Tactile Sensing with Accelerometers in Prehensile Grippers for Robots

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Abstract

Several pneumatic grippers with accelerometers attached to their fingers have been developed and tested. The first gripper is able to classify the hardness of different cylinders, estimate the pneumatic pressure, monitor the position and speed of the gripper fingers, and study the phases of the action of grasping and the influence of the relative position between the gripper and the cylinders. The other grippers manipulate and assess the firmness of eggplants and mangoes. To achieve a gentle manipulation, the grippers employ fingers with several degrees of freedom in different configurations and have a membrane filled with a fluid that allows their hardness to be controlled by means of the jamming transition of the granular fluid inside it. To assess the firmness of eggplants and mangoes and avoid the influence of the relative position between product and gripper, the firmness is estimated while the products are being held by the fingers. Better performance of the accelerometers is achieved when the finger employs the granular fluid. The article presents methods for designing grippers capable of assessing the firmness of irregular products with accelerometers. At the same time, it also studies the possibilities that accelerometers, attached to different pneumatic robot gripper fingers, offer as tactile sensors.

Keywords: Tactile sensing; Gripper; Grasp contact; Hardness; Pick and place; Accelerometer

1. Introduction

Human hands are capable of carefully manipulating products of different shapes at high speed and classifying them according to the response of their internal tactile sensors. Human manipulation is widely used for the packaging of horticulture products. The introduction of industrial robotics into the primary packaging of food has a huge potential [1,2]. To meet this challenge, robot grippers have to improve their capability to handle irregular products and incorporate reliable and robust tactile sensors.

For a gripper, handling irregular products with varying shapes is a challenging task and more so if the products are sensitive, like some fruits or vegetables. Different approaches have been followed in an attempt to achieve the necessary dexterity. Robotic hands seek to come close to the degrees of freedom of the human hand with complex mechanisms, sensors and control systems. In general, they are too complex and cannot achieve the necessary speed, reliability and cost to accomplish the industrial requirements [3]. Grippers with simple mechanisms and controls are required. Underactuated mechanisms reduce the number of actuators without reducing the degrees of freedom of gripper fingers, and increase the grasping dexterity to adapt to different product shapes [4]. Underactuation can be used to develop robot hands [5] even in some industrial applications [6]. The design of underactuated mechanisms requires a large amount of arduous work to find the best solution [7], their behavior is nonlinear and specific algorithms are necessary to estimate their contact forces [8].

Compliant fingers or gripper mechanisms help the gripper to grasp irregular products. A distributed compliant gripper made of silicone allows adaptation to products with varying shapes and surfaces [9]. In robotic hands, some developments can be found with a fully compliant robot hand [10], with a concentrated compliant in the fingers of an underactuated robot hand [11] or a robot hand with a compliant actuator [12]. Some authors [13] tested fingers covered with a membrane with inflatable rubber pockets. If a membrane is filled with granular material, the pad easily adapts to the product shapes. The control of the inside pressure of an elastic membrane filled with granular materials has been used to adjust its stiffness by means of the jamming transition. This property has great potential in robotics for developing robot grippers [14], for example, with this technology it is possible to develop a universal gripper [15]. The jamming transition can be used for the control of stiffness in the fingers of parallel grippers [16, 17].

In robotics, a tactile sensor is “a device or system that can measure a given property of an object or contact event through physical contact between the sensor and the object” [18].

Tactile sensors for robot grippers can be intrinsic when the sensor does not need to be in direct contact, and extrinsic when the sensor does need to be in contact [19]. Since intrinsic sensors are not in direct contact with the product, this can affect the quality of the signals received. But intrinsic sensors can be embedded away from the risk of damage from direct contact and it is not necessary to use an array of sensors, which simplifies installation and control. Despite these advantages most of them are extrinsic. Conductive silicone rubber has been used as an intrinsic sensor in compliant joints [20] and has been embedded in a compliant gripper [21] to detect the presence of objects with different sizes and orientations. This material has high hysteresis but its behavior can be predicted with an adaptive neuro-fuzzy inference system [22]. Another possibility is the use of micro-electro-mechanical devices with low hysteresis and quasilinear behavior as intrinsic sensors. Load cells in continuum robots allow force sensing to evaluate product softness [23]. A tri-axial accelerometer fitted to a probe that slides over several surfaces [24] is used as a texture perception sensor. A similar solution has also been implemented in a humanoid robot [25]. Accelerometers, in a pneumatic gripper, can monitor the instant in which the contact occurs and may be combined with a force sensor to regulate the grasping force [26]. Intrinsic sensors are able to sort fruits by means of an online algorithm analyzing the current of an electric motor gripper [27]. IR phototransistors and a small three-axis force [28] were used to develop an embedded flexure and force sensor. Some extrinsic tactile sensors can evaluate product hardness by using a piezoelectric transducer [29] in combination with a pressure sensor [30]. [31] have developed a flexible tactile sensor with piezoresistive rubber to classify rigid and deformable objects. Between intrinsic and extrinsic sensors, product hardness has also been evaluated with a quasi-static intrinsic sensor that measures sensor displacement, while the internal sensor chamber is deformed under pneumatic [32] or magnetic actuation [33]. Piezoresistive sensors placed on the fingers allow tomatoes and peppers to be classified according to their ripeness [34].

The purpose of this research is to study the information that accelerometers attached to the fingers of grippers can provide as tactile sensors and the potential use of this technique in industrial pick-and-place robot processes. The grippers use accelerometers to identify the phases of the actions they perform while grasping an object and several methods are proposed for measuring the hardness of the grasped products. Hardness is estimated by processing deceleration time during the grasping action, by the severity of the deceleration at the first product/finger contact, and by the highest deceleration peak. These methods can be extrapolated to other prehensile grippers.

In common robotic primary packaging processes, robots pick products up from a conveyor belt. Product shape and orientation are defined by computer vision, and product position is coordinated with a conveyor belt tracking system. Even though there is an error in product positioning, the robot gripper should be able to grasp and sense products despite these inaccuracies. A specific robot gripper operation is developed taking these inaccuracies into account. The gripper prototypes have been tested to estimate the firmness of eggplants and mango fruits. In order to improve the gripper's capabilities for grasping products with different shapes, they have fingers with underactuated motion or fingers with pads filled with a granular material capable of jamming transition. All the grippers have been tested on an ABB IRB 340 robot.

2. Embedded accelerometers in an angular gripper

Pneumatic gripper I is a prototype angular gripper designed for handling products with cylindrical shapes. It was designed for robotic pick-and-place processes. The gripper's fingers are made of Ultra High Molecular Weight Polyethylene (UHMWPE) plastic, and finger A is underactuated because it is connected by two standard plastic ball sockets and can rotate around an inclined vertical axis. The gripper actuator is a standard pneumatic aluminum cylinder. An electro-valve controls the open-and-close actions of the fingers. Two adjustable flow-rate valves allow manual regulation of the velocity of the gripper fingers.

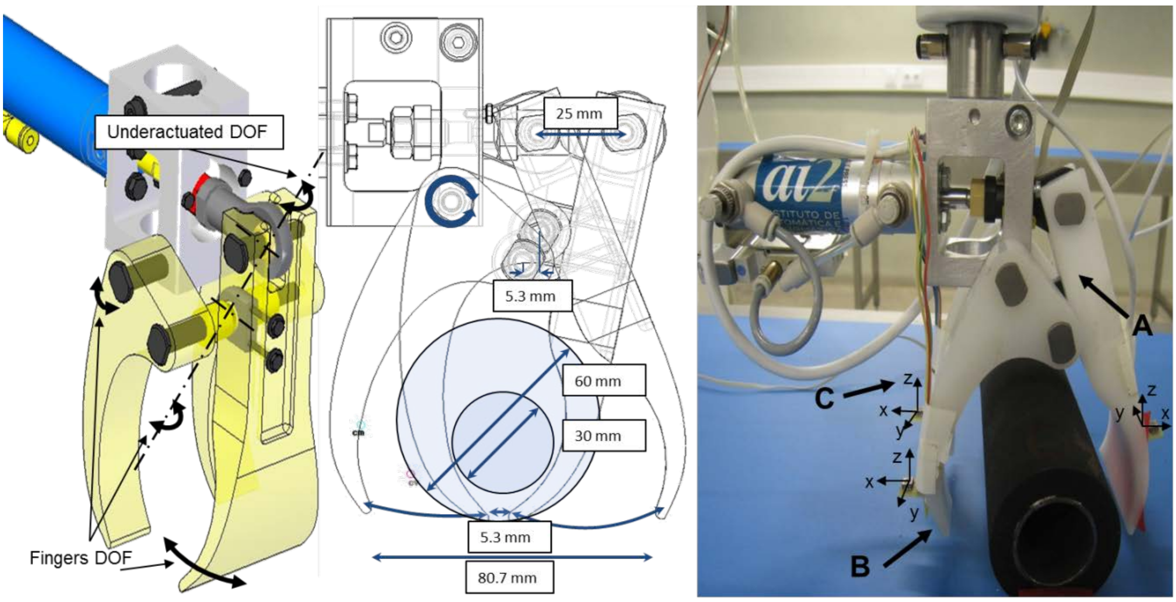

Figure 1. From left to right: gripper I with its axis configuration and degrees of freedom (DOF), gripper range specifications, and the location of accelerometers A, B and C.

Each finger gripper has a biaxial accelerometer, X and Y, attached to its rear side (Figure 1). ADXL278 accelerometers have a measurement range of +/- 50g and provide six analog signals, Ax, Ay, Bx, By, Cx, and Cy. They can also measure both dynamic acceleration (vibration) and static acceleration (gravity). These signals and digital electro-valve activation are collected by means of an A/D data acquisition unit USB NI-6210 module that sends the information to the computer. One purpose-built software application developed in LabVIEW was used to record decelerations and another one processed and analyzed them.

2.1. Gripper grasping phases

Accelerometer signals can be used to recognize the duration of the grasping action performed by the gripper. Figure 2 shows the accelerometer gripper response of finger B in direction X when gripper I grasps a wooden cylinder. The same figure illustrates three different phases of the decelerations, which occur in less than 0.2 seconds.

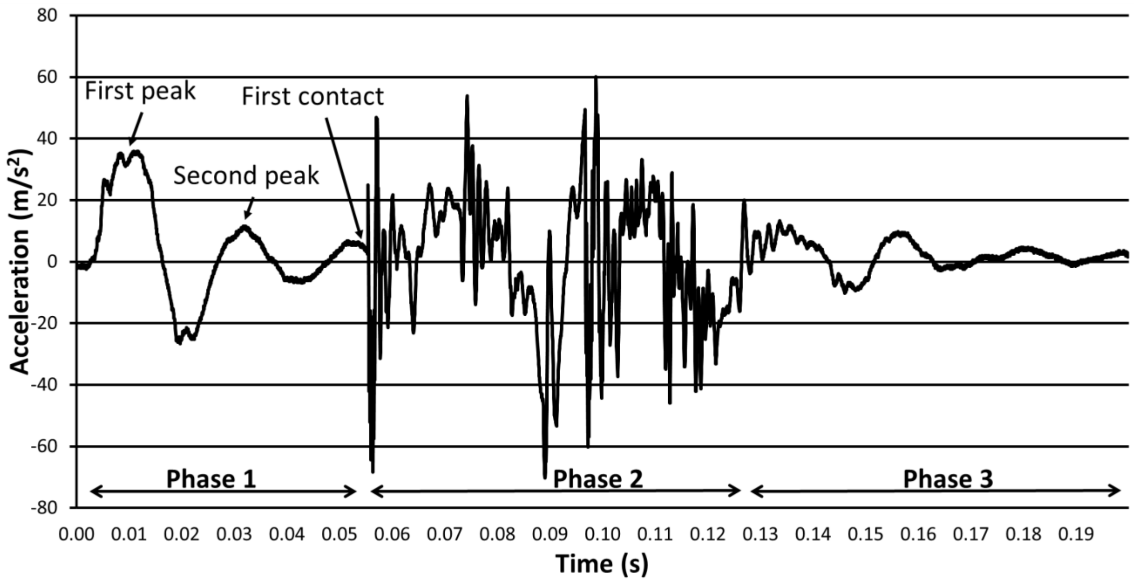

Figure 2. Finger B deceleration in direction X when gripper I grasps a wooden cylinder.

• Phase 1 or approximation phase. The gripper finger starts its movement and continues until it establishes contact. In Figure 2 this phase is approximately a sinusoidal underdamping acceleration signal. Flow meters control the speed of the pneumatic cylinder, and for this reason the acceleration fluctuates until the cylinder achieves the nominal speed.

• Phase 2. All the product finger impacts are collected until the final approaching and pushing motion, where there is no relative movement between product and gripper. During this phase the force between product and finger is smaller than when there is no relative motion. If the robot moves at high speed during this phase, the product could fall over or may be moved outside the tool center point of the gripper.

• Phase 3. Dynamic forces until a static equilibrium is found while product and gripper finger move together with an underdamping movement. The product is grasped with higher and more constant forces. The robot can move the gripper and product at a higher speed than during phase 2.

2.2. Gripper's finger position and force

The decelerations of the first phase of grasping can be used to track the position of the gripper fingers and to estimate the force of the gripper. The decelerations during the approximation phase, from the moment the gripper fingers start to move until the nominal speed is reached, will be more powerful if the pneumatic pressure in the actuator increases. During this phase the first and second acceleration peaks (Figure 3) are higher if the pneumatic pressure increases. The difference between the first and the second deceleration positive peak increases when the pneumatic pressure of the actuator varies from 1.5 to 4 bars. With an analysis of four samples in steps of 0.25 bars, the linear correlation between pneumatic pressure and the difference in the deceleration peaks has a coefficient of determination R^2 of 0.98. The gripper finger speed is adjusted through flow meters at the entrance of both pneumatic cylinder chambers. For this case, the gripper fingers reach a stable and approximately constant speed in 0.03 seconds (Figure 3) with a pneumatic pressure of 3 MPa; during this time the finger moves 8 mm.

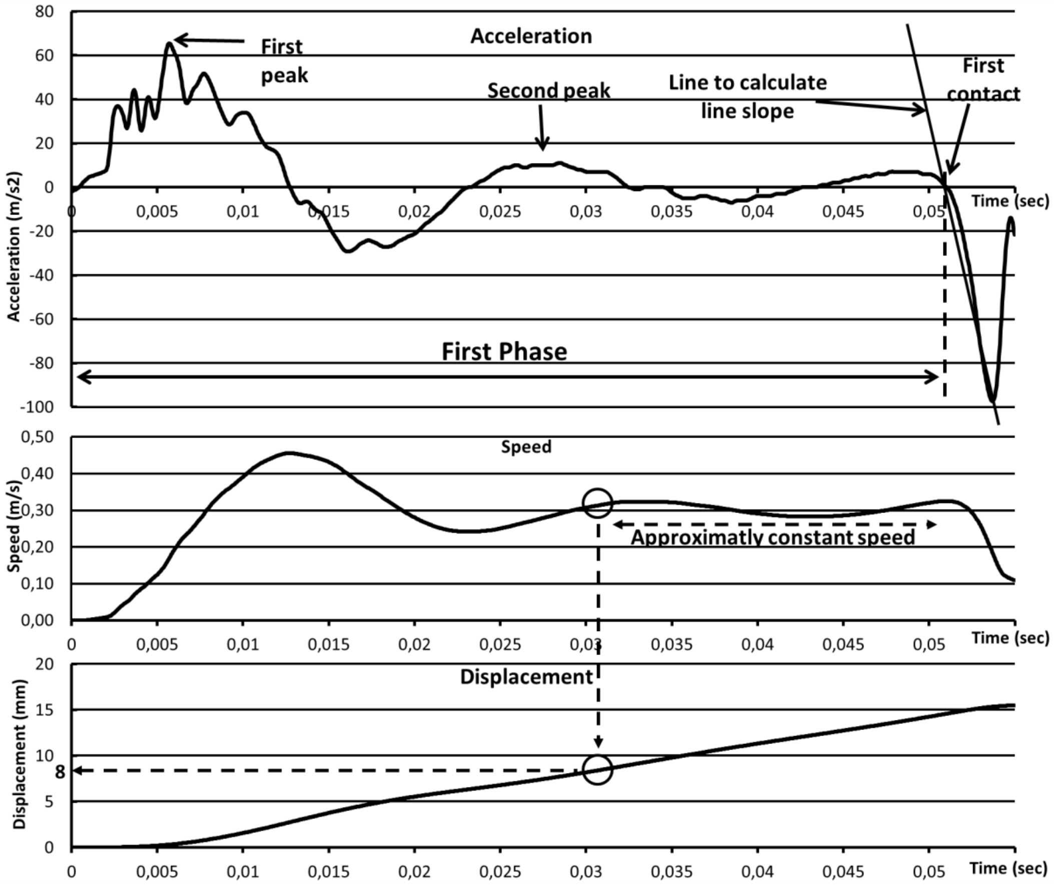

Figure 3. Analysis of the first phase of grasping. From top to bottom: gripper deceleration, speed and displacement for finger B while gripper I grasps a wooden cylinder.

2.3. Hardness estimation with accelerometers

The experiment was performed using gripper I and grasping five cylinders with a diameter of 50 mm from a fixed cradle, the process being repeated 40 times. The cylinders are covered with rubber with hardnesses of 20, 30, 40, 50 and 60 Shore A, and weights of 416, 435, 435, 447 and 457 g respectively.

Accelerometer signals are processed to obtain different parameters, which are then used to estimate the hardness of the cylinders grasped by gripper I. These parameters are extracted according to different methods.

a) Parameters extracted from the analysis of the signal during the time in which the fingers start to be in contact with the product until the product and gripper move together (Equations 1-4).

$$VA = \int_{t_0}^{t_1}(Ax^2 + Ay^2)dt \; ; (1)$$

$$VB = \int_{t_0}^{t_1}(Bx^2 + By^2)dt \; ; \; (2)$$

$$VC = \int_{t_0}^{t_1} (Cx^2 + Cy^2) dt \; ; \; (3)$$

$$Vtot = VA + VB + VC; \; (4)$$

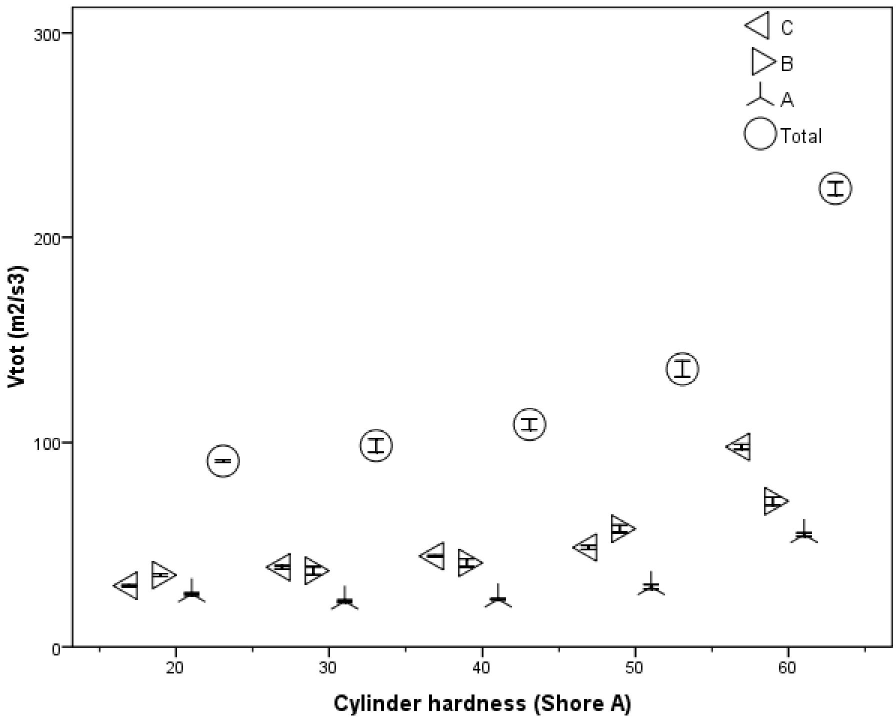

Figure 4. The evolution of Vtot, VA, VB and VC (Equation 4) when gripper I grasps cylinders with different hardnesses. Error bars denote the standard deviation over 40 samples.

The results in Figure 4 show an increase in Vtot, VB and VC for harder cylinders but not always for VA. If the speed of the fingers, before starting to be in contact with the cylinders, is approximately similar, then the hardness estimation with this method should be good regardless of the diameter of the cylinders grasped. With the adjustment of gripper I that was used, an approximately constant speed of the fingers is achieved if finger B moves 8 mm or more (Figure3).

b) The maximum decelerations achieved during the impact between finger and cylinder.

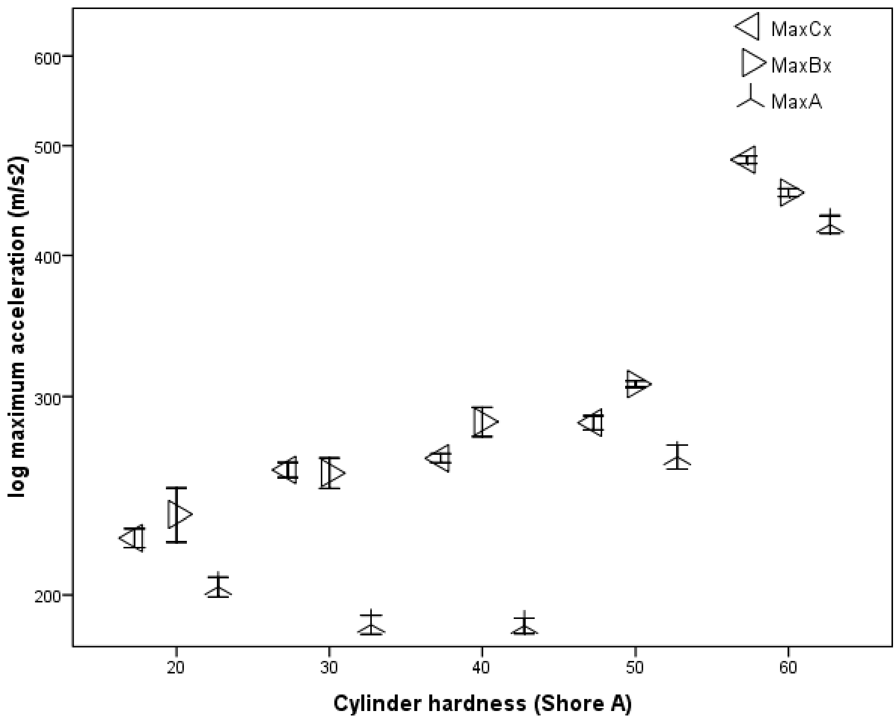

Figure 5. Maximum deceleration after the initial finger contact against the product for signals Bx, Cx and A versus different cylinders with distinct hardnesses. Error bars denote the standard deviation over 40 samples.

From the results in Figure 5, maximum deceleration signals for B and C are always bigger for harder products, while the signals for A are not always higher for harder products.

c) If the products that are grasped are hard, then the fingers of the gripper undergo a more violent deceleration than in the case of softer products. This is the severity of the decelerations after the initial impact, and can be extracted as the line slope of the first deceleration peak produced after the first contact between the finger and the cylinder (Figure 3).

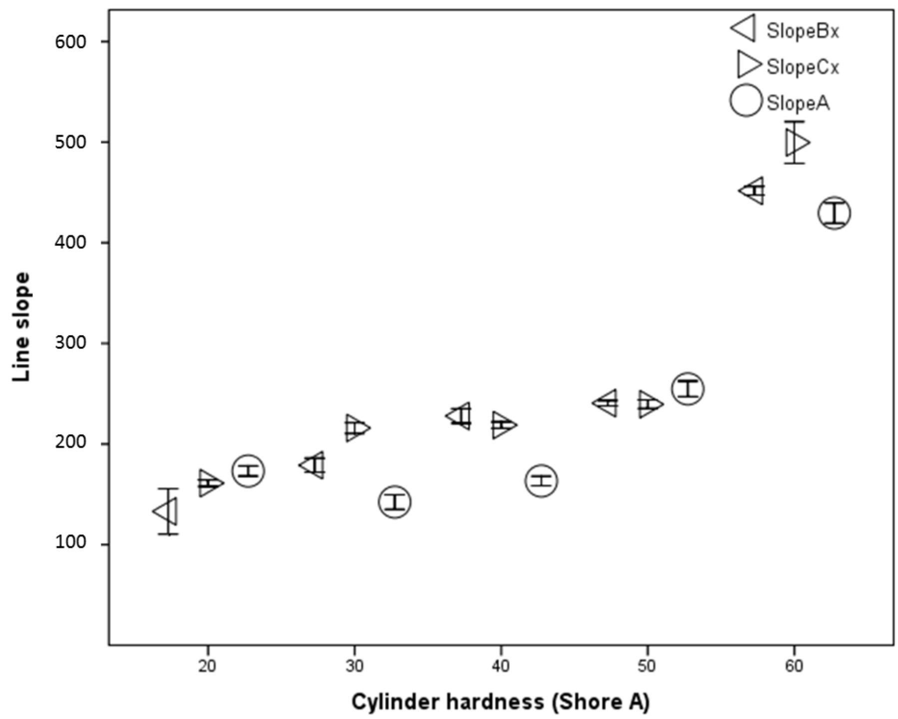

Figure 6. Line slopes of the first deceleration peak for Bx, Cx and A versus different cylinders with distinct hardnesses. Error bars denote the standard deviation over 40 samples.

In Figure 6 the line slopes for signals Bx and Cx are always capable of distinguishing between the different hardnesses, but this is not true for signal A. The results in Figures 4 to 6 were obtained when products are grasped from a fixed cradle and the relative position between gripper and cylinders is the same. The responses of these methods are different if the relative position between gripper and product varies. Figure 7 analyzes the Vtot parameter (Equation 4) versus the variation in product hardness when the relative position between the gripper and the cylinder change in direction X (Figure 1). With a fixed position between the gripper and the cylinder it is always possible to distinguish its hardness, but the results are different if the same product is grasped in different positions. This also happens if the cylinders are rotated around the Z axis.

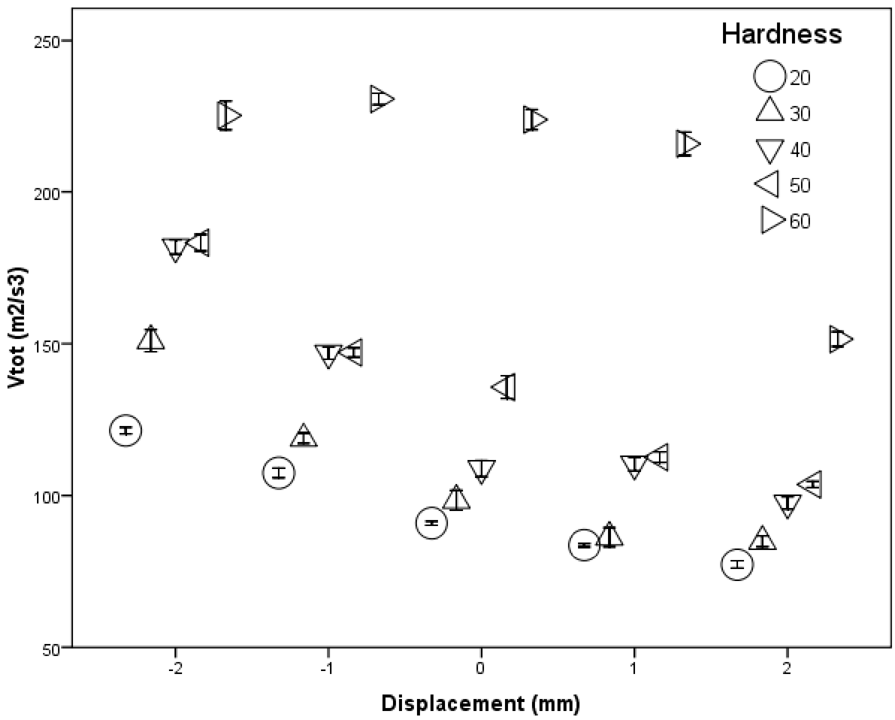

Figure7. Vtot recorded by accelerometers (Equation 4) while cylinders, with different hardnesses, are displaced in direction X. Error bars denote the standard deviation over 40 samples.

3. Embedded accelerometers in parallel grippers

The firmness of fruits and vegetables is related to their ripeness. Firmness is evaluated in horticulture by means of destructive methods like the Magness Taylor penetrometer. The industry has an interest in and an opportunity to develop robot grippers capable of handling and sorting fruits and vegetables by their firmness, without the need for destructive tests.

Estimation of the hardness by gripper I is clearly affected by the relative position of the product gripper and its use is restricted to products with cylindrical shapes. Gripper II (Figure 8, [35]) was developed for grasping eggplants and assessing their firmness regardless of the relative position between eggplant and gripper. The motion of the gripper fingers is underactuated, and they can rotate around a vertical axis and also around the pneumatic cylinder rod. The rotations improve the adaptation of the gripper fingers to grasp products with different shapes, like eggplants. One pneumatic cylinder moves finger A and the other pneumatic cylinder moves fingers B and C and a suction cup.

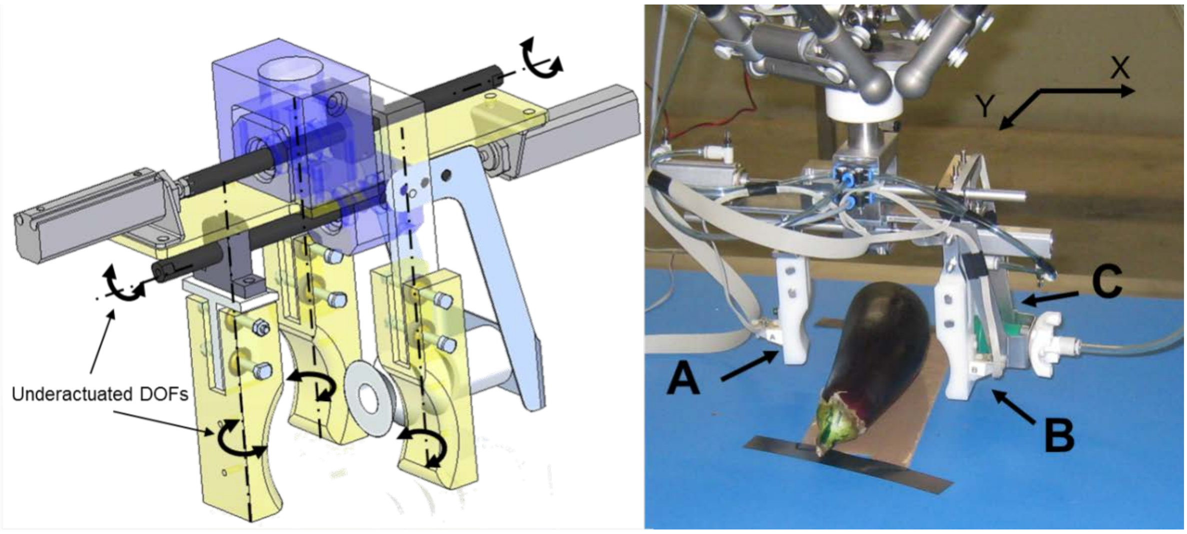

Figure 8. From left to right: gripper II, its axis configuration and degrees of freedom (DOF), location of accelerometers A, B and C.

The gripper grasps eggplants located on the conveyor belt. The gripper fingers rotate around their vertical axis until they are parallel to the surface of the eggplants. The robot moves the gripper up with the eggplant, activates the suction cup to maintain the eggplant attached to fingers B and C, and starts a loop that quickly opens and closes the gripper fingers five times. The gripper analyzes the decelerations of its fingers during the open/close loop when the product is not in contact with the conveyor and the surfaces of the eggplant and the fingers remain parallel to each other. This process reduces the noise in the deceleration signals because there are no interferences from the friction forces between the conveyor belt and the eggplant. The tactile sensing response is related to the area where the fingers are in contact with the eggplant and it is not influenced by the relative orientation between the gripper and the eggplant. To estimate the firmness of the eggplant, more time is needed than with the previous gripper. Eggplants received one impact when grasped from the conveyor belt and five more to assess their firmness. Despite the number of impacts, no damage was found in the eggplants.

With a forward stepwise multiple regression model (Figure 9) to estimate the slope of the line of the deformation force in the compression test and all the parameters extracted from the three accelerometers of the gripper, the model achieves an adjusted R^2=72.45. In this case the model was developed with 30 eggplants.

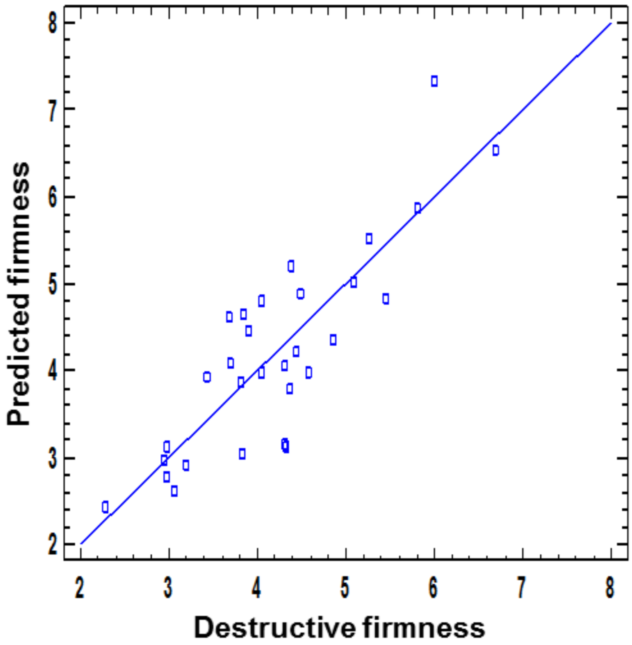

Figure 9. Firmness predicted by a multiple regression model of all the parameters obtained from the accelerometers of gripper II and the observed values from the destructive test of the eggplants.

This gripper is capable of grasping eggplants gently and assessing their firmness if the eggplants remain attached to fingers B and C by means of the suction cup. Assessment of the firmness of the eggplant can be estimated several times during the cycle loop. The shapes of the fingers are rigid and cannot always ensure a wide contact surface. Compared to gripper I, gripper II needs more time to assess the firmness of eggplants, but the process could be optimized if the eggplants were hit while the robot motion goes from pick to place.

3.1. Gripper improvement using jamming-based adaptation to product surface

Gripper III (Figure 10 [17]), which was built with a new finger A that is covered with a latex membrane filled with granular material, was constructed as an improvement on gripper II. The jamming transition of the granular material offers the possibility of changing the surface of finger A from fluid-like to solid-like. This shift is controlled by valve 3 (Figure 11), which controls the pneumatic pressure from positive to vacuum. Before eggplants are grasped, a positive pressure is exerted for 0.03 seconds inside the membrane of finger A, thereby ensuring a soft surface. This soft state is used during the grasping action and during the first impact of the open/close loop. The fluid-like state is soft enough to copy the shapes of the eggplants and to ensure a gentle grasp. A solid-like state is achieved when there is a vacuum inside the membrane of finger A, thus ensuring a hard parallel surface between eggplants and the membrane of finger A. This state is maintained during the cycle loop for sensing the firmness of eggplants.

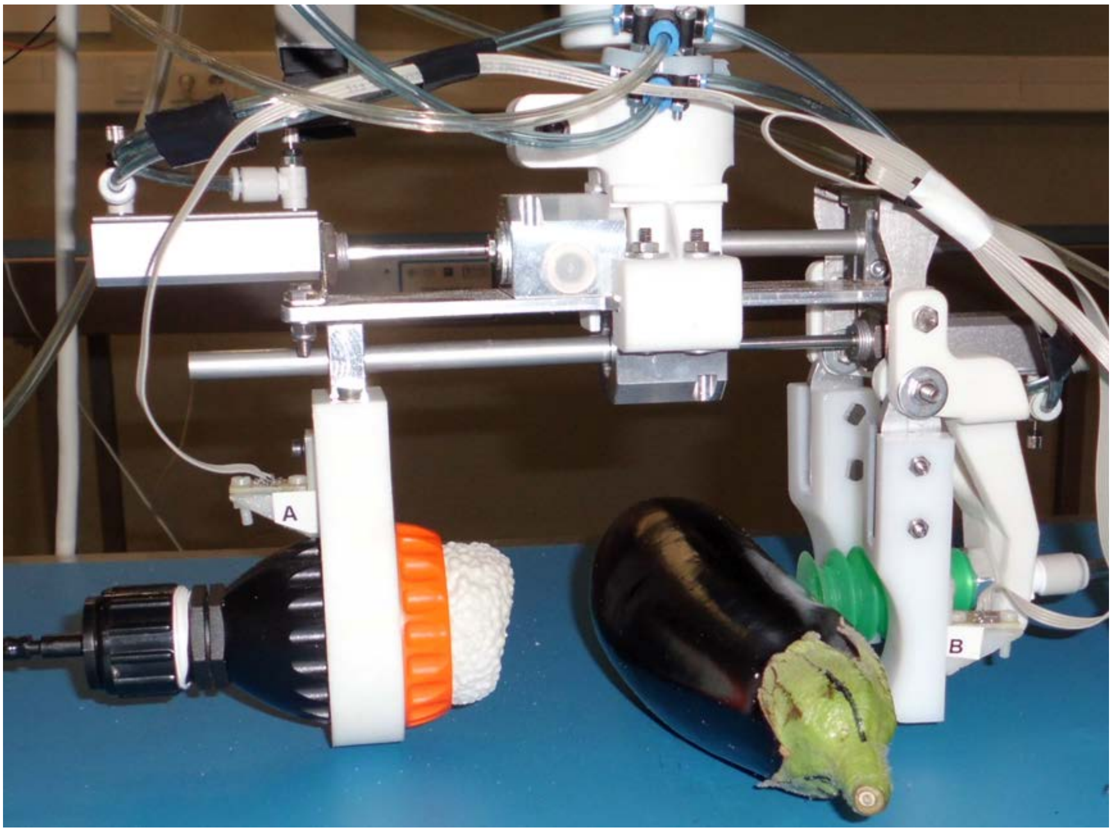

Figure 10. Gripper III with the new design of finger A.

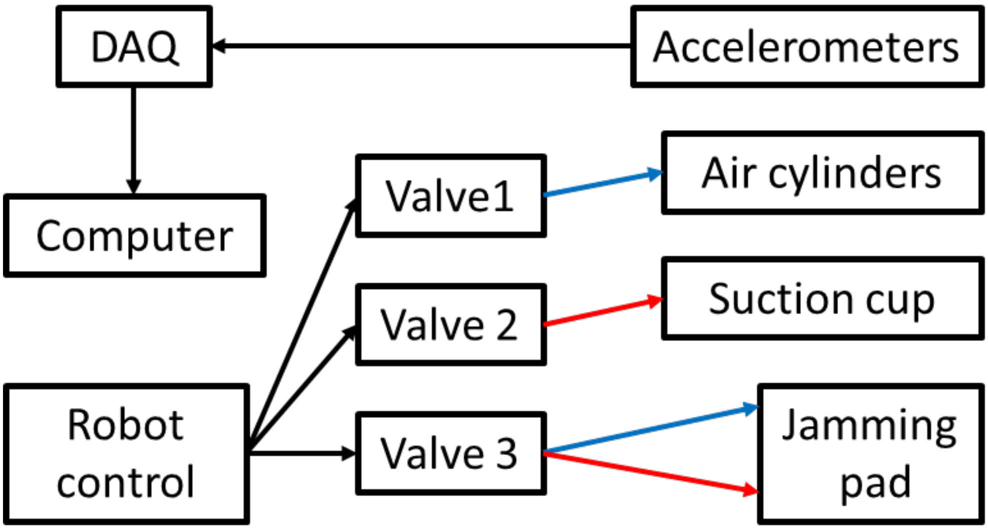

Figure 11. A diagram of the devices for controlling gripper III. Electrical connections are shown in black, positive air pressure in blue, and vacuum in red.

With gripper III it becomes possible to ensure a larger, more rigid contact area between eggplants and finger A. If the membrane of finger A adapts to the lower side of the eggplants, then the forces needed to lift the eggplants can be reduced. As happened with the previous gripper, fingers B and C adapt to the eggplant because they rotate freely around their vertical axis. With the same procedure as in the case of gripper II, gripper III can estimate the firmness of the eggplants with an R^2=76.00 (Figure 12). The prediction model that can be obtained with only the parameters extracted from the accelerometer on finger A is R^2=64.50, from finger B it is R^2=24.07, and from finger C it is R^2=33.58. In this case the model was developed with 234 eggplants.

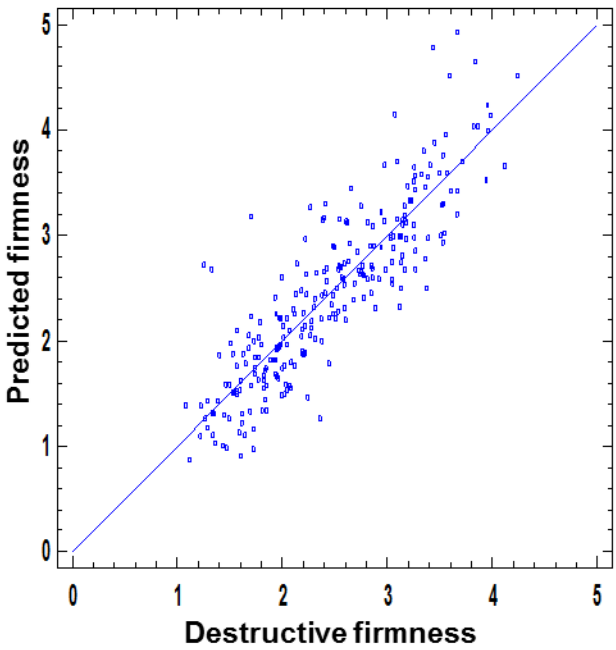

Figure 12. Firmness predicted with a multiple regression model of all the parameters obtained from the accelerometers of gripper III and the values observed from the destructive testing of the eggplants.

3.2. Gripper enhancement for firmness estimation and mango fruit test

Gripper III was tested with mangoes but some difficulties were encountered in the adaptation of fingers B and C because mango fruits have different shapes from eggplants ([36]). Gripper IV (Figure 13 [16]) was designed and manufactured for handling mangoes, and it estimates their firmness. The fingers of gripper III have parallel movements without any rotation around the pneumatic cylinder rod. The motion of the fingers is linked mechanically and hence the products are self-centering at the same relative gripper/product position. The configuration of gripper IV is similar to that of gripper III with three fingers. In gripper IV, fingers B and C are connected by ball joints and can rotate freely around their three rotations. The pad of finger A has the same membrane as the previous gripper.

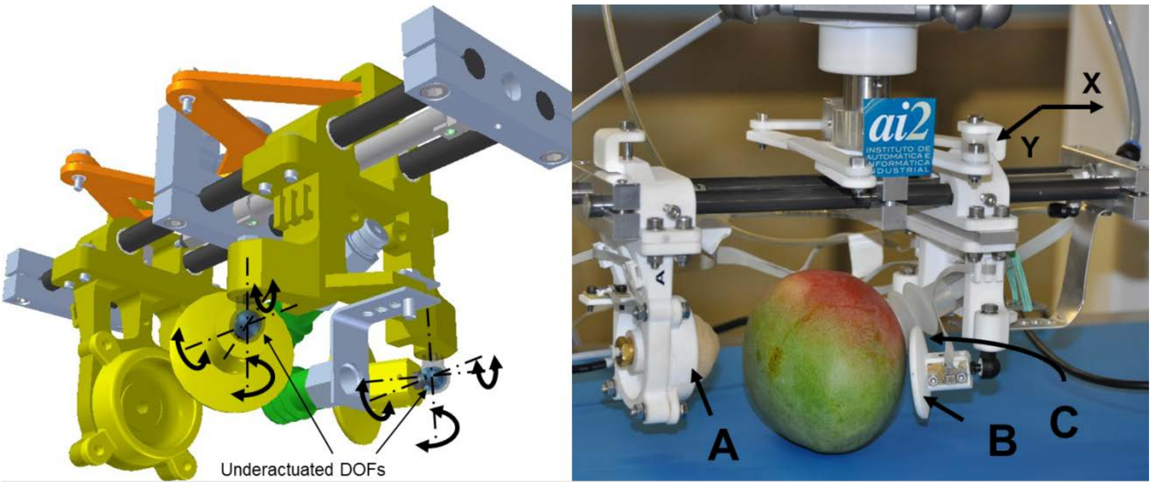

Figure 13. Gripper IV. On the left, the original CAD model with its linked bars mechanism and the underactuated degrees of freedom of the gripper fingers. On the right, the final model used during the experimental test.

In the first test of gripper IV, with the original setup (Figure 13, left), all the fingers are moved by the same pneumatic cylinder. With this configuration some difficulties are encountered when it comes to handling and sensing the firmness of mangoes. The pneumatic cylinder moves finger A directly, and a mechanism of linked bars transmits the motion to fingers B and C. Due to the kinematics of this mechanism, the deceleration signals are influenced by the dynamics of the articulated bars. In this case the decelerations of the fingers have noise from the gripper mechanism, which not only collects information about the impacts between fingers and mangoes, and hence it is more difficult to distinguish when mangoes are more or less firm. In order to mitigate those noises, fingers B and C are fixed and only finger A moves (Figure 13, right). This mechanical configuration reduces the noise. In the original design, with two suction cups, sometimes one of them does not adjust to the shape of the mangoes, thus producing vacuum leakage. The best results are obtained with only one suction cup that helps to lift the mangoes a little bit while keeping them in contact with fingers B and C.

Figure 14 shows the deceleration of the fingers of gripper IV while the fingers hit one mango. In this example the deceleration of finger A had two peaks due to rebounds during the impact. The second deceleration peak could sometimes be higher than the first one, such as the case in Figure 14. In those cases the severity of the deceleration after the first contact varies if the position of the highest peak varies. In order to improve this situation the signals are smoothed (Figure 15) until a signal with a single peak is obtained. With the smoothed signals it was possible to achieve a single peak for estimating the slopes of the line of the first deceleration peak (Figure 16) as the slope of the line between the maximum value and the value 80 samples earlier. Deceleration signals are sampled at 30 KHz.

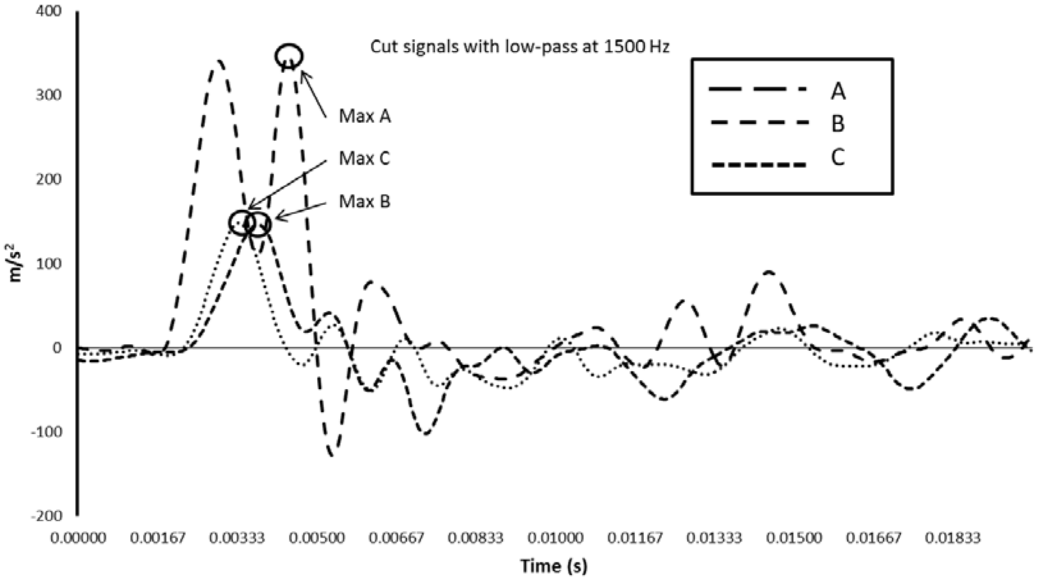

Figure 14. The decelerations of phase 2 of gripper IV during a mango gripping action.

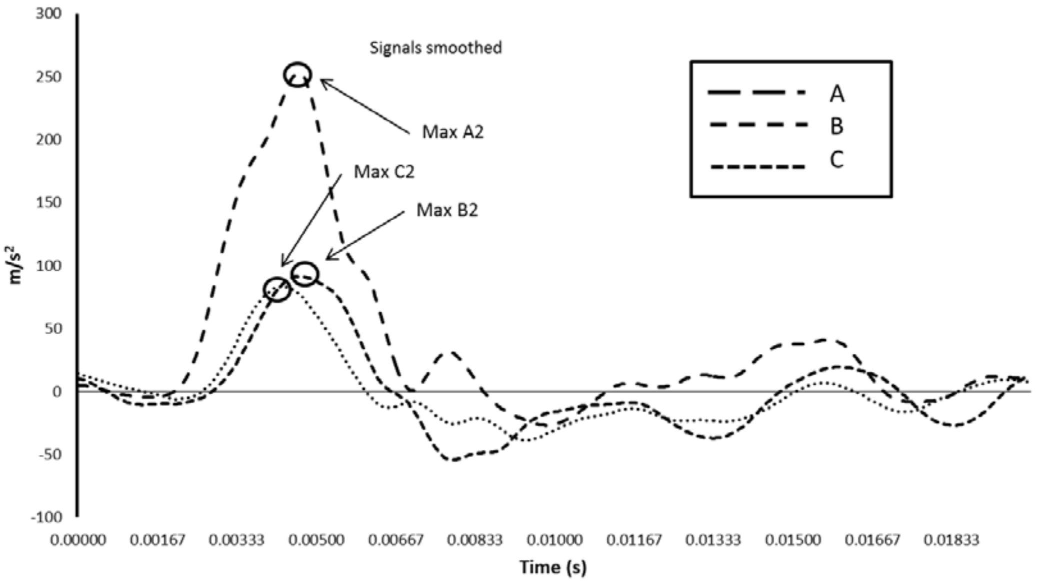

Figure 15. Smoothed decelerations of phase 2 of gripper IV during a mango gripping action.

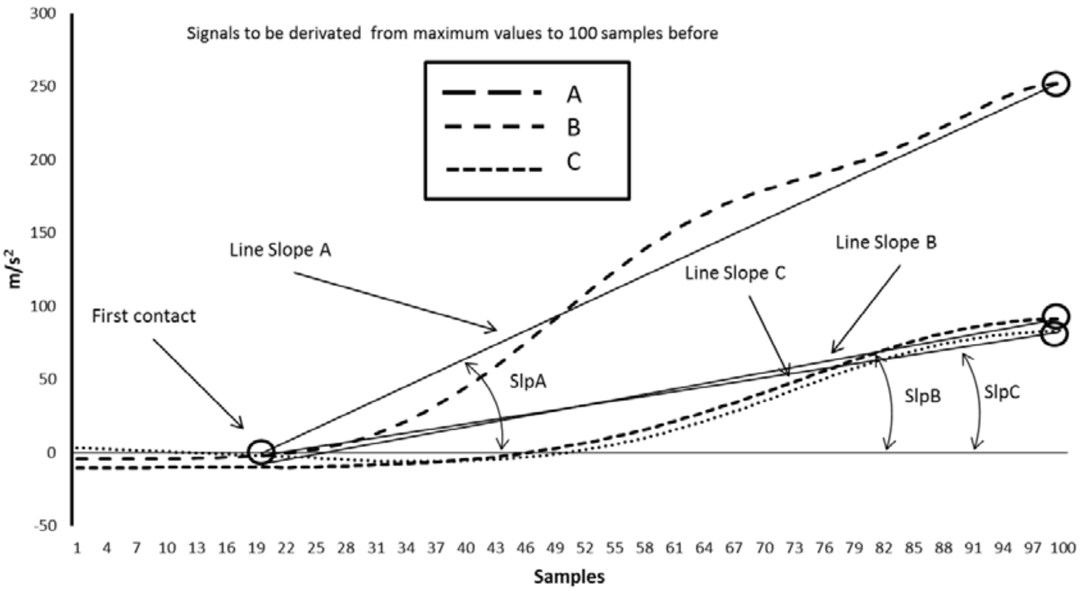

Figure 16. Line slopes of the decelerations of gripper IV after the first contact with a mango.

With the use of accelerometers it is difficult to define, with a robust algorithm, the exact point of the first finger/mango contact. Due to this difficulty, the algorithm could add some errors during the calculation of the line slope. The derivative function of the decelerations (Figure 17) represents the fluctuations in the line slopes. In these signals it is easy to compute the maximum values of the slopes of the lines, and the area is an estimation of the average of the slopes.

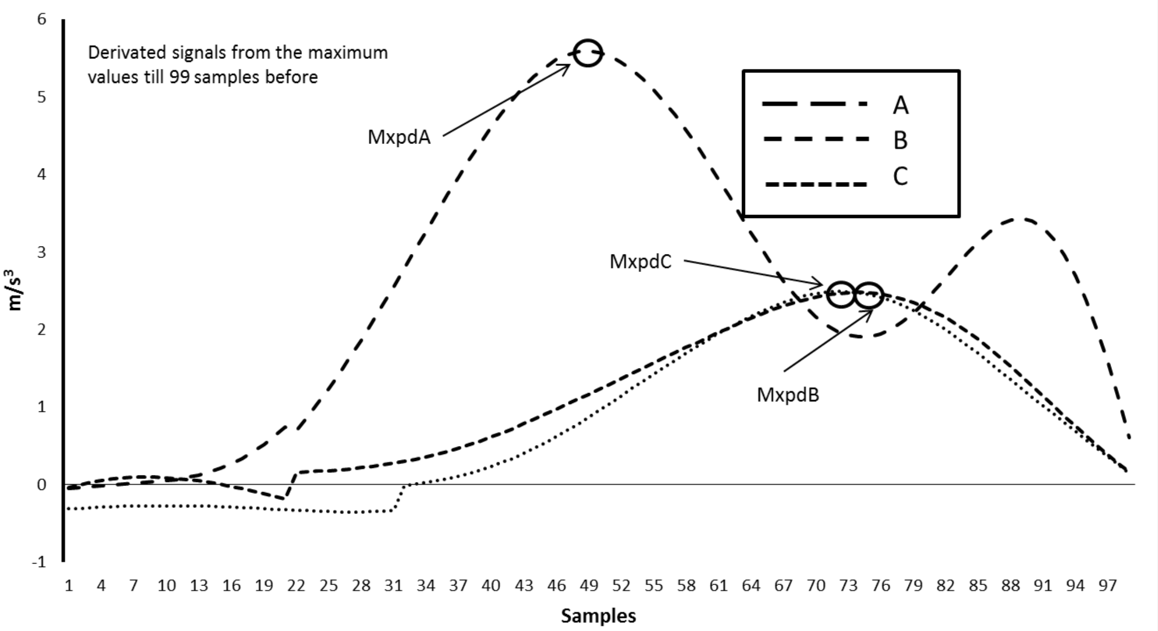

Figure 17. The derivative function of the decelerations during the first finger/mango contact.

In this trial the width of the mangoes ranges from 73 to 92 mm and the length from 113 to 141 mm. Following the same method as for the other grippers, the multiple regression model achieves an adjusted R^2=87.18. In this case the prediction model (Figure 18) that can be obtained with the use of the parameters extracted from the accelerometer of finger A is R^2=78.63, finger B: R^2=79.99, and finger C: R^2=52.23. In this case the model was developed with 140 mangoes.

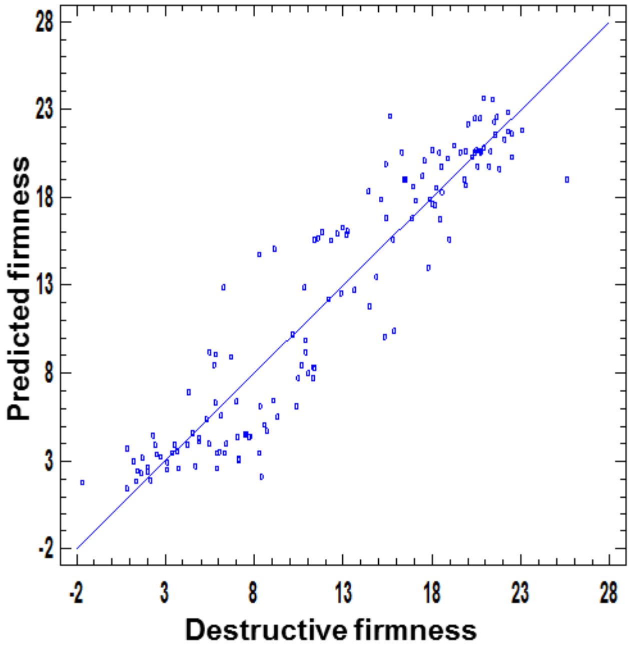

Figure 18. Firmness predicted with a multiple regression model of all the parameters obtained from the accelerometers of gripper IV and the values observed from the destructive test of the mangoes.

The results of the firmness estimation are fairly good for fingers A and B. The concave semispherical shape of those fingers adapts well to the mangoes. Even when fingers B and C do not move, the results are still good.

4. Results and discussion

This article shows and compares the design of four grippers developed for grasping and sensing the firmness or hardness of products dynamically by means of accelerometers attached to their fingers. The fingers of the grippers studied have both parallel and angular motion. With a parallel gripper motion it is possible to ensure the same grasp force regardless of the size of the products.

The motion of the fingers of gripper I is angular and it is capable of grasping cylinders from 30 to 60 mm in diameter. The gripper can grasp conical shapes because its finger A can rotate freely around its underactuated DOF, and it is capable of estimating the hardness of cylinders while gripping them. With this gripper the major issue for estimating the hardness of cylinders with accelerometers is the response variability when the relative position between gripper and product changes. The finger decelerations are influenced by the friction forces between the cylinders and conveyor belt or cradle and by the inertial effects when the product is grasped in different positions. In grippers developed at a later stage, this issue is solved by a new robot gripper process and the incorporation of a suction cup that keeps the product in contact with the fingers. Products are grasped from the conveyor belt but estimation of the firmness is carried out by hitting the products in the air while a suction cup holds the product in contact with some of the gripper fingers.

The motion of the fingers of gripper II is parallel, each finger having one extra underactuated DOF, and it was designed for grasping eggplants. The estimation of the firmness of eggplants achieves an R^2 of 72.45. With this gripper the relative position between eggplants and the gripper tool center point could be displaced during the robot movements. This is because the product can rotate around the pneumatic cylinder rods and the motion of the fingers is not mechanically linked. With the robot gripper process it is possible to estimate the firmness of products several times during a pick-and-place process, each estimation of firmness taking 0.25 seconds to perform.

Gripper III is an improvement on gripper II. For example, it adapts better to eggplants because finger A has jamming fluid inside it, and the tactile sensing for estimating eggplant firmness is improved, R^2=76.00. Finger A, with its jamming transition, needs time to ensure an adequate adaptation to the eggplants and to change from fluid-like to solid-like states. Firmness estimation is affected by the residual shearing forces between the membrane of finger A and eggplants. During the time that finger A adapts to the shapes of the eggplants, the membrane deflates while it is in contact with the eggplant and some residual shearing forces are maintained between the membrane and the eggplants. This affects the estimation of the firmness during the first open/close cycle process.

The finger motion of gripper IV is parallel and it is capable of grasping and sensing the firmness of mangoes. Gripper IV achieves a better estimation of firmness than grippers II and III: R^2=87.18. The most significant differences between the two designs are: (i) gripper IV uses only one actuator, which does not move the product; (ii) the mechanical design of gripper IV is simpler than the others; and (iii) fingers B and C adapt better to the products because they are more underactuated, with three underactuated DOFs instead of one. In gripper IV, the estimation of the firmness of fingers A or B is similar, which means that finger A could be simplified using the same mechanical joint as finger B without affecting the results. Finger B is fixed to the gripper chassis and achieves similar results to finger A, which is linked to the rod of the pneumatic cylinder. Assessment of the firmness of mangoes can be performed in a gripper with a finger that is not linked to the pneumatic actuator.

The kinematics of grippers II, III and IV always maintain the relation of the forces between the piston and the fingers constant. With the designs of grippers II, III and IV, if during the open period finger A does not achieve the maximum open position then, during the close period, finger A will have the same speed and this speed is regardless of the size and the shape of the product.

The method developed to assess the firmness of eggplants and mangoes with accelerometers in robot grippers requires the use of suction cups and hence is limited to products capable of being handled with such cups.

5. Conclusions

The configuration of the degrees of freedom of the gripper fingers and their shapes is critical to ensure suitable manipulation of irregular products like eggplants or mangoes. The best results are obtained when the fingers increase their degrees of freedom.

With an adequate pneumatic gripper and accelerometers attached to its fingers it becomes possible to assess the firmness of eggplants and mangoes or the hardness of the cylinders, to analyze the grasping process in detail, to monitor the position of the fingers, and to estimate the pneumatic pressure.

The tactile sensing capabilities of accelerometers are influenced by interferences and noise produced during the grasping process. These interferences and noise disturb the tactile sensing responses of the accelerometer. The most significant sources of noise are from the friction forces that arise between the product and conveyor or cradle and the mechanical configuration of the gripper. The robot gripper operation and the configuration of the mechanical gripper should be designed to reduce the potential disturbances of the decelerations. Different finger configurations have been tested to adapt the fingers to the surfaces of irregular products. The jamming transition of a granular fluid located on the pad of the fingers, and fingers with three free rotations yield the best performance for adapting the gripper fingers to irregular shapes.

Better performance of the inertial sensor is achieved when the gripper fingers increase their adaptability to the shapes of the products grasped and better estimation of the hardness is achieved when the mechanical configuration of the gripper is simpler.

The software for processing the signals needs to be adjusted to each gripper configuration and the results exert an influence if the gripper adjustments change, because the decelerations of the gripper fingers will be affected.

Accelerometers as tactile sensors for robot grippers have a fast time response, a low cost, and are easy to integrate into industrial robot grippers by embedding accelerometers inside gripper fingers. Accelerometers can be used with different gripper forces, gripper finger speeds, and product properties because they are not in direct contact with the product and are therefore free of the risk of suffering from wear and tear.

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