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Review. Technologies for robot grippers in pick and place operations for fresh fruits and vegetables

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Abstract

Robotics has been introduced in industry to replace humans in arduous and repetitive tasks, to reduce labour costs and to ensure consistent quality control of the process. Nowadays robots are cheaper, can work in hostile and dirty environments and they are able to manipulate products at high speed. High speed and reliability and low robot gripper costs are necessary for a profitable pick and place (P&P) process. However, current grippers are not able to handle these products properly because they have uneven shapes, are flexible and irregular, have different textures and are very sensitive to being damaged. This review brings together the requirements and phases used in the process of manipulation, summarises and analyses of the existing, potential and emerging techniques and their possibilities for the manipulation of fresh horticultural products from a detailed study of their characteristics. It considers the difficulties and the lack of engineers to conceive of and implement solutions. Contact grippers with underactuated mechanism and suction cups could be a promising approach for the manipulation of fresh fruit and vegetables. Ongoing study is still necessary on the characteristics and handling requirements of fresh fruit and vegetables in order to design grippers which are suitable for correct manipulation, at high speed, in profitable P&P processes for industrial applications.

Additional key words: food manipulation; horticulture grasp; postharvest science and technology; robotic product handling.

Resumen

Revisión. Tecnologías en garras robotizadas para operaciones de coger y dejar productos hortofrutícolas frescos

La robótica ha sido introducida en la industria para reemplazar a los humanos en tareas arduas y repetitivas, reducir mano de obra y para asegurar una calidad constante de los procesos. Actualmente los robos son más baratos, capaces de manipular productos a alta velocidad y de trabajar en ambientes hostiles. Por tanto, los robots pueden trabajar en operaciones de "coger y dejar" (*pick & place*, P&P) con frutas y hortalizas frescas. Para un proceso rentable de P&P, son necesarias una alta velocidad y fiabilidad, así como un bajo coste de los sistemas de agarre. Este artículo de revisión recopila las necesidades y fases empleadas en el proceso de manipulación, reuniendo y analizando las técnicas existentes, potenciales y emergentes y sus posibilidades de aplicación para la manipulación de productos hortofrutícolas frescos a partir del estudio detallado de sus características. Considera las dificultades y la falta de ingenieros para concebir e implementar soluciones. Los autores proponen las alternativas más prometedoras para acometer este difícil problema y consideran la necesidad de seguir estudiando las características de frutas y vegetales frescos y las necesidades de manipulación. Las garras de contacto con mecanismos infra-actuados y ventosas o agarrar el producto sin contacto pueden ser las alternativas más prometedoras para manipular frutas y vegetales frescos. Es necesario continuar estudiando las características de las frutas y vegetales frescos y las necesidades de manipulación para diseñar garras correctas que puedan trabajar a alta velocidad, haciendo rentable un proceso de P&P industrial.

Palabras clave adicionales: ciencia y tecnología poscosecha; manipulación alimentaria; manipulación hortofrutícola; manipulación robotizada de productos.

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Abbreviations used: DOF (degree of freedom); P&P (pick and place).

Introduction

According to a recent report at a European level (Hamman, 2007), the food industry, with 3.8 million people employed in 2005, is the largest sub-sector within manufacturing in the European Union (EU), accounting for 14% of industrial production, ahead of the automobile and chemical subsectors. Automation and robotics are already present in some operations for many food industries (Ruiz-Altisent *et al.*, 2010). Automated systems are able to handle a great amount of information compared to conventional machines. However, it is necessary to understand the diversity and complexity of the biological products involved.

New regulations imposed by the EU and the US Administration to track food products across the supply chain are forcing companies to invest in new automated approaches. These solutions facilitate quality control in production lines, better process efficiency with more productivity, lower manufacturing costs with higher profit margins, and also help to achieve improved presentation as customers request. Food quality and safety are central issues in food economics today (Grunert, 2005). The high labour costs in developed countries make cost-cutting inevitable to remain competitive production. The growth in products packaged for the market, the increasingly strict hygiene regulations, the need to reduce risks at work, cut costs, and control product quality are all calling for the development of technologies that enable robots to be used for these tasks. In fact, robotics has a great opportunity in this industry and in particular for Pick & Place (P&P) operations (Wilson, 2010). But the physical and physiological properties of fresh fruit and vegetables and the need to avoid damaging them, make it necessary to seek flexible handling solutions for a wide range of products.

There has been some recent progress in introducing robots into food handling (Erzincanli and Sharp, 1997; Wallin, 1997; Chua *et al.*, 2003), but there are no clear advances for robot grippers adapting properly to handling fresh fruit and vegetables in P&P processes. This article introduces and reviews new technologies and approaches that can help to design robot grippers for P&P operations in fresh fruit and vegetables.

The manipulation process

Handling objects is one of the necessities of any manufacturing automation. Profitable robotic P&P facilities must have low cycle times per product. The gripper characteristics, the robot features and the facility layout design, must all be considered to get an adequate approach to the design of any manipulation process. Figure 1 shows a flow chart process with all the elements that influence the design of a robotic manipulation cell, which are the phases and the features that must be optimised in order to achieve lower cycle times (Bloss, 2006).

In P&P operations, grippers must have fast grip actions with quick and short movements, including fast operations to grasp the product in a stable way, and must facilitate the releasing operation to place the product.

P&P robot grippers in horticulture applications for fresh fruit and vegetable manipulation have to fulfil some special requirements such as high speed activation, adaptation to a variety of shapes, maximum adherence and minimal pressure, no damage to the product, low maintenance, high reliability, low weight, be approved for contact with foodstuffs, low energy consumption, required positional precision for both gripping and releasing of the product, ease of cleaning, easy and fast ejection of the product (important for products of low weight).

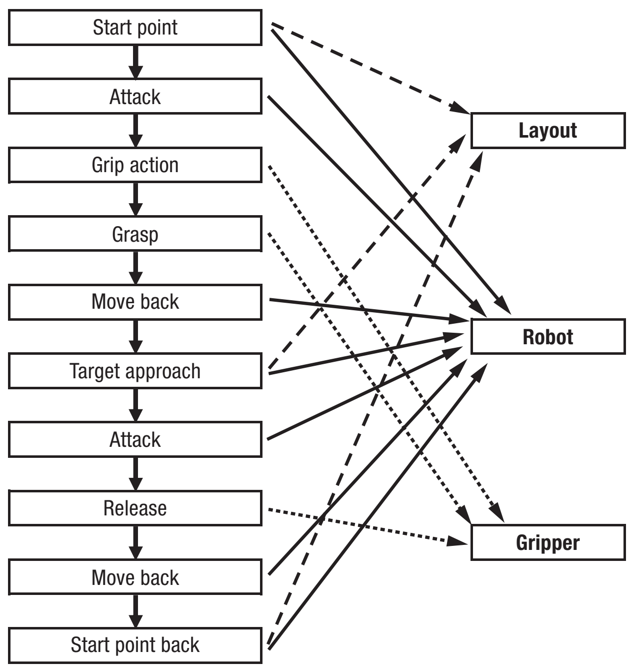

Figure 1. Flow chart process of a P&P operation (left), main areas of a robotic cell (right) and arrows that represent working relationships.

A low cycle time per product can be reached with a multi-pick process, but this approach will increase gripper complexity and the tool can be very heavy. Nevertheless, if the quantity of products to be handled per machine-cycle decreases, robot speed should increase to maintain good throughput. Then the load will be transported at higher accelerations, which is only possible when the gripper is light.

Robots with an adequate end-effector can transport, grip and orientate products (up to six DOFs). They are also re-programmable, have high repeatability, can work in hostile environments, etc. In the food sector, the robot has to comply with special needs: hygienic design (ANSI DIN EN 1672-2), easy cleaning, ingress protection of at least 65, and resistance to corrosion. To achieve a fast return on the investment, a high handling speed is necessary.

Parallel kinematic robots, also known as Delta robots, are the ones that adapt best to these needs for high acceleration with a low load (Brantmark and Hemmingson, 2001). In recent years there has been a significant proliferation of this kind of robot on the market, especially for food product handling. For low loads and limited work-areas, these robots are the best solutions. On the other hand, articulated or anthropomorphic robot-arms seem more adequate for higher loads and bigger work-areas, possibly using multi-pick grippers to reduce cycle times. With these features, both solutions fit the requirements of postharvest applications with fresh fruit and vegetables very well.

A suitable cell layout enables necessary movements to be reduced, thereby reducing the global cycle time. The design of a compact cell is a critical issue and only possible when the design considers how to improve the size of the global system.

In the most demanding P&P applications, robots need computer vision to recognise product shape and orientation, and also need conveyor tracking systems in order to allow manipulation during product motion on the conveyor track. Moreover, computer vision can provide more information to classify every product.

The final solution is a compromise between all the features, taking into account how this system involving the layout, the robot and the gripper works as a whole. The cell design must be integrated into the choice of these three features. To achieve better efficiency, it is essential to reduce the constraints in product positioning, thereby aiding operational handling capability. The use of robotic cells designed in this way enables productivity to be increased, monitoring and control of production improved, as well as an increase in flexibility compared to transfer lines.

There are numerous techniques for the manipulation of objects to reach the desired end position. The manipulation process can be divided into four possible phases: i) gripping, grasp or start of contact; ii) positioning, the object is moved from one point to another with a movement defined by three Cartesian axes; iii) orienting, object is orientated by three rotations related to Cartesian axes; and iv) placing, release or loss of the contact.

Some simple manipulation techniques do not require the use of every phase while the most complex techniques will need all of them. The complexity of the manipulation mechanism depends on the number of phases involved. In general, the achievement of a specific orientation will be more difficult, as the number of degrees of freedom (DOFs) that need to be set is increased.

The idea of manipulating without grasping is only possible in simple cases. A conveyor belt or a tube with fluid may provide not only the necessary transport but also the desired handling.

Manipulation processes need the object to be located with a given accuracy. The handling system must provide adequate precision and repeatability. When error margins are very low, the mechanical complexity of the whole system will be very high.

In P&P operations it is essential to know and analyse the needs undentified in order to handle the object. Aspects such as the accessibility of the product, the product orientation, the maximum acceleration that the product can resist, the available pneumatic or electrical supply, the protection against collisions, overloads or misalignments are essential to achieve proper integration of the gripper into the robot.

Product manipulation and physical properties of horticultural products

Automation is already present in some fruit and vegetable packinghouse operations: palletizing, packing, grading and sorting, and quality assessment [Fomesa (Valencia, Spain, www.fomesa.es), Serfruit (Náquera, Spain, www.serfruit.com), Roda-Maf (Alzira, Spain, www.roda-maf.com), Sinclair (Fresno, United States, www.sinclair-intl.com), Greefa (Tricht, Holland, www.greefa.nl), Sacmiibérica (Castellón, Spain, www.sacmiiberica.com)]. According to Kondos' (2010) review, operations in grading systems have become highly automated over the last ten years with the use of technologies such as near-infrared computer vision and robotics. There has also been progress in automating packing operations. However, robotic applications for standard packs of horticultural products are relatively easy compared with handling individual fragile and heterogeous horticultural products (Maldonado, 2010). Robotics has limitations in P&P operations due to the difficulty in achieving gripper solutions capable of manipulating fragile and heterogeneous fresh fruit and vegetables.

Sarig (1993) reviewed state-of-the-art of robotics in harvesting, pointing out the necessities to optimize R&D work required for the realization of robotic harvesting. Achievements in fruit and vegetable handling have been found in picking harvesting systems for products such as: strawberries (Hayashi *et al.*, 2010), cucumbers (Van Henten *et al.*, 2009), tomatoes (Monta *et al.*, 1998a,b; Ceccarelli *et al.,* 2000), aubergines (Hayashi *et al.*, 2002), apples (Setiawan *et al.*, 2004), chicories (Foglia and Reina, 2006), and oranges (Muscato *et al.*, 2005).

Since the study of the physical properties of grain related to combine harvesters started, researchers have continued testing the physical properties of agricultural products related to harvest and postharvest equipment (Morrow and Mohsenin, 1968; Bachmann and Earles, 2000).

Fresh fruit and vegetables are products of uneven shape and size. There is great wide variety between different products from the same field or plant, and even within the same piece (Kader, 1983).

Horticultural products are susceptible to enzymatic and microbiological changes, and their tissue cells breathe (Studman, 2001). They are affected by temperature, humidity and gas exchange.

Fresh fruit and vegetables have viscoelastic behaviour, which can be described by the Maxwell or Kelvin-Voight models (Sharma and Mohsenin, 1970; Peleg and Calzada, 1976; Lichtensteiger *et al*., 1988). The Maxwell model is based on tension relaxation behaviour. The Kelvin-Voight model is based on reversible viscoplastic deformation behaviour.

Hertz contact analysis has been applied to study fruit contact areas related to fruit bruising (Mercado-Flores *et al.*, 2005). However, this model has some limitations due the assumptions made in its derivation, especially for materials as complex as fruit flesh (Lewis *et al*, 2008). Different approaches have been developed to study and simulate fruit bruising. Bruise prediction models based on discrete element methods have been used to simulate bruise damage during fruit transportation and handling (Van Zeebroeck, 2005; Van Zeebroeck *et al.,* 2006b, 2007). A bruise prediction model connects the impact characteristics (drop height and peak contact force) with bruise damage, taking into consideration some fruit factors (temperature, ripeness, etc.) that determine sensitivity to bruising.

In automatic horticulture processes, product damage depends on the aggressiveness of harvest and postharvest machinery and on sensitivity to bruising. Fruit sensitivity is related to its physical properties and environmental conditions that determine the physical properties changing susceptibility (Menessatti and Paglia, 2001; Bielza *et al*., 2003). Many studies have been undertaken to evaluate the effect of the physical properties of fruit on susceptibility to bruising [potatoes (Peterson and Hall, 1975; Bajema *et al.*, 1998), apples and pears (García *et al.*, 1995), peaches (Brusewitz and Bartsch, 1989) and tomatoes (Allende *et al.*, 2004)].

The use of impact and pressure electronic spheres allows an estimation of the aggressiveness of harvest and postharvest machinery (Herold *et al*., 1996; Barreiro *et al*., 1997; García-Ramos *et al*., 2004; Fischer *et al*., 2009). Other approaches to the problem have been developed such as Geyer *et al*. (2006), who implanted into perishable fruits a miniaturized impact-detecting device consisting of a data transmitting part to receive the data in real-time.

For the horticulture sector, P&P operation is the most difficult one due to the lack of specific designs for robot gripping systems.

Some attempts have been made to design special grippers for non-rigid food products (Chua *et al*., 2003). Saadat and Nan (2002) classified the industrial applications for handling flexible products into three areas according to the product shape: linear, flat or three-dimensional. Within the classification, there is a section for handling in the food industry. Stone and Brett (2002) refer to possible manipulation by means of flexible fingers which on inflating adapt to the shape of the products. Seliger and Stephan (1998) classified the manipulation methods into four groups: mechanical, pneumatic, adhesive, and electrostatic. Seliger *et al.* (2000) devised an extended classification for flexible objects. Other studies combine grasping systems with suction cups for harvesting or use “scoop up” systems.

According to these considerations, the manipulation problem can be approached with one or more strategies.

The manipulation strategy is the base or starting point for the definition of the approach to handling an object. For example, manipulation strategies can be based on air, on contact or on intrusion. Once the strategy has been selected, a handling method should be selected. The set of strategies and methods must satisfy the requirements created by gripping, positioning, orienting and placing. Table 1 shows gripper handling capabilities according to strategies and methods. It also gives an overview of gripper damage types: bruising, tearing, breaking and deformation that could be produced in horticulture P&P processes. This evaluation is a general overview, but a specific gripper can produce different damage for a given product. A manipulation tool can be combined with several strategies and methods to produce efficient grasping systems for very complex products, or when its properties do not allow simple manipulation systems.

Manipulation strategies

Strategies based on air

One of the most commonly used methods of robot gripping is based on suction cups. The suction created enables forces to be transmitted to the product due to a pressure difference so that it can be manipulated. In industrial factories, a vacuum can be produced by different kinds of pumps: volumetric ones with high pressure and a low flow rate, centrifugal ones with low pressure and a high flow rate, or by the Venturi effect. Zhu *et al.* (2006) propose a new vibrating suction method.

The features of the product must allow for the creation of a vacuum. Therefore, the suction cup must close down over it correctly and the product must have low porosity. Mantriota (2007a) provides studies on the capabilities of suction cups according to the pressure generated and the kind of force applied. Mantriota (2007b) also analyses the case of using several suction cups. This approach is usually applied when a single suction cup does not create enough force. Table 2 shows the advantages and drawbacks of using air for a robotic P&P of fruit and vegetables.

One of the strongest advantages of these systems is the ease of combining them with other gripping mechanisms. Monta *et al.* (1998a,b) use a gripper to pick tomatoes combined with a parallel-jaw-type gripper equipped with a suction cup, but the stalk is detached directly from the tomato. Van Henten *et al.* (2003) found a solution for the robotic picking of cucumbers. His gripper combines suc-

Table 1. Classification of manipulation strategies and methods

Strategy	Method		Handling ability				Damage type			
			Gripping	Positioning	Orienting	Placing	Bruise	Tear	Break	Deformation
Air	Vacuum	Suction cups	Yes	No	No	Yes	Low	Low	Low	Low
		Pipes	Low	Yes	No	Yes	Yes	Yes	Low	Low
	Pressure	Bernoulli	Yes (no contact)	Low	No	Yes	No	Yes	Low	Low
		Blow	No	Yes	Low	Yes	No	No	Low	No
Contact	Gripper	Electric	Yes	No	Yes	Yes	Low	Low	Low	Low
		Pneumatic	Yes	No	Yes	Yes	Low	Low	Low	Low
		Hydraulic	Yes	No	Yes	Yes	Yes	Low	Yes	Yes
		Rubber	Yes	No	No	Yes	No	Low	No	Low
		Robot hands	Yes	No	Yes	Yes	Low	Low	No	No
	Multibody mechanism		Yes	No	Low	Yes	Low	Low	No	Low
Ingressive	Needles		Yes	No	No	Yes	Yes	No	Yes	No
Fluid	Rheological change		Yes	No	Low	Yes	Low	Low	No	Yes
Product properties	Gravity		No	Yes	Low	Yes	Yes	Low	Yes	Yes
	Piling up, pushing		No	Yes	Low	Yes	Yes	Low	Low	Yes
	Dynamic		No	Yes	Low	Yes	Yes	Low	Yes	Yes
	Scooping up		No	Yes	Low	Yes	Low	Yes	No	No
	Vibration		No	Yes	Low	Yes	Yes	Yes	No	No

Table 2. Advantages and drawbacks of using air in a gripper for a P&P process in fruit and vegetables

Strategies based on air	
Advantages	**Drawbacks**
• Widespread standardization with materials approved for contact with foodstuffs. • Good resistance to different temperatures. • Increasing the number of lips improves: – Vertical dimensional tolerance. – Performance with dynamic forces. – Adaptation to different shapes. • Reducing the number of lips improves: – Positioning. – Load capacity. • It is possible to manipulate several products at the same time.	• Works poorly on irregular, rough surfaces, dirty products. • Surface can be damaged and must have little or no porosity. • Handling times are higher when vacuum volume to be created increases. • Uncertain final position grows by increasing the number of lips. • Poor performance: – In dirty environments. – Under shear stress. – On irregular, rough and dirty products. • High energy consumption when the vacuum system is working continuously. • The fruit or vegetable may possibly get marked.

tion cups with a parallel-jaw-type gripper together with a cutting system that uses a hot wire to cut off the stalk. Sdahl and Kuhlenkoetter (2006) propose a system that uses modules with linear actuators and suction cups of several lips that can adapt to the variability of shapes.

Suction cups have traditionally been used for handling foodstuffs, but now are being innovative and more advanced industrial systems have been developed. In the food industry, *Fatronic Tecnalia* (San Sebastián, Spain, www.fatronik.com) has a prototype with suction cups to handle mackerel (*Scomber scombrus*) by introducing a system to identify the female. In the fruit and vegetable section, *Serfruit* (Naquera, Spain, www.serfruit.com) has large suction cups for mandarins; *Inmotx* (Frederikshavn, Denmark, www.inmotx.com) for apples. They have an inner surface that increases product contact, prevents air suction from being blocked, improves the distribution of forces on the product, and increases the ability to transfer forces.

The Bernoulli principle generates lift force by the use of high speed airflow between gripper and product. There are manufacturers that use this technology in robot grippers for light, flat and rigid products but not yet for foodstuffs. The system is fast, enables handling without touching avoiding contamination through contact, and is simple and easy to clean. However, it is only valid for light products, the air has to be filtered, it creates turbulences and has a dehydrating effect (Davis *et al.*, 2008). Petterson *et al.* (2010a) and Sam and Nefti (2010) managed to a Bernoulli gripper that can handle some 3D shapes of fresh fruit and vegetables such as grapes, cherry tomatoes, apples, strawberries, raspberries etc.

Strategies based on contact

The use of contact for grasping methods is one of the most important ones in robot grippers (Monkman *et al.*, 2007). A gripper for a P&P operation in fresh fruit and vegetables can be made with strategies based on contact (Table 3). The existing number of manufacturers and products on the market is very high.

The most standard method in strategies based on contact is jaw grippers. Many manufacturers have standard grippers with different kinds of mechanisms (Penisi *et al.*, 2003). To select a gripper the most significant features are: i) its opening range (distance from open to closed states); ii) maximum applied force; iii) type of movement (angular, parallel or self centered); iv) actuator type that supplies the motion (pneumatic, hydraulic, electric motor, magnetic…); v) jaw or finger shape, and vi) grasp strategy (external or internal grasp).

A simple standard gripper with a set of jaws can provide an adequate robot gripper solution. Ceccaralli and Nieto (1993) described the phases that characterise the gripping process.

The use of electronic actuators enables position, acceleration and force sensors to be introduced easily, increasing the gripper's control ability, but they are more expensive than pneumatic systems.

Grippers using pneumatic actuators are full open-close grippers. They can work abruptly without mechanical damping devices and/or flow rate systems. On the other hand, they have easy control, high grasp force with a pressure feeder, and high speed with a simple flow valve. They are cheap, highly robust, fast, easy to clean, and have an easy power supply. Their features

Table 3. Advantages and drawbacks of using contact in a gripper for a P&P process in fruit and vegetables

Strategies based on contact	
Advantages	**Drawbacks**
• Gripper can adapt to the shape of the product and to the range of all available products. • Adaptation to the range of all available products. • High repeatability. • Can achieve required end precision. • Possibility of varying the forces according to the mass, shape, and surface of product. • Simple models have easy maintenance and control, high reliability and low cycle times. • Opportunity to get information about fruit ripeness during gripping process.	• High speed grasp contact can damage sensitive fruit and vegetables. • Gripper complexity increases in the same way as complex shapes. • Complex grippers are less robust, heavy and bigger. • Gripper components should be approved for food contact and have good fatigue resistance. • Design should be easy to clean, without hollows and cavities, with good ingress protection. • Picking products very close to other products is difficult. • Avoidance of hollows and cavities or hidden areas where leftovers can accumulate in order to make the gripper cleaning easier.

are adequate for the requirements of a robot gripper in a P&P process for fresh fruit and vegetables.

Hydraulic actuators need a complex and external power supply system, allow easy speed and pressure control, but are heavy and too slow. Therefore, hydraulic actuators are used on grippers when high forces are needed.

There are contact grippers based on deformation by the inflation of rubber. For example, inflating balloons is commonly used to manipulate bottles or similar weak products. Other systems are designed to simulate the movement of a gripper. On the market there are fingers that use the inflation principle to achieve movements and which can be used to handle delicate products: *Sigpack Delta Robotics* (Waiblingen, Germany, www.sigpack.com) has 4-fingered models; *Inmotx* (Frederikshavn, Denmark, www.inmotx.com) presents a model for a bakery pie; and Setiawan *et al.* (2004) picked apples by means of inflating balloons inside a tube. Instead of inflating a rubber that will deform a jaw gripper, there is another way to achieve a similar effect by using electro-polymers (Bar-Cohen *et al.*, 1999) and shape-memory-alloy (Zhong and Yeong, 2006). These methods cannot be used themselves as grippers for a P&P in horticulture but they can adapt to complex shapes so they have a good potential when used in combination with other methods.

The human hand has an outstanding ability for manipulation. Robot hand designs attempt to simulate these aptitudes with the aim of grasping any kind of product. The idea is to increase the DOFs of the gripper fingers and incorporate sensors in order to adapt as much as possible to the gripping needs. There is great complexity involved in how to carry out and control the effect of grasping a product.

For fresh fruit and vegetable P&P operations, the low response time, high cost and complexity of robot hands limit their application. But there extraordinary ability for adapting to highly complex shapes, the control possibilities and the recent appearance of new simpler robot hands (Bicchi, 2002) will ensure their incorporation into industrial processes.

Similar products with regular shapes can be handled gently by a simple gripper with fingers of parallel shapes. In this case, a gripper with few parts and a low number of DOFs can achieve soft grasping with a lot of contact points. For irregular and sensitive products with complex shapes, like fresh fruit and vegetables, the same solution will create hard contact points. In this case grippers need more contact points for gentle and effective handling. A multibody mechanism gripper, with more mobile parts for grasping the product than a simple gripper, can create more contact points during handling and be suitable for irregular shapes like fruit and vegetables. If mobile gripper parts have their displacements from the actuator movement defined, the gripper actuator will stop when it clashes against the product and the system will not ensure all available contact points. Then it is possible to find hard contact points. A solution for this problem consists of using more gripper actuators for mobile gripper parts, increasing the gripper DOFs.

There are flexible mechanisms capable of adjusting to the product shape with one or a low number of gripper actuators. The aim of these devices is to achieve a greater amount of possible movements adapted to the product shape with a minimum number of actuators. Hirose and Umetani (1978) have a model capable of adapting to the product shape actuated by tightening wires. All these mechanisms can be called underactuated, due to the possibility of having more output DOFs than input ones. Underactuated mechanisms have some adaptation advantages in grasping irregular products and reduce the quantity of hard contact points and decrease the pressure needed for grasping the product. However, there is a lack of trajectory control and the mechanism can be unstable. Meijneke *et al.* (2011) has designed a robot hand with an underactuated mechanism for P&P operations able to handle fresh fruit and vegetables.

The main difficulty for the use of underactuated grippers for P&P fruit and vegetable postharvest industrial applications is the increase in gripper complexity and weight, the reduction of gripper speed, and the difficulties of finding design solutions.

Other strategies

Air, with suction cups, and contact grippers are the main strategies used by robot grippers and also for the manipulation of fresh fruit and vegetables. Further strategies are much more difficult to implement in robot grippers but they represent new perspectives on handling approaches for the complex problem of the manipulation of fresh fruit and vegetables.

Intrusive needle grippers are widespread in industry. Manufacturers such as *Techno Sommer*, *SAS Automation* (Glatten, Germany, www.schmalz.com) and *Naiss* (Berlin, Germany. www.naiss.de) have various models. With needle grippers it is feasible to handle porous objects such as foam, felt, and fabrics or other flexible items where inserting needles does not reduce the quality of the product. In the food industry, they are used mainly for handling frozen fish and industrial bakery products. For handling fruit and vegetables, this kind of gripper inflicts damage on the product, adapts badly to curved surfaces and runs the risk of food contamination if breakage of a needle occurs. But these grippers could be used to handle fruit and vegetables from disposable parts.

Rheological fluid can vary in its viscosity according to the magnetic or electrical field applied. The magnetic particles in suspension undergo a change of orientation with the magnetic field. These kinds of fluids are used in variable shock absorbers and clutches. Some patents (US Patent 6158910) propose using these fluids for gripping systems. Pettersson *et al.* (2010b) design gripper pads filled with magnetorheological fluid for handling delicate food products. Brown *et al.* (2010) developed a universal shape adaptation gripper applying vacuums that provide the jamming of a granular material. The biggest difficulties in applying this strategy in fruit and vegetable postharvest industry are the risk of food contamination, the complexity in creating the desired shape with a magnetic or electrical field, and the high cycle time necessary for a P&P operation. Granular vacuum jamming systems such as pads in jaw contact grippers are simpler and represent a good perspective.

Fluid surface tension is used for handling in electronics. Steam freezing can be used for handling textiles (Kordi *et al.*, 2007) and also for foodstuffs (Seliger *et al.*, 2000). But none of these two principles can apply to the handling of fruit and vegetables.

Product properties

Product properties have been used to manipulate agricultural products in harvest and postharvest operations. Density, firmness and vibration characteristics have been studied in order to classify products (Chen and Sun, 1991). In combine harvesters, grain density and aerodynamic properties are used to thresh grain from straw. The physical properties of weeds are used to design harvesters that separate weeds according to their dimensions, weight, bulk density, shape and aerodynamic properties (Hauhouot-O’Hara *et al.*, 2000). In potato harvesters, product properties are used to separate clods from potatoes using the difference in their rebound trajectories (Feller *et al.*, 1985).

Dynamic handling is also feasible by means of fast mechanical and automated systems. The main operations that can be performed are rotation, translation, turning over and sliding off. Akella *et al.* (1997) described how to orientate the objects with a single actuator with one DOF. Amagai and Takase (2002) described how to achieve dynamic P&P handling on a flat surface without gripping.

Scooping up delicate heterogeneous objects allows the manipulation of the product without gripping it. For the food industry, Foglia and Reina (2006) provided a system for collecting red cabbages which encloses the product between two scoops that also serve to cut the root. For food slices, Marel (patent ES 2 291 935 T3) provides various solutions that use the solution of scooping up as a high speed P&P solution. This method could be used for handling fresh fruit and vegetables gently.

Vibration has been studied to position polygonal objects (Akella and Mason, 1999; Han, 2007) and to transport objects (Huang and Mason, 1997; Baksys *et al.*, 2009). For harvest and postharvest applications, vibration is used to separate and to position horticultural products.

Discussion

The physical properties of products, such as their geometry, texture, dimension, surface area, material, coefficient of friction, centre of gravity and damage susceptibility, can significantly affect the manipulation process. A food classification (Wurdemann *et al.*, 2011) system will help to define the robot gripper. Fast grasping and releasing robotic P&P operations can affect fresh products, due to their susceptibility to damage producing a reduction in product quality. For this reason, highly complex robot-based handling operations for fruit and vegetables have not been successfully implemented.

The gripper design is based on the position and orientation of the object to manipulate. The gripper design specifications define the maximum accelerations according to the location of the product and pressure required for its manipulation and, in many cases, it is necessary to consider other components to protect against collisions, overloads and misalignments. All these considerations affect not only the gripper, but also the selection of the robot and cell layout.

More flexible materials that are resistant to wear and new tooling techniques provide innovative opportunities in suction cups. Contact grippers improve the situation for dirty conditions. A contact gripper with an underactuated mechanism may be suitable for a wide variety of shapes, but it would require specific designs based on designer knowhow and skills. These mechanisms should be based on simple, reliable and robust systems of low cost that enable the facilities to be profitable.

Contact grippers with suction cups and balloon inflation systems have been used in prototypes to harvest fruit and vegetables. Universal contact grippers with granular vacuum jamming pads provide very high possibilities of grasping irregular shapes, but currently these systems still have speeds and grasp reliability which are too low for normal P&P operations.

A combination of suction cups with underactuated contact mechanisms, using specific sensors to obtain product state information, is the most promising approach for the manipulation of fresh fruit and vegetables in a P&P process. However, the increasing complexity and weight of these combined systems requires great efforts from the design engineer (Wilson, 2010) to simplify mechanisms and reduce the weight of the gripper.

New solutions can be found by using plastic materials with specific properties and using the latest generation sensors. Moreover, by incorporating new non-destructive techniques (Naghdy and Esmaili, 1996), grippers can acquire new skills, and product quality could be checked during the grasping process.

As an alternative approach, the desired manipulation could be achieved without gripping the product: pushing, scooping up, translating, rotating, placing or turning over operations can achieve the desired manipulation. As a previous step to the design of this strategy, it is highly advisable to study the global process carefully in order to reduce the handling requirements.

As a final conclusion, it is still necessary to continue studying fresh fruit and vegetable characteristics and handling requirements in order to design grippers which are suitable for correct manipulation at high speed, without producing damage to fresh horticultural products in profitable P&P operations for industrial applications.

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