skilled human worker. A hierarchical control scheme is proposed based on a fuzzy force controller and grasp criteria. The higher control level constantly monitors the distribution of forces to the fruit for incorrect grasping between the fingers, via the pressure profile sensor (PPS) arrays installed on the fingers. A decision-making process provides a reference force to the low-level control, that consists of the fuzzy controller and is able to successfully apply that force to the strawberry under the high uncertainties of the process.

2. Requirements of the Harvesting Process

The analysis of the grasp affordance of the strawberry is implemented through observation of human demonstration. A number of skilled workers is observed picking strawberries in a greenhouse and their technique is analysed and quantified with laboratory measurements. The results are used for the mechanical design and the control strategy.

2.1. Harvesting techniques

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 because it is needed for decreasing the rate of degradation of the fruit. The stem must be removed since it can wound other fruits during packaging and also because it is required by the vendor. The selected fruit for harvesting must be unwounded before and after harvesting. The selection of the fruits is conducted with visual inspection for maturity. The worker distinguishes the fruits among entangled stems and finally the fruits are placed in a container with a specific orientation according to the vendor's specifications.

From the in-site observations two main grasping techniques, that share some common characteristics, are recognised. In Fig. 1(a), 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 their 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.

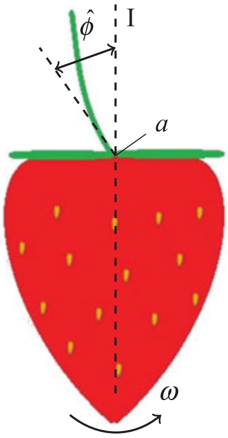


Fig. 2. Strawberry illustration. $\hat{\phi}$ determines the angle between the tangent axis of the stem on point a and the axis of the strawberry.

In Fig. 1(b) 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) to bend the stem and then the hand is retracted in order to detach it. Both techniques share the following 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 force, since the encapsulation of the fruit by the fingers leads to relatively lower pressure. The latex gloves apart from protecting the hand, prevent the damage and contamination of the fruit. When the fruit has a thicker stem the required detachment force is higher and the latter technique (b) is preferred because 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 trial 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 these techniques on a robot gripper, this optimality could be inherited in the automation and the fruit can be easily detached without any damage.

2.2. *Detachment force 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(a), where the detachment force is measured. A number of fresh strawberries (nine) 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 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 Table I the average diameter of the stems is shown as well

Table I. Stem diameter and required force for detachment using two different techniques (A & B).

	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

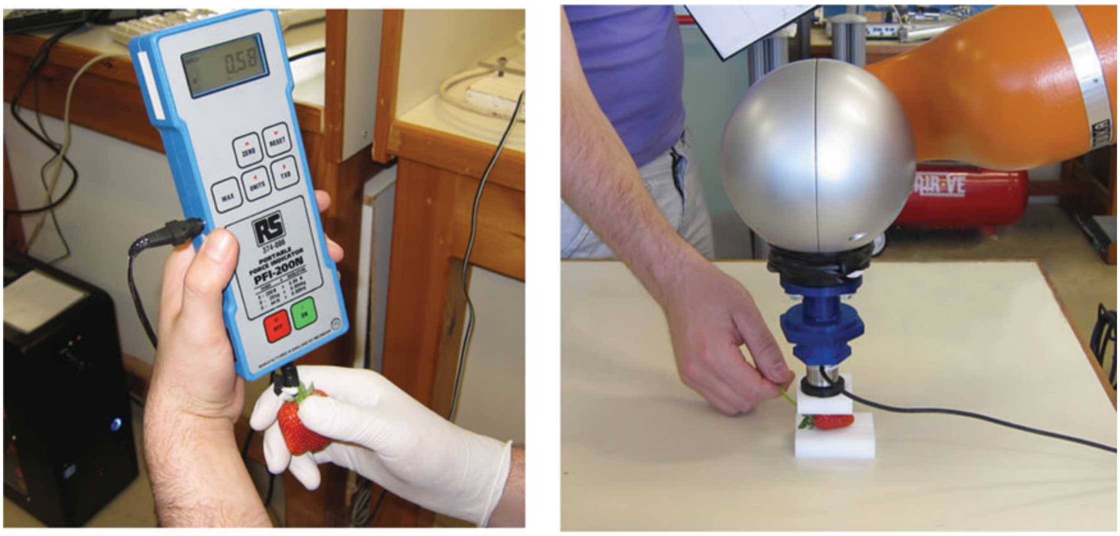

(a) (b)

Fig. 3. Measuring (a) the detachment force with a portable force sensor and (b) the required gripping force with a KUKA LWR robot and a force sensor.

as the maximum detachment force that is measured. In the first three measurements a tensile force is applied (technique A, Fig.1(a)) while in the last six measurements a combination of bending and tensile is applied (technique B, Fig.1(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 axis **I** that passes through point **a**. The direction of rotation ω in the example of Fig. 2 is counter-clockwise. This rotation ω imposes the stem to bend towards axis **I** and create strain concentration at point **a**, where the maximum strain is achieved.

For the first picking technique, 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 tension (technique A) needs excessive detachment force which can result to the separation of the sepal, as occurred on sample 1. The required detachment force with technique B does not depend on the stem diameter.

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. 3(b)). A force sensor is attached to the end of the robot arm and is coated with 1 cm 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 foam is used to maximise the area of contact and diffuse the contact reaction forces in order to reduce the pressure and avoid damage. 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 controller, and particularly to find the maximum allowable force that can be applied to strawberry without damaging it.

An initial compressive force equal to 1 N 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 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 1 mm and apply a 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 conducted tests, the visual inspection showed small deformations and wounds on 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 surface must be increased. The wounds are caused mainly 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 Table II. 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 10 N, then there is no obvious damage to the fruit and it 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 for.

3. Mechatronic Gripper Design

In this section the mechatronic design of the gripper is presented based on the experimental and the in-site observed data. It begins with a quick presentation of the mechanical structure of the gripper since the conceptual mechanical design and the kinematic analysis can be found in a previous work.[16] It continues with the hierarchical controller design as well as the electronic sensors embodied. Finally, the grasping evaluation techniques as well as the implementation of the fuzzy control law are presented.

3.1. Mechanical design

The designed gripper consists of three identical 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. 4. Every finger is a part of a four-bar mechanism (slider-crank) with three rotational joints and one driving translational joint. All fingers are connected in the same translational joint and move simultaneously with a lead-screw mechanism. The fingers are designed so as to encapsulate the strawberry having as much contact area as possible in order to minimise the force required to grasp it.

The motion of the fingers can be achieved with a single actuator, which is a stepper DC motor. By using only one actuator we are able to lower the weight, the complexity, and the cost of the gripper. The fingers provide a wide surface to attach polyurethane foam, and their formation enables the grasping at a large contact area to distribute the forces and prevent damage of the fruit. The foam has the ability to form its shape according to the characteristic geometry of the strawberry and in conjunction with the concave surface, the fruit is securely and evenly grasped.

Table II. Measurements of the required gripping force and the corresponding stem diameter.

Diameter (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

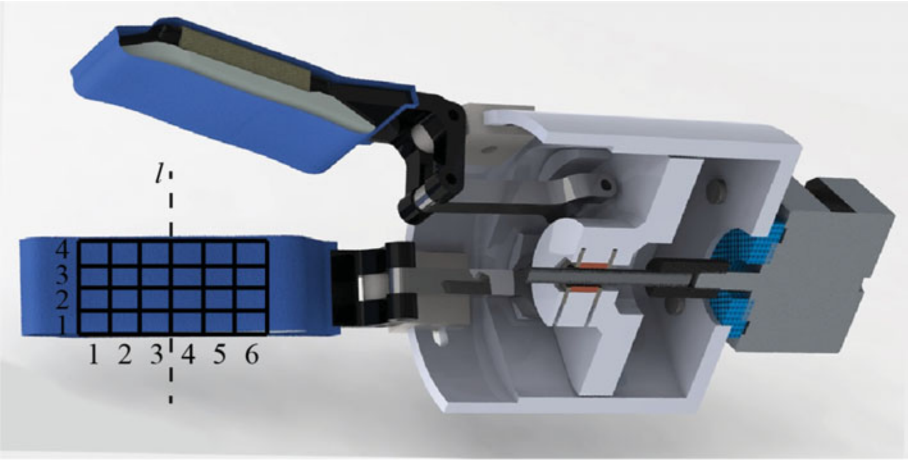


Fig. 4. Section view of the 3D model of the gripper. The grid on the finger represents the capacitive PPS and the numbering convention that is used.

Fig. 5. Functional experimental prototype of the gripper created on a 3D printer, grasping a fresh strawberry.

The sensor array on each finger covers the middle part (axis *l*), where the strawberry should be grasped according to the observed technique B. As it is shown in Fig. 5, this position and orientation reduces the stress applied to the fruit. The sensor array allows to detect offsets from axis *l*, uneven distribution by all fingers and the equivalent force applied to the fruit. Even if the target is grasped at the tip of the fingers, the sensors are still able to detect it because of the foam material that diffuses the applied force. This sensor ability is used in the hierarchical control system to reposition the gripper if the strawberry is grasped incorrectly.

3.2. Controller design

In order to pick the strawberry with the proposed gripper, the following actions should take place:

1. Approach the strawberry with the manipulator to the coordinates given by the vision system.
2. Grasp the fruit by applying even distribution of force.
3. Rotate the wrist of the robot at the correct angle and retract.

Concerning the first action it is assumed that the position and orientation of the strawberry can be provided by the vision system. Although advances in this field have enabled rapid and accurate

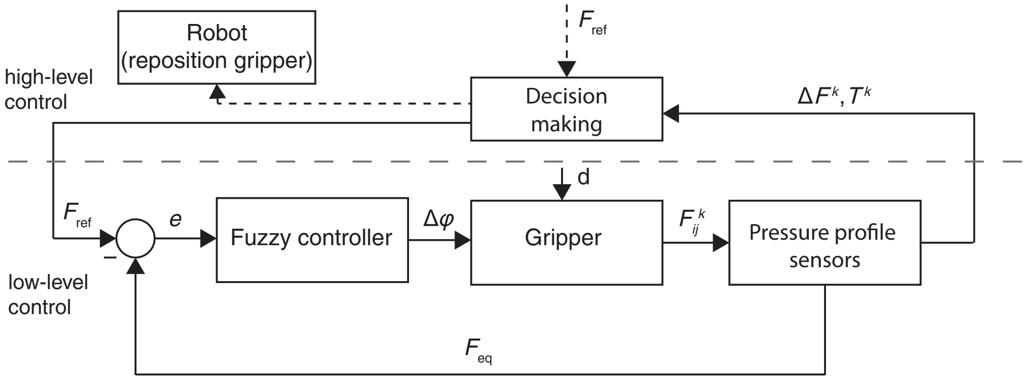


Fig. 6. Block diagram of the overall control system. The decision making block is described by Algorithm 1.

localisation of fruits,[17,18] the approach of the manipulator could displace the target. Visual servoing cannot always be applicable to compensate for this disturbance, because the gripper is very close to the target and obscures the field of view. As a result, it would be beneficial to incorporate a sensing capability inspired from the tactile function of the human hand. Tactile sensing provides local information for the grasped strawberry location in a more precise way than any vision system.[19,20] This is accomplished by using PPS arrays on each finger that can sense the distribution of forces along the finger. The information from these sensors can be used to reposition the gripper in order to meet certain criteria and firmly grasp the strawberry. The present work focuses on the development of a control strategy using the PPS array, assuming that is part of a hybrid control law using tactile and vision, without fusing any vision and pressure data. The vision system and the robotic manipulation of the gripper are not considered in this paper.

The proposed control strategy consists of a hierarchical control scheme as is illustrated in Fig. 6. The high-level control receives the user input and constantly monitors the distribution of forces applied to the fruit via the PPS for incorrect grasping between the fingers. If the strawberry is correctly grasped, a fuzzy force controller in the low-level control loop regulates the error between the reference force F_{ref} and the equivalent force F_{eq} measured by the PPS towards zero.

3.3. Grasping evaluation

The criteria for the evaluation of the grasp are defined according to the investigation of fruit handling by skilled workers and the design of the gripper fingers. To minimise the damage to the fruit, a worker encapsulates the strawberry in the middle of his fingers by applying even distribution of the force, using technique B of Fig.1(b). The fingers of the proposed gripper follow this technique by having a curved surface and by being covered with foam so as to maximise the contact surface with the strawberry and thus minimise the pressure. The placement of the PPS on each finger allows us to detect two types of displacements from the correct position, which can result in damage of the fruit and failure to securely grasp.

More specific, the fruit is prone to offsets from the correct position, because of errors in the vision system and displacement of the target during the approach of the manipulator. The occurrence can be detected by calculating torque T^k applied around the virtual axis l (see Fig. 4) from each column of sensors as follows:

$$T^k = \sum_{i=1}^{3}\left\{(4-i)\times\sum_{j=1}^{4}F^k_{ij}\right\} + \sum_{i=4}^{6}\left\{(i-3)\times\sum_{j=1}^{4}F^k_{ij}\right\} > T_{\text{crit}}, \tag{1}$$

where F^k_{ij} is the compression force measured by the sensor on finger k ($k = 1, 2, 3$) in row i & column j and T_{crit} is the threshold value of the torque. An illustration of an offset grasp that activates the rule is shown in Fig. 9(a), where all fingers touch the strawberry by their tip. The threshold value for T_{crit} is selected equal to 3 (N × length units) by trial and error. This is particularly useful when the strawberry is grasped by the tips of the gripper, because it is not secured and can easily slip.

Moreover, due to the geometry of the finger and the location of the pressure sensor, the foam might be unable to take huge strain and the hard material of the finger could damage the strawberry.

Another misplacement that has to be taken into consideration is the uneven distribution of forces. The locations of the fingers relative to the base of the gripper have been selected according to the grasp affordance of the strawberry. However, if the strawberry is not in the middle of the gripper, it will be grasped by only two of the fingers. For the detection of such a misplacement, the following criterion is proposed that calculates the variation ΔF^k between every two fingers:

$$\Delta F^k = \left|\Sigma F^k - \Sigma F^{k+1}\right| > F_{\text{crit}}, \quad \Sigma F^k = \sum_{i=1}^{6}\sum_{j=1}^{4} F_{ij}^k. \tag{2}$$

ΣF^k is the total force detected by all elements in each finger and F_{crit} is the threshold value, selected equal to 3 N by trial and error. It can be seen in Fig. 9(b), that the first finger senses no force in comparison to the other two, because the strawberry is being held non-uniformly only by two fingers. Lower thresholds would cause the gripper to identify a misplacement sooner, causing a false positive rule activation.

If the strawberry is not in the correct location and at least one of the grasp criteria is activated, the reference force to the controller switches to zero in order to release the misplaced strawberry. Then, the manipulator of the gripper must be commanded accordingly to reposition the end-effector in the right direction. For the first rule the end-effector should be moved parallel to the axis of the cylindrical base in order to reset the target to the correct location. The direction depends on the sign of T^k and the magnitude is equal to the distance between axis l and the sensor element with the maximum force (Fig. 9(d)). For the rule of uneven distribution, the end-effector should translate in the direction that the strawberry approaches the finger with the least ΣF^k (2), as in Fig. 9(e). After the correct location of the fruit relative to the figures is obtained, the higher control level resets the reference force to low-level force control. The decision-making and action processes during the control loop are illustrated in Algorithm 1. In every sampling period, the decision-making process calculates T^k and ΔF^k from the PPS sensor input and if one of the criteria is activated, then the manipulator is commanded for reposition of the gripper with $F_{\text{ref}} = 0$ N. Otherwise, the low-level fuzzy force control is activated with reference force $F_{\text{ref}} = 6$N.

Algorithm 1 Decision making process of the control algorithm.

```
loop                                                              ▷ control loop
ReadSensors( )                                                    ▷ read PPS sensors
    if $T^k > T_{crit}$ or $\Delta F^k > F_{crit}$ then RepositionGripper( )     ▷ check criteria
    else  FuzzyControl( )                                         ▷ force control of the fingers
    end if
end loop
```

3.4. Fuzzy force controller

The force regulation of the grip is of vital importance for a secure grasp, that does not damage the strawberry. Apart from the difficulties in modelling the dynamics of the proposed gripper due to backlash of the mechanical system and viscoelasticity of the foam covering materials, there are uncertainties due to the different sizes and the variant properties of the strawberries. Moreover, the motion of the fingers should be quasistatic to avoid damage of the fruit, therefore the dynamic model of the system is not investigated. Unlike classic control methods, an intelligent fuzzy control scheme is considered necessary to cope with these unmodelled parameters. By using a classic PID controller, the integrator (I) and derivative (D) terms are expected to cause problems because of the integration wind-up[21] in free-space motion of the fingers and the low sampling frequency of the sensors respectively. A proportional fuzzy controller can achieve a non-linear relationship between the inputs and outputs of the controlling process that outperforms a classic P controller, particularly in the absence of a model.

Table III. Fuzzy controller rule-base.

Input (e)	NVL	NL	NS	Z	PS	PL	PVL
Output ($\Delta\phi$)	NVL	NL	NS	Z	PS	PL	PVL

The proposed controller is a single-input–single-output fuzzy system that implements a position-based force control on all fingers simultaneously. The controller receives as an input, error $e = F_{\text{ref}} - F_{\text{eq}}$, between the reference force F_{ref} and the equivalent force F_{eq} (measured by the sensors), and determines the relative position of the motor that opens or closes the gripper, as shown in the block diagram of Fig. 6. The relation between the motor rotation and the finger motion is reported in previous work.[16] The reference force, that represents the desired equivalent grasping force of the gripper, is derived by the high-level decision-making process (Algorithm 1) as follows:

$$F_{\text{ref}} = \begin{cases} 0\text{N} : \Delta F^k \geq F_{\text{crit}} \textbf{ or } T^k \geq T_{\text{crit}} \\ 6\text{N} : \Delta F^k < F_{\text{crit}} \textbf{ and } T^k < T_{\text{crit}}. \end{cases} \tag{3}$$

When one of the criteria presented in Section 3.3 is activated, the strawberry has to be released and the reference force is set to zero. Otherwise, the controller is commanded to a reference of 6 N, which is an average value for secure grip without damaging the strawberry as it is derived from the analysis of the harvesting technique (see Table II). The equivalent force is calculated from the weighted average value of the total force applied on each finger according to their configuration on the cylindrical base:

$$F_{\text{eq}} = \left(a_1 \times \sum_{j=1}^{6} \sum_{j=1}^{4} F_{ij}^1 + a_2 \times \sum_{j=1}^{6} \sum_{j=1}^{4} F_{ij}^2 + a_3 \times \sum_{j=1}^{6} \sum_{j=1}^{4} F_{ij}^3 \right) / (a_1 + a_2 + a_3), \tag{4}$$

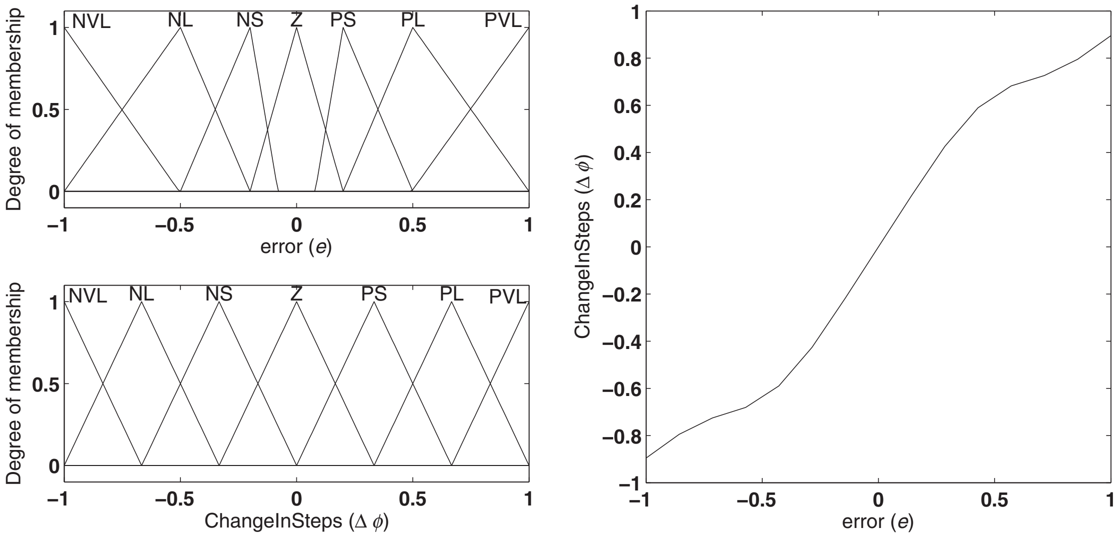
where $a_1 = 1,\ a_2 = a_3 = \cos 45^\circ$ are the coefficients for the equivalent force. These values derive from the configuration of the fingers on the base of the gripper and determine the direction of the maximum stress to the fruit. The advantage of using all sensors to calculate the equivalent force is that during the detachment of the strawberry by a robot, the developing forces are distributed evenly between the fingers and F_{eq} remains invariant. Any disturbance force d acting on the gripper, particularly during the detachment, is eliminated by the force controller by minimising error e.

The fuzzy controller consists of seven input membership functions of triangular type, which are intuitively distributed around zero as it is shown in Fig. 7(a). The membership functions are more dense around zero for achieving higher resolution on the input error, therefore better control close to the set point. Each membership function represents a linguistic variable that facilitates the creation of the rule base and the tuning of the controller. The membership functions used both in the input and in the output are: "NVL" for negative very large, "NL" for negative large, "Z" for no change, "PS" for positive small etc. The output of the fuzzy system represents the relative position $\Delta\phi$ for the stepper motor and consists of seven membership functions which are evenly distributed. The ranges of both the input e and output $\Delta\phi$ are normalised between -1 and $+1$ and the tuning gains that are used are determined experimentally ($g_{\text{in}} = 0.3,\ g_{\text{out}} = 200$). The operations for implication, aggregation, and defuzzification are product, sum, and centre of gravity respectively.

The rules of the fuzzy system form a complete and consistent rule-base, meaning that for every input there is a valid conclusion. The rule-base is illustrated in Table III and can be interpreted by IF... THEN sentences as follows:

- IF error e is negative very large (NVL) THEN $\Delta\phi$ is negative very large (NVL).
- IF error e is zero (Z) THEN $\Delta\phi$ is zero (Z).
- IF error e is positive small (PS) THEN $\Delta\phi$ is positive small (PS).

A positive error e ($F_{\text{eq}} < F_{\text{ref}}$) for example, represents that the motor will turn towards the positive direction ($\Delta\phi > 0$) to close the grip and minimise the error. The input–output mapping achieved by the rule-base is a non-linear relationship as it is illustrated in Fig.7(b). It enables small changes in the position of the motor for accurate control in small errors (linear section e: $-0.4...0.4$) and rapid movement for large errors.



(a) (b)

Fig. 7. The input and output membership functions of the fuzzy system (a) and their mapping (b) by the rule-base.

4. Experimental Evaluation

The grasping performance of the gripper and the proposed hierarchical controller are evaluated with experiments conducted in a lab environment by grasping fresh strawberries and detaching them from their stem (Fig. 8). The experimental setup consists of the fully functional prototype of the gripper and the implemented hierarchical controlled running on conventional desktop computer. The PPS sensors and the stepper motor controller module communicate with the computer through Universal Serial Bus (USB). A bipolar stepper driver is used that allows the control of the position, velocity, and acceleration of the motor. The control system of the gripper is implemented by a custom-written application operating at a sampling frequency of 25 Hz. A higher frequency could possibly improve the performance of the controller, however, it is bounded by the capacitive sensing operation of the PPS sensors.

Since only the control scheme is investigated, the gripper is not attached to a robot rather it is manipulated by an operator with his arm. The tested strawberries are guided to the gripper and the reference force is provided to the decision-making system of the hierarchical controller. When the grip is closed and the reference force is reached, the gripper is retracted with the appropriate technique (technique B; Table I) until the fruit is detached from its stem (Fig. 8).

A number of fresh strawberries of various sizes, shapes and varieties are tested in two sets of experiments to evaluate the overall control scheme. The first set involves 24 randomly selected strawberries that are positioned incorrectly relative to the gripper. The operator positions half of the strawberries at random positions towards the edges the fingers (Fig. 9(d)) and half at non-uniform distribution (Fig. 9(e)), simulating offset from the resting location and uneven distribution of forces respectively. The hierarchical controller is set to $F_{\text{ref}} = 6$ N and the gripper grasps the fruit. In Table IV, the mean and standard deviation of the maximum equivalent force F_{eq} are presented since it is the most influential parameter considering the quality of the strawberry. The mean values for both of the tested criteria with incorrect fruit location remain within 1 N and 2 N with small standard deviation, and the success rate is 100% for offset detection and 75% for uneven distribution detection. The latter presents 17% of false negative results, meaning that the decision-making process detected the wrong criterion, mainly because of wrong positioning by the operator. The false negative percentage of 8% in the detection of uneven distribution represents failure to detect any incorrect positioning.

The second set of experiment involves 42 randomly selected strawberries that are positioned by the operator at the correct grasping location of the gripper in order to evaluate the fuzzy force controller during the detachment. After the controller is set to $F_{\text{ref}} = 6$ N and the strawberry is expected to be securely grasped, the gripper is retracted by the operator and the strawberry is detached from the stem. The mean value of the maximum force F_{eq} in each experiment is 6.45 N with a very small standard deviation. Although the maximum equivalent force F_{eq} exceeds the reference F_{ref} due to

Table IV. Statistics from experimental evaluation of the control scheme in fresh strawberries.

			Incorrect positioning	
		Offset position	Uneven distribution	Correct positioning
Max F_{eq}	Mean	1.28	2.09	6.45
[N]	S.D.	0.66	0.30	0.19
Success rate		100%	75%	65%
False positive		0%	17%	35%
False negative		0%	8%	–

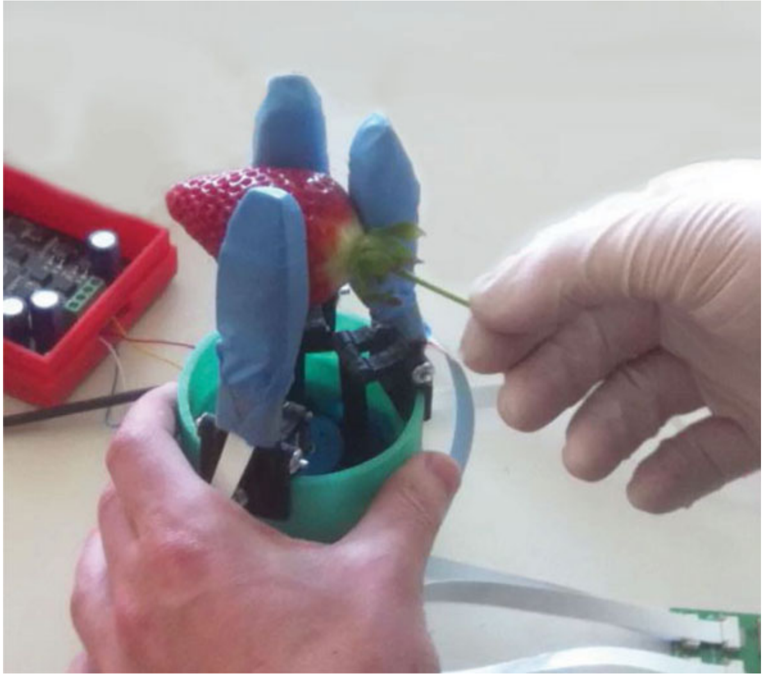


Fig. 8. Experimental procedure for detaching the strawberry from its stem.

overshooting and disturbance rejection during the detachment, no physical damage to the fruit occurs since there is a margin of up to 10 N and the overall maximum measured force is 7 N (Table II). The success rate is 65%, while 35% of the experiments result in incorrect activation of the grasping evaluation rules (false positive). This percentage occurs because of the conservative values of the evaluation rules and is acceptable since none of the tested strawberries is damaged.

A representative illustration of the equivalent force $F_{eq}(t)$ over time is shown in Fig. 10. At the initial grasp attempt (t_1), the target is placed incorrectly and one of the grasp criteria is expected to be activated. Indeed, for time t_2 the controller detects the offset without causing excessive force to the fruit and the reference force F_{ref} switches to zero releasing the strawberry. The force profile at t_2 is shown in Fig. 9(b). After a small time period, at which the gripper has been repositioned, the fuzzy controller is re-enabled to the reference force (6 N). The rise time to the steady state is 2 s and an overshoot of 10% is observed, which is acceptable as it does not damage the strawberry. When steady state error is within ±3% (t_4), the strawberry is considered securely grasped, the grasping criteria checks are disabled and the gripper is ready to be retracted. For $t = 22$ s the gripper is retracted and successfully detaches the strawberry from the stem without affecting the grasping or damaging the strawberry.

The proposed controller achieves very good performance and manages to sustain the desired force without being affected by the externally applied forces during the detachment process. The grasping evaluation successfully detects any misplacement at a substantial time and before large forces are applied that can damage the fruit. A video demonstration of the gripper is available online.[22]

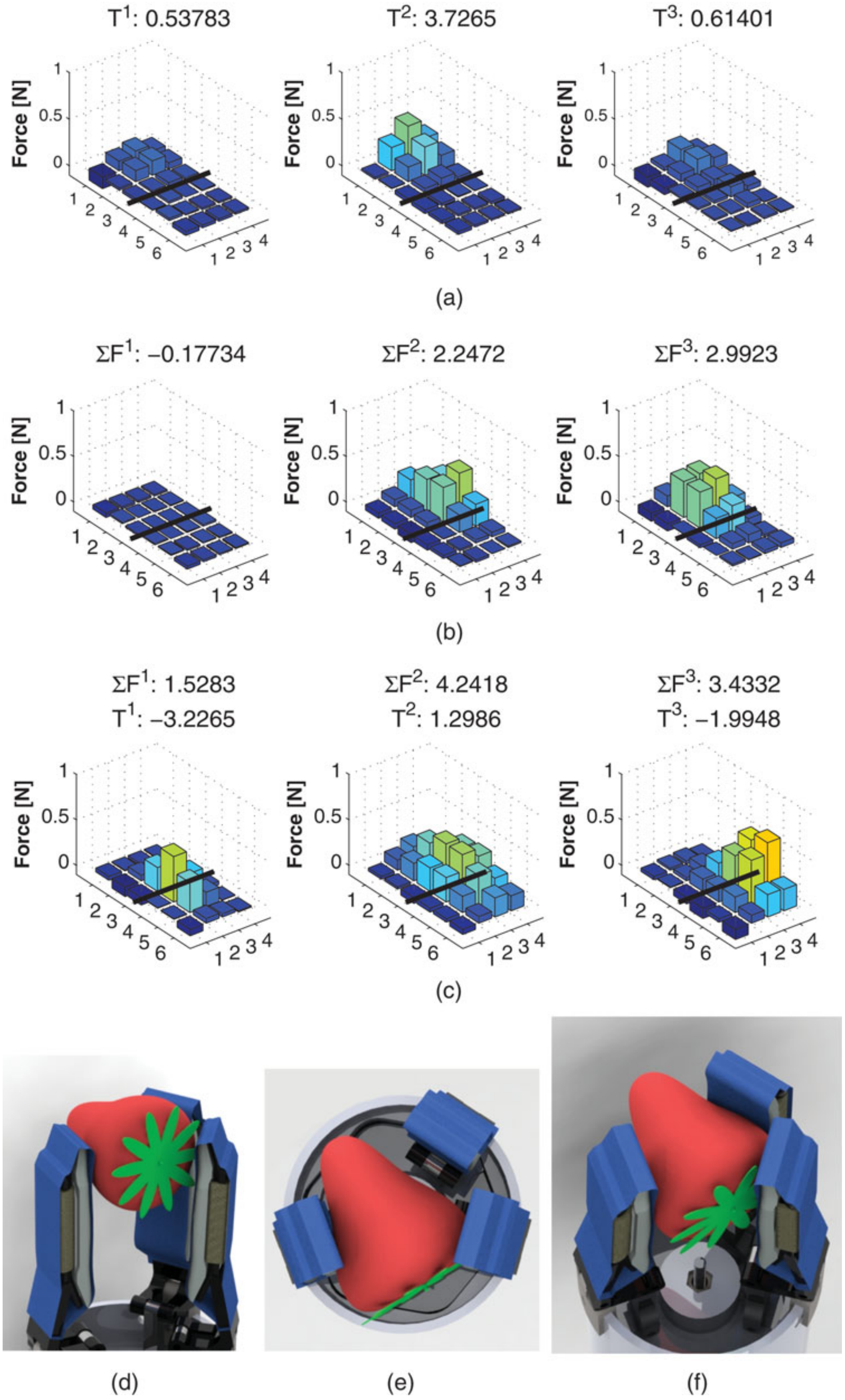


Fig. 9. Force distribution during misplaced grasping with offset from the correct position (a), with uneven distribution of forces where finger 1 has not touched the strawberry (b) and with correct distribution on steady state (c). The black thick line represents the axis l. The corresponding images of each distribution are shown on the right (d)–(f).

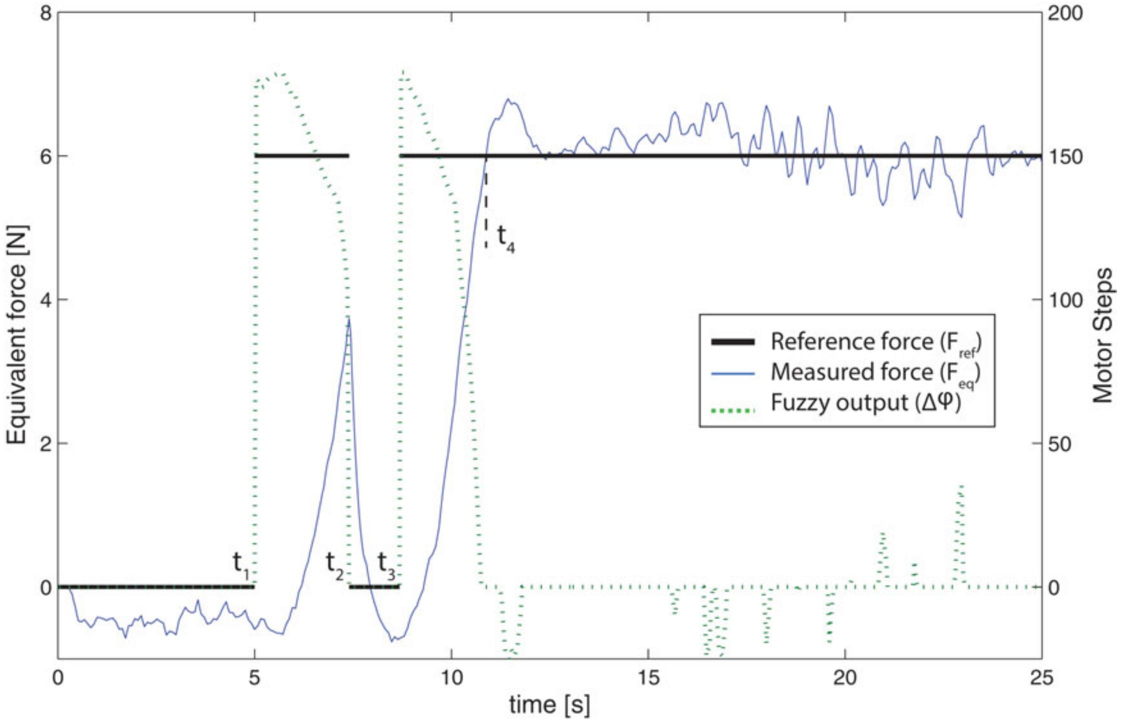


Fig. 10. The equivalent force F_{eq} illustrated during force control in one of the experiments. A step reference force $F_{ref} = 6\,\mathrm{N}$ is given at t_1 and a misplacement is detected at t_2. A repositioning takes place and the second step reference force is given at t_3. The rise time to the reference value is 2 s. After t_4 the strawberry is securely grasped and the gripper can be retracted. The output of the fuzzy controller ($\Delta\phi$) is represented in relative motor steps.

In order to calculate the overall cycle time with the proposed gripper, the complete robotic system has to be utilised. The total cycle time of other robotic systems with vacuum grip[9] is 31.3 s and with scissor detachment[8] is 11.5 s. Apparently, the quality of the harvested fruit has a great impact on the cycle time because poor quality product does not require gentle manipulation. In the proposed gripper, the rise time of the controller is limited by the actuator and can be further improved to a competitive level. Furthermore, the haptic operation of the proposed gripper, which also prevents damages to the fruit, can improve dramatically the success rate that ranges from 60% to 80% on current visual servoing strawberry picking systems.[8,9]

5. Conclusions

In this paper, a novel design and control scheme of a new gripper for harvesting strawberries is presented that is inspired from the handling and manipulation of a skilled field worker. In an effort to identify the grasp affordance of the strawberry, a number of skilled workers are observed. In addition, measurements are conducted in order to quantify the maximum gripping force without damaging the fruit and the required detachment force under a variety of picking techniques.

The results of the measurements are used in developing a three-finger, single-actuated gripper with simple operation and low-cost mechanical design. A prototype gripper is developed that operates with a stepper DC motor, and PPS arrays are attached on each finger. These sensors enable a tactile feedback to the gripper, that can be used to detect misplaced grasping. The tactile capability of the sensor reduces the dependency on the vision system for accurate grasping and high success rate.

A hierarchical controller strategy is proposed that consists of a low-level fuzzy force controller and a higher level decision-making process. The fuzzy controller is used to regulate the desired equivalent force to the strawberry while, two criteria are developed that can detect incorrect grasp. When one of the criteria is activated, the decision-making loop switches the reference input to the force controller for releasing the strawberry and the end-effector is repositioned accordingly.

The initial experiments demonstrate promising results although on-field tests have to be conducted that could lead to further improvements. As a future work, modifications on the actuator have to be conducted for improving the grip time and the overall control strategy can be converted to minimal force according to the slip of the fruit on the gripper.[14] Moreover, computer vision techniques for fruit detection, robot scheduling, and motion planning are investigated towards an efficient strawberry harvesting system.

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