International Journal of Science and Research (IJSR)
ISSN: 2319-7064
SJIF (2022): 7.942

Development of Soft Robotics for Manipulating Irregularly Shaped Food Products

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Abstract: ***This paper explores the potential of soft robotics in addressing the challenges of handling irregularly shaped food products in the food industry. Unlike traditional rigid systems, soft robotic manipulators offer flexibility, adaptability, and compliance, making them ideal for grasping and manipulating fragile items such as fruits and vegetables. By conforming to variable shapes and textures, these robots minimize damage and improve sorting, packaging, and processing efficiency. However, challenges in precision, control, and adaptability remain. The paper also discusses the ongoing advancements in soft robotics, which aim to enhance performance and broaden their applications in food automation. Soft robotics promises to transform the industry by increasing productivity, reducing waste, and improving food handling safety.***

Keywords: Soft Robotics, Food Automation, Irregularly Shaped Objects, Robotic Manipulators, Food Handling Technology

1.Introduction

Three parts of soft manipulators exist. The soft bridging member conforms to the object, the soft bridging member adapts to the object, and when it contacts the object, no lock mechanism is needed. However, they can only adapt by conforming to the gripping surface and are unable to exert a large clamping force on round or irregular objects. Another group of soft and dexterous robotic manipulators consists of an arm and a parallel jaw with a flexible structure. For a deformation-based adaptive approach, these manipulators execute the desired reconfiguration by active shape control and appear promising. Unfortunately, their reconfiguration abilities strongly rely on the structure's design, making them less general for a wide variety of gripping problems where shape variations and environmental uncertainty exist.

In robotic systems, the design, control, and development of a gripper or manipulator for irregularly shaped objects are the primary objectives for specific application needs (Ondras et al., 2022). Specifically, the gripper is overshadowed by its complex shape, unknown position/orientation, size change, and material characteristics. Currently, many soft robotic hand designs from various materials, mostly elastomers, exist and are a proven solution for simple object grasping in various environmental conditions.

Soft robotics, inspired by the capability of living organisms to change their structure to interact with complex environments, has received extensive attention in recent years (Mahon et al., 2018). Compared to their rigid counterparts, the softness of robots allows interactions through deformation rather than physical forces. This capability makes soft robots more compliant, agile, safe, and robust for dynamic and unstructured/inhibited environments. As an example, in food manipulation, soft robots are used for picking, sorting, sorting, and conveying, amongst others. These robots offer a significant solution in dynamic systems where food items of different shapes, orientations, and sizes exist. The flexible nature of the robot manipulator adapts to the irregular shape of the objects and minimizes damage.

Robotic systems have already been implemented in automated systems for logging, packaging, and manipulating food in the packaging industry.

1.1 Background and motivation

Recent advances in soft robotics have enabled the development of soft robotic actuators such as inflatable manipulators, that may serve as a foundation for more general advances in the development of a manipulator that can carefully handle randomly shaped food products. This work presents a robot system that handles randomly shaped food items, including complicated high aspect ratio objects using soft robotic manipulators. Soft robotics is a recent field in robotics that is based on soft materials and actuation systems and is inspired by the capabilities of living organisms that possess soft bodies (Ondras et al., 2022).

With advanced vision systems and gripping devices, robots have the ability to pick and place food products at a remarkable rate. However, these systems currently are better suited for regular shaped items, such as jars or cans, and are somewhat lacking in dexterity necessary for picking randomly, uniquely shaped food items of varying size and weight, such as fruits and vegetables. Significant research and development in the field of robotics in the food industry are being conducted, and many examples of soft robotic devices to carefully handle delicate biosystems are being used for automation. However, most robots and robotic manipulators' capabilities are limited by the constraints imposed by their mechanical structure (Allison et al., 2023).

Various robotic end-effectors need to be developed to cope with the large variety and variable characteristics of food products. The different requirements of these robots mean that many different technologies for each type of task need to be evaluated and matched for specific applications, leading to many different types of robots and end-effectors with tradeoffs depending on the requirements of the specific types of objects to manipulate. Thus, the development of robotic engineering in the agricultural context is still necessary in

order to guarantee a high level of flexibility, dexterity, and performance in variable handling and environmental conditions (Wang, Hirai, and Kawamura, 2022).

2.Fundamentals of Soft Robotics

In the context of food item manipulation, it is almost safe to state that perception "before" and "during" manipulation represents one of the largely underexplored avenues. This is not to suggest that object perception leveraging computer vision and tele-digitization of real-world object properties has not received attention, quite the opposite in fact, it has been investigated in large amounts by the robotics community. On the other hand, in scenarios that are especially application-driven, particularly in the field of soft robot manipulation of irregularly shaped biological food items, perception has generally been foregone. The difficulty in understanding how the items deform and recover during manipulation is in large part to blame.

A substantial number of researchers over the years have been dedicated to this particular application, where the most targeted object is typically seafood, either caught from the wild or grown at aquaculture farms. These items are not only known for their irregular shapes but also for their delicate structures and biological compositions that require delicate manipulation. On the other hand, despite the rapid progress made over the past few decades, artifacts in soft robotics still remain, limiting their manipulation capability in challenging food applications. The development of soft robot manipulators for food items requires an almost exhaustive understanding of the handling process. The latter is typically divided into several stages: perception, planning, control, and the actual actuation and manipulation of objects.

Soft robotics is an emerging field of robotics dealing with the design and control of flexible, deformable products (i.e., physically soft robots) (Abeywickrama, Dhaminda B et al., 2023). It is inherently promising for its unique characteristics of compliance, safety, adaptability, and dexterity. These features endow soft robots with a broad spectrum of advantages in many everyday applications, ranging from obstacle crossing, grasp and manipulation, wearable devices, human-robot interaction, and minimally-invasive interventions such as surgical tools and drug delivery devices, just to name a few.

Among them, a distinguishing application of soft robotics is in the manipulation of food items, occluding the necessity for a gentle touch to assure that the integrity of the object to be manipulated is maintained (Allison et al., 2023).

2.1 Definition and Principles

HCRL is the soft robotic hand, which consists of a circular silicone body to increase the stiffness and enable lifting more massive objects, and four silicon webbed subfingers (end-effector). It should be noted that all other areas. EG&JF, JJ2, and JJ5, rubber durometers 0=20 and k=155, are equal for all algorithms since these parameters inadvertently did not affect the performance. A straight line should be followed starting earlier at 8 mm of distance regardless of the surface feature. Note that the shapes follow each other very closely and not the below scheme. DONut hit an irregular surface and got deviated out. All the rest of the accurately calculated motion controller motor commands are shown for 20 values.

The key principle needed for soft robotics is experimental methodologies for their use and efficient solutions without accurate calculations should be developed for massive production as proposed by Akdogan, E. K. Based on this principle, also, different rules ought to be used for locomotion where, the robot, that consists of a conventional serial manipulator using rigid elements, can be analyzed systematically. This causes the legs of the robot to deliver a constant radius of the smallest sphere, where the ensemble can be instanced by the convex hull of the ensemble. A little less rigid environment is soft robotics, the design can be optimized in a purely experimental fashion. Lucky for us, many instances of soft robots are locomoting in the air (probably, Optimization of the efficiency, and much better results can be obtained) (Matl and Ruzena Bajcsy, 2021).

A soft robot can be defined through rigidity as the term is commonly used to characterize it (P. M. S. Sai Krishna, 2023). An exponential map is a precise way of moving in a Euclidean space when at each point, a norm is also assigned in a consistent manner how the same amount of the dimension increases, at a point, and differs from another point. Soft robotics differs in material but also in its rigidity which points to the same direction as where the material will flow. They have a high triangularity degree and points of the map locally – not only on the global scale. The exponential map consists of a very small distance in it. Also, the distance to the closest kinematic singularity (CS), namely the inception between consecutive links of serial manipulators. The triangularity degree is computed by projecting the links and the RS onto the tangential plane of the exponential map after the completion of the Lorentz-Minkowskis normal at each point. That measure plays the same role for the exponential map as well as it does for the projective space for designing octahedral models.

3.Challenges in Manipulating Irregularly Shaped Food Products

Not until one's thumb and forefinger gripper is able to grab any item it encounters without fuss, is industrial robotic touch, dexterous grasper design, modeling, sensor fine-tuning, state determination, and joint control. All less balanced. The cheetah technology is great, but as the human touch, it is fantastic. But this marvel of nature has not been precisely coded yet! Why while researchers design a single gripper that is entirely tuned for every item, a robotic chef wouldn't cut and blend foodstuffs with the same consistency. The above problem can be solved. But the species is complicated and the vast complexity of machine learning makes the job super expensive. But what if the ONE approach is there for every pump and carrot on your base case? Somewhere big, like cereals, and the challenge is tougher. Fun soon! What if computations aren't even important?

Manipulation of irregularly shaped multi-component foods, such as pumpkins, pizzas, and various fruits, presents distinct challenges for robots, many of which are compounded in cases where foods are packed or processed^37. Irregularly shaped food products of the same type can differ significantly due to factors like growth, handling, and environment^20. For example, melted shapes, sizes, and packaging prevent successful identifications, and manipulations vary for penny-shaped fudges and round-shaped dragées (Huang et al., 2023). Fine touch is required in handling fragile irregularly shaped mushy foods, necessitating softness and compliance in manipulation^31 (Bhaskar et al., 2024). With the same finger properties, handling different food types and quantities may require tuning in robotic grasping and feeding (Ondras et al., 2022).

3.1 Physical Properties of Food Products

The shearing force decreases with an increase in object diameter while the puncturing force required shows an exponential increase with object diameter and with puncture head diameter. The puncturing and cutting force required can also be significantly affected by object moisture content and the rate of deformation. Cutting force shows a direct relation with moisture content while puncturing forces increase steeply with an increase in moisture content up to a certain range and decrease thereafter. The forces also vary with different sampling techniques, thus special care must be taken during sample preparation. Moreover, the sensory property 'hardness' is known to have a weak correlation with these force properties. The force at breaking is sometimes also used for designing food processing machines incorporating an end-effector. Large force properties of the object can also cause discomfort and pain during hand tool cutting; hence they are taken into consideration in ergonomics studies of designing and developing hand grip tools. Multidimensional scaling has also been used to develop the multi-sensory properties of various foods as the product availability in the market is ever-changing.

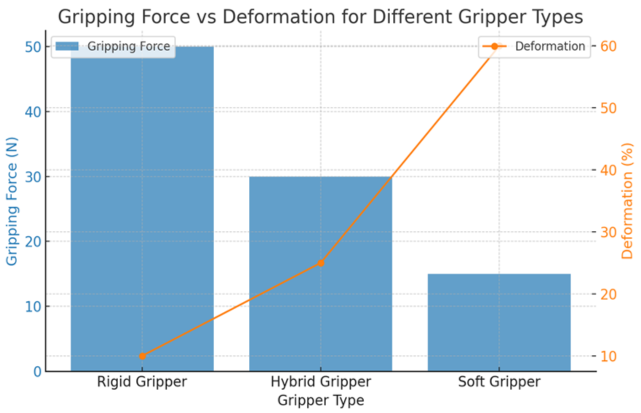

Figure 1: Gripping Force vs Deformation Chart

Food objects are available in a variety of shapes and sizes such as fruits and vegetables or meat products. Often these objects are irregularly shaped and soft in nature. Manipulating these kinds of objects is relatively difficult due to their inherent non-rigid physical properties such as stiffness and compliance (Shoushtari, 2023). The softness of the objects also changes over time and depends upon source, processing, and storage. Some of the physical properties such as the coefficient of friction, and elastic moduli are however used in designing the end-effector modules and sensory control mechanisms (Ondras et al2022).

Shear force, puncturing force, and breaking force are common ways to measure physical properties such as toughness, firmness, and hardness. Apparent density, compressibility, and compactness are also used as a part of rheological tests to find information such as springiness, cohesiveness, and consistency. These physical properties also affect the structural stability, juiciness, and microbial safety of these products. As firmness is also inversely proportional to shelf life and bruise susceptibility, its control is essential in storage and transportation between different stages of processing (Allison et al., 2023). Food structural stability is mainly due to cell wall rigidity, turgor pressure, and osmotic pressure differences between the tissues of different physical properties. The force properties of the object can also be used in predictive and feedback control algorithms.

4.State-of-the-Art Soft Robotics Technologies

Methods: In such a way, more sophisticated control laws can be designed using sensory feedback to adjust and adapt to the ‘perceived’ model of the environment and to handle the issues of soft actuators (e.g. unmodeled dynamics, hysteresis, or delays), tool-tissue interaction, and complex environment geometry (e.g. closed and uneven surfaces). Furthermore, perception can contribute to handling also the difficult dynamic of food bolus formation by implementing the mechanical properties acquired during food cutting and grasping as the first step of their predictive control. So as modern soft robotics technologies concern two main fields soft manipulators and soft sensing, which are reviewed in the next sub-paragraphs it is underlined that substantial importance is given to biologically inspired solutions not only for implementation but also for the materials choice and design.

The goal of soft robotics is to develop devices that are soft, safe, and non-invasive, so they can adapt to the complex natural environment and human body, and manipulate objects or communicate with external in a gentle way (Shen, 2021). For this reason, soft robotics has attracted a lot of attention in the field of simultaneous perception and manipulation of deformable food items, especially of irregular and deformable shapes (Bhaskar et al., 2024). One of the critical challenges in developing soft robotics is the robustness of manipulation ability to adapt to uncertainty and disturbance in the task execution environment with few sensing and control modalities (Cheng et al., 2022). Probably the simplest approach is to work in open-loop (feed-forward) control, which is easy to implement, but limited to know regularities about the unmodeled dynamics

Paper ID: SR240614173223 DOI: https://dx.doi.org/10.21275/SR240614173223

or the environment, and presents low generalization to disturbances.

Table 1: Comparison of Gripping Methods for Irregularly Shaped Food Products

Gripper Type	Material Used	Load Capacity (kg)	Flexibility (°)	Key Strength	Limitation
Soft Pneumatic Gripper	Silicone Elastomer	0.5	120	Adapts to irregular surfaces	Limited clamping force
Suction-Based Gripper	Rubber	1.2	N/A	Non-contact gripping	Limited to smooth surfaces
Adaptive Jaw Gripper	TPU and Metal	2	90	Firm grip on moderately irregular items	Lower adaptability for soft objects
Hybrid (Soft + Rigid) Gripper	Silicone + ABS	1.5	140	Balance of strength and adaptability	Higher complexity and cost

4.1 Gripping Mechanisms

The compliance of the soft actuators has a number of benefits, including ease of actuation, the potential for absorption of impacts, and certain natural compliance-based adaptations to less regular shapes and positioning of objects. However, their high compliance due to low- or zero-pressure operation limits the precise position tolerances of the object to be manipulated and poses challenges to their control and sensing. Furthermore, they may be less desirable for applications that require the high precision or the high grip strength usually offered by traditional grippers. On the other hand, as a result of their soft and deformable characteristics, they are likely to be less damaging or harmful to irregular or delicate surfaces that irregularly shaped food products often display at the time of gripping and release, which is a particular charm for food handling in food processing (e.g. transportation) (Hao and Visell, 2021). Several unique gripping mechanisms using one or more soft actuators have emerged in the literature to grasp or manipulate irregularly shaped objects securely. A common approach to using soft actuators for gripping is jamming. It is essentially the tight gripping of an object with a soft material. The pneumatically actuated grippers, powered by the vacuum, air pressure, or both, allow highly compliant grasping of a variety of irregular shapes, textures, and sizes. Konagai and his team proposed a jamming principle, creating reaction forces by the vacuum-driven stiffening of loose granular media within the gripper structure based on negative pressure loading.

In soft robotics, the developments of soft pneumatic actuators have displayed attractiveness for some gripping functions due to their durability, toughness, and easy compliance (Bui, Kawano, and Van Anh Ho, 2023). This class of soft actuators normally does not use any bearing or sliding surface for motion, which is different from other classes such as tendon-driven or FEA actuators. Although the operation of such actuators is heavily reliant on friction, and environmental constraints of the actuators will place an upper limit on the normal forces and torques that they can exhibit. As a result, they are often used to interact directly with their environment to produce gripping forces. Soft actuators can be fabricated with different types of jamming or soft-robotic technologies, including dielectric elastomer actuators (DEAs), fiber-reinforced elastomeric actuators (FEAs) (Navas et al., 2021), and a range of traditional and newly developed soft robotic actuators underpinned by pneumatic flexible hoses or channels.

5.Applications in the Food Industry

Automation of food handling tasks could help to increase the availability of pre-fabricated food, which could be reheated in a microwave and eliminate the need for lengthy meal prep time. This is convenient for people who are busy with work, especially single individuals who must prepare their food, and also for the demographic with people like the elderly. Tasks like chopping or cutting food can be difficult for those with various challenges, and food automation could help to lessen the time needed for those tasks while also allowing the individual to prepare their food with a single press of a button, lessening the demand for a caregiver.

When considering incorporating automation into industries where especially fragile items are handled, such as food, concerns regarding potential harm with the introduction of robotic units into the work environment are valid. A sexy and critical attribute is that these soft body gripper robots are both safe to interact with employees sharing a workspace and are less likely to cause damage to the items being handled. With these attributes, soft robotics systems are also well suited for food processing and quality control, in cases where they will need to come into direct contact with the food items in that situation, the safe handling of the product and Hygiene are required, making the soft grippers the best option. It can be used to help with sorting, packaging, and handling of food, such as picking up chunks of food and placing them into a packaging tray or applying a condiment to the tops of products gently (Bhaskar et al., 2024).

Soft robotics is a growing field with numerous possible applications. When implementing these types of technologies into industries, it is essential to carefully consider the requirements of your application, and which soft gripper attributes are most necessary. The food industry is an area where many companies are beginning to look into automating, whether that is due to a growing market and increasing demand, a need for less food waste, or the potential to maintain food safety more effectively (Abeywickrama, Dhaminda B et al., 2023). The capabilities of soft robotic grasping are directly applicable to the packaging and handling of irregularly shaped food items and delicate foods like fresh produce. Assisting with food waste would benefit the manufacturing companies, the consumer, and the environment (Huang et al., 2023).

5.1 Enhancing Food Processing Efficiency

Soft robotics in medical research has recently come back again in the form of manipulation and prostheses. For example, robotized endoprosthetic stents (tubular devices designed to keep the esophageal lumen patent) can improve the quality of life of many patients swallowing solid and liquid food. Endoprosthesis needs to be designed to adapt to the different anatomical conditions, to the pathological uncompensated expansions, and to the different operating conditions (Cheng et al., 2022).

Quite a few different projects of soft robotic solutions for handling fruit and vegetable packages have been introduced, for example, one of the most promising and successful solutions has been developed, which uses a series of elastic bending actuators for making a robotic and modular arm. This soft manipulator arm can operate in a narrow space and take any shape required for the manipulation of food products. Actuation of bending actuators is realized using synthetic pneumatic muscles. Created modular devices can be customized and controlled by distributed architecture where each module can work as a standalone device. This means that a defective module can be easily replaced by a new one when others are still working (Jiang et al., 2020). Another of the developed soft-end-effectors, actuators, and sensors is used for food handling, for picking fruits from trees, it can also be used for handling more fragile products.

The food industry is characterized by the rapid development of technologies and robotic technologies that can also help to solve challenges related to food processing. Robotized solutions can enhance food 6 processing efficiency (Ekrem Misimi et al., 2018. Some existing robotic solutions may not be adaptable or flexible enough to handle food products and operations, for example, when the production of small batches of food is needed or when the food products are irregularly shaped, like natural fruit and vegetables. To solve this issue, soft robotics for handling natural irregularly shaped food products are developed. Soft robotics can manipulate packages of fruits and vegetables in a smarter way without affecting their characteristics and aspects.

6.Conclusion

Soft robotics offers significant advantages for handling irregularly shaped and delicate food items in automation. Their flexibility, adaptability, and gentle touch make them ideal for tasks like sorting, packaging, and handling, addressing challenges that traditional rigid systems face. While current limitations in precision and control remain, advancements in soft robotics technology promise to enhance their capabilities. As the food industry moves toward more automation, soft robotics presents a promising solution for improving efficiency, reducing waste, and ensuring safe food handling.

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Paper ID: SR240614173223 DOI: https://dx.doi.org/10.21275/SR240614173223

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Author Profile

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