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ROBOTIC GRIPPERS IN FOOD INDUSTRY: A SHORT REVIEW

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A B S T R A C T

This review presents current trends and challenges in the field of robotics, with an emphasis on the development of grasping methods in the food industry. The problems of soft, weak and unstructured materials are considered, as well as hygiene requirements and discoloration of products. Various gripping methods are discussed, including pinch grips, penetration grips, and pressure limiters. The authors highlight the importance of effective capture in environments where traditional methods are insufficient and propose innovative approaches to ensure safe and efficient food processing. Overall, the article draws attention to the importance of developing gripping technologies to improve automation in the food and other industries.

1. INTRODUCTION

Since George Devol invented the first industrial robot in 1959, the gripper has been a key component (Wu et al., 2018). Robots basically represent non-human beings designed to perform tasks normally performed by humans. Both in manufacturing and in other human jobs where automation is applied, robots are tasked with replacing human actions (Pfeiffer, 2016). Many of these tasks require grasping and manipulating objects, whether for simple transportation or more complex operations involving tools and machining.

Over time, the concept and application of robots has evolved far beyond the original industrial goals outlined in Devol's patent. In the beginning, industrial robots focused primarily on material handling. Consequently, the gripper has emerged as a critical element of robot design (Shintake et al, 2018).

Although robot arms, control systems, and sensor systems have been the main focus of research activities in the field of robotics, grippers have not received much attention (Billard & Kragic, 2019). Research efforts are mainly focused around robot control theory, arm structures, kinematics, dynamics and sensor systems. Grippers, despite their importance, are often considered too simple to warrant extensive research, especially when compared to the more complex and mathematically challenging aspects of robotics.

Traditionally, grippers can be as simple as devices with two mechanically actuated fingers capable of gripping objects (Tai et al, 2016). These simple handles are sufficient for many basic control tasks, which has led researchers to focus on more complex and intellectually stimulating areas of robotics (Metta et al, 2010).

However, the landscape of robotics is changing. Simple grip technology has been extensively researched for common situations. Today, the robotics industry faces the challenge of handling soft, weak, and unstructured objects that are prevalent, especially in the food industry (Licardo et al., 2024). These objects, such as fruits, vegetables, and various types of meat, pose unique challenges that traditional capture methods have difficulty solving.

Since the turn of the millennium, there has been an increasing understanding and development of more sophisticated gripping methods and technologies adapted for soft, weak or unstructured objects. As these advances mature and reach industry standards, they open new opportunities for automation in a wide range of industrial applications.

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In this context, the term "hard grip" refers to tasks involving objects that have well-defined shapes and sufficient strength to withstand clamping or similar gripping techniques, such as metal screws or plates. On the other hand, "soft grip" characterizes tasks in which objects are made of soft materials that are easily affected by the gripper's strength and speed, often exhibiting irregular shapes that vary from object to object of the same type (AboZaid et al., 2024). Holding a piece of beef indicates a soft grip task.

Although both hard and soft grip technologies are covered in this section, the focus will be on soft grip due to its increased relevance and challenges, especially in industries such as food processing (Whitesides, 2018).

Food processing automation presents unique challenges not typically encountered in non-food products. Although some problems such as softness and slow behavior are also observed in textiles, certain plastics and rubber products, the combination of difficulties in handling food products is different (Chua et al., 2003).

Although some containment solutions developed for non-food sectors can be adapted for food handling purposes, the specific requirements of the food industry must be carefully considered. As a result, innovative and unique gripping solutions developed specifically for the automatic handling of food materials have emerged. These solutions meet the specific requirements of the food sector, taking inspiration from existing gripper technologies in other industries (Zhang et al., 2020).

2. CHALLENGES FACED BY GRIPPERS

2.1. Soft materials

Many food materials present unique challenges due to their soft properties. Food materials are usually vegetable or meat-based, with meat consistently exhibiting mild characteristics. Vegetables can have different surfaces from soft to hard.

Soft food materials present two main problems:

1. Soft materials tend to deform, causing traditional fixed-width grippers to lose their ability to grip the object.
2. Holding force applied to soft materials can potentially damage their surface or internals, leading to reduced quality and selling prices or shortened lifespan.

To solve these problems, soft materials require a handling method that reduces deformation and minimizes surface damage.

In the case of meat from terrestrial animals, the second type of problem is generally negligible, because the meat is strong enough to withstand the normal forces from grip.

Fruits present different challenges. Soft fruits in particular require gentle handling as they are susceptible to damage. Even semi-hard fruits such as apples and tomatoes are very sensitive to crushing and local pressure, which makes the grip unsuitable for working with them.

Conversely, other vegetables, such as nuts and various root vegetables, are generally more resistant to grip forces, making them easier to handle than soft fruits.

2.2. Uneven surfaces

Uneven surfaces are common among naturally grown objects, ranging from slight irregularities to rough surfaces. Surface quality plays an important role in determining the suitability of grip methods.

Objects with hard and rough surfaces are generally easier to grip because they can withstand higher grip forces. However, soft objects with rough surfaces pose challenges. Kiwi fruits are the best example of this category, because of their rough skin texture, they are very sensitive to crushing and local pressure, which makes vacuum trapping techniques practically impossible.

Similarly, meat from both fish and land animals presents handling difficulties due to uneven surfaces. The unpredictable surface structure of these meats makes it difficult to effectively apply the vacuum technique in many cases.

2.3. Unequal forms

Organic bodies have imperfect geometric shapes, unlike fictitious objects that can exhibit perfect external geometry. While certain food products, such as chocolates produced using molds, may exhibit precisely regular shapes, naturally grown objects consistently exhibit irregularities.

Similarly, many portable food products have irregular shapes. Different cuts of meat from animals inevitably show some irregularities on the surface, despite attempts to maintain uniformity in the cutting process. Breads, cakes and pastries can be formed into relatively regular shapes; however, there is a customer preference for these products to have an irregular appearance similar to household products.

The non-uniform shape poses a significant challenge to the design and methods of the holder. However, recent technological advances supporting capture tasks have introduced numerous new options for developing reliable capture solutions.

2.4. Hygienic requirements

Ensuring the hygiene of food products during harvesting and processing is an absolute necessity for their intended consumption. There are three main categories of pollution to watch out for:

Toxic pollution. It is imperative that no toxic substances come into contact with food during harvesting and processing, as the toxic substance can stick to the product and pose a risk to consumers. Therefore, considering that certain engineering materials may have toxic properties, all containment devices and methods should be made of non-toxic materials to avoid potential harmful effects.

Bacteriological and fungal contamination. Organic materials, along with suitable humidity and temperature, create favorable conditions for the growth of bacteria and fungi that can easily form in food processing plants.

Catchment methods that involve physical contact with the object carry the risk of small amounts of mobile material remaining in the catchment device, potentially facilitating the growth of bacteria and fungi. To reduce this risk, catchment facilities should be designed in such a way that it is possible to minimize the accumulation of organic material by effective cleaning methods to maintain hygiene standards.
Discoloration. Certain handling and handling methods, while not harmful, can result in discoloration leaving small traces of material visible to consumers and perceived as a quality defect. Although not a direct health hazard, it is still desirable to minimize discoloration to maintain the perceived quality of the food product.
The first two categories of hygienic requirements are absolute necessities, and the third category is considered desirable, but does not pose a direct health risk.

2.5. The physics of gripping

All grippers must effectively transfer the necessary force from the robot arm to the object to transmit motion. Motion naturally contains acceleration, which is affected by factors such as gravity and local trajectory. It is determined by changes in the value and direction of the acceleration vector of the local trajectory.
The acceleration due to gravity always acts perpendicular to the local horizontal plane. During vertical movements, this momentum complements the local trajectory momentum, resulting in the highest force applied during the control operation.
Certain grip methods require at least partial closure of the object, as seen with pinch and cap grippers. Others work on a single surface of an object, such as under pressure and surface effect grippers.
Pinch grippers use two or more fingers to apply force to a controlled object. Flat fingers usually rely on the friction between the object and the fingers to hold it securely during handling. Alternatively, grooved or rounded fingers can transmit force through local perpendicular force vectors, resulting in a firm grip known as a "hard grip." Release is achieved by moving the fingers away from the object.
Gripping grippers use fingers with large surfaces to partially or completely enclose an object. The enclosure must be complete to prevent any potential escape routes. The necessary force transfer to the object is obtained from the vector sum of all normal force vectors of the surfaces in contact with the object. This type of grip, known as "soft grip", involves forces acting on the object no greater than gravity and propulsive forces from the retaining walls.
Upon release, the gripper allows the closure surfaces to be adequately separated from each other to release the object, creating an opening of sufficient size for the object to exit.
Pins, or penetration grips, usually have several sharp-tipped pins that penetrate toward the center area of the object and are pressed into the object to create a locking pattern.
During the fixation or penetration method, the holder is equipped with multiple sharp needles or pins that are pressed into the object creating an interlocking pattern. Typically, this involves a configuration directed towards the central area of the object.
Pressure arresters, also known as suction or vacuum arresters, use a controlled low-pressure level within the containment area rather than operating under a total vacuum. Low pressure refers to a situation where the local pressure inside the containment is lower than the ambient pressure, creating a pressure differential that forces the object against the containment area. Release is achieved by relieving low pressure, sometimes slightly overpressure is required for consistent release.
Surface effect retainers, also known as surface phase transition retainers, achieve retention by cooling the contact area to a temperature significantly below the freezing point of water. When this cold surface comes into contact with a wet object, a thin layer of ice immediately forms on the surface of the object in contact with the cold-retaining surface. This thin layer of ice provides enough grip for many objects, especially objects with a high surface water content, such as meat. Release is accomplished by heating the contact area or by slicing the object with a thin knife.
Low pressure arrester: these arresters are often called vacuum arresters. However, they rely on a certain amount of pressure in the containment area, not a total vacuum. It is called a low-pressure trap because the local pressure in the trap area is lower than the ambient pressure. This creates a force due to the pressure difference that forces the object against the catch area.
Release is usually achieved by relieving low pressure, and in some cases a slight overpressure may be applied to facilitate consistent release.
Surface effects or surface phase transitions can provide retention by cooling the specific contact area to a temperature significantly below the freezing point of water. When this cooled surface comes in contact with a wet object, a thin layer of ice forms on the object's surface, which immediately contacts the cold-retaining surface.
This thin layer of ice effectively adheres the object to the gripping surface, providing sufficient grip for many objects. There is usually enough water on the surface of the meat to facilitate this gripping action.
To release the object, the contact area is heated, melting the ice and releasing the grip on the object. Alternatively, the object can be cut from the gripping surface with a thin blade (Gjerstad et al., 2006).

3. CLAMPING AND CLOSING OF GRIPPERS

The squeeze gripper represents the original concept for robotic grippers and remains a simple yet robust method for a wide range of gripping tasks. There are many variants of this gripping principle, such as two rigid

finger pneumatic grippers and polygonal finger grippers, the former being more common in practical robotic applications (Wolf et al., 2005).
For practical robotic applications, two and three-finger rigid variants are preferred. Figure 1 shows examples of these types of holders.

a) b)

Figure 1. (a) Typical two-finger gripper, (b) Typical three-finger gripper (https://onrobot.com/en)

3.1. Two-finger solutions
Typically, two-finger grips have a prismatic body with two fingers extending from one side. These fingers can either move in parallel or rotate around a shaft located at their base. Although most are pneumatically actuated, electric and hydraulic actuation options are also available. In addition, the fingers can have flat faces, and can also be equipped with circular or V-shaped grooves.
Two-finger flat-faced finger grippers rely on friction to generate the force necessary to hold an object securely. This force changes depending on the direction of acceleration during movement.
In each case, the gripper fingers exert a force F_f that opposes sliding across the gripper surface:

$$F_f = n \times F \times \mu \quad (1)$$

Here, F_f is the frictional force opposing sliding, F is the normal force on the finger surface, μ is the coefficient of friction between the object and the fingers, and n is the number of fingers.
To prevent sliding, the friction force F_f for a two-finger gripper must satisfy the following conditions, depending on the direction of movement:
Vertically up:

$$F_f > m \times (g+a) \quad (2)$$

Vertically down:

$$F_f > m \times (g-a) \quad (3)$$

Horizontal parallel to the face of the finger:

$$F_f > m \times (\sqrt{g^2 + a^2}) \quad (4)$$

Horizontal normal to finger face:

$$F_f > m \times g \quad (5)$$

In the case of horizontal motion normal (perpendicular) to the faces of the fingers, the driving force will increase the total force on one face while decreasing it by the same amount on the other face. But the sum of the forces remains constant, ensuring that the equation can be applied to all accelerations.

Grooves will provide a holding force with the closing action of the form. This is called form fitting. The gripping force is determined by the sum of the individual normal force vectors from the contact surfaces. The calculation for this type of grip is presented in the multi-finger grip section.

3.2. Two-finger servo gripper

A two-finger servo gripper is applied to solve the problem of excessive grip force. This type of gripper is electrically controlled to achieve a specific gripper clearance or grip with a specific gripper force (F).
Additionally, these servo grippers (Figure 2) differ little from pneumatically operated grippers, except that the actuator housing is slightly larger. They are more expensive, but the extra cost is easily justified by the greater versatility of this type of holder.

Figure 2. Two-finger servo gripper (https://schunk.com/us/en)

A servo gripper requires a digital command that determines the finger clearance and grip force if force control is implemented. Typically, this command is transmitted from the control system to the receiver via a serial link.

3.3. Multi-finger grippers
Multi-finger grippers can be divided into three main classes:

1. Simple hard finger grippers equipped with three or four fingers.
2. Handles with multiple rigid fingers that partially enclose the object.
3. Human-like finger grippers designed with jointed fingers.

Formulas (1), (2), and (3) apply to grippers with any number of flat-faced hard fingers when oriented vertically along the gripper centerline. When operated in other directions, these grippers act as partial form fit grippers. Form-fitting grippers rely on partial closure of the object with the fingers, sometimes using grooved or contoured fingers.
A form-fitting grip does not require high force from the fingers to create the frictional force necessary to grasp an object. Instead, this grip method relies on the fingers' ability to withstand the normal force at the contact points under varying positions and acceleration. Consequently, a form-matched grip typically results in a lower finger grip force than a force-matched grip.

Anthropomorphic (human-like) grippers are ideally designed to mimic human behavior as closely as possible. However, many grippers in this category have fewer degrees of freedom than the human hand, so fully mimicking the dexterity of the human hand remains a challenge. Only a few laboratory specimens closely resemble the mechanical functionality of the human hand. Additionally, it has proven extremely difficult to replicate the sensitivity of the human hand, particularly through tactile and force feedback via the human nervous system.

Moreover, the complexity of humanoid finger grippers often leads to prohibitive costs, making them economically unfeasible for industrial use at the current stage of development. However, this situation may change in the future (Mouri et al., 2002; Thayer and Priya, 2011).

4. DISCUSSION OF HYGIENE PERFORMANCE

All grippers of the clamp and fastener class have some sort of moving mechanical element outside the main body of the gripper. Hygienic performance of clamping and clamping grippers is particularly important in industries where cleanliness and sanitation are essential, such as food production. These elements always raise concerns about hygienic requirements.

Another factor to consider is the design of the gripper fingers. Catches should be designed with materials and features that allow for easy cleaning and prevent the accumulation of dirt, debris or contaminants. Some gripper fingers have a serrated surface on the grip face, but this may not be suitable for many food applications because the serrated grooves can collect particles and are difficult to clean.

In addition, the gripper mechanism requires lubrication for smooth operation. Long-term leakage can be difficult to prevent. It is preferred to use water-lubricated roller bearing materials or polymer-composite roller bearings that can perform efficiently without the need for additional lubricants.

Finally, the materials that come into contact with the transported food must meet hygienic standards. This typically involves the use of stainless steel and polymers for the gripper fingers and outer case walls.

5. CONCLUSION

To sum up, the article reviewed the evolution and current trends in the field of robotic gripping, focusing on solutions for soft and unstructured objects, especially in the context of the food industry. Various types of grippers and their application are considered depending on the characteristics of objects, such as softness, surface irregularities and shape. Hygiene requirements and the importance of maintaining food safety standards were also discussed. While traditional gripping solutions have been effective for many applications, modern challenges such as handling soft and unstructured objects require new innovative approaches that can be tailored to the specific needs of industry. Further research into the development of grippers, especially in the context of soft materials and hygiene requirements, could significantly improve the efficiency and reliability of robotic systems in various industrial applications.

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