Universidad de Valladolid

Escuela de Doctorado Universidad de Valladolid

PROGRAMA DE DOCTORADO EN
INGENIERÍA INDUSTRIAL

TESIS DOCTORAL:

CONTRIBUCIONES AL DISEÑO Y MODELADO DE GARRAS ROBÓTICAS MULTIFUNCIÓN CON MATERIALES DEFORMABLES

CONTRIBUTIONS TO THE DESIGN AND
MODELLING OF MULTIFUNCTIONAL ROBOTIC
GRIPPERS WITH DEFORMABLE MATERIALS

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Abstract

The adoption of robotic manipulation in industrial settings has reached significant maturity, enabling process automation, efficiency gains, and cost reductions. However, applying similar technologies to sectors such as agriculture remains an underexplored challenge. Agriculture requires robotic systems capable of safely operating in unstructured environments, handling delicate objects like fruits and vegetables, and ensuring compatibility with dynamic and unpredictable tasks. Soft robotics, characterized by the use of compliant and adaptable materials, emerges as a transformative solution for these challenges. By utilizing materials with elasticity moduli comparable to biological tissues such as muscles or skin, soft robotics enables precise manipulation and interaction with the environment, making it particularly suitable for agricultural applications.

This thesis investigates the potential of soft robotics in agriculture, focusing specifically on the design, modelling, and control of soft grippers for harvesting tasks and pick-and-place operations. Through the development of three soft gripper designs, this research explores the use of advanced materials such as thermoplastic elastomers (TPE) and polydimethylsiloxane (PDMS), alongside manufacturing techniques like 3D printing and moulding, to create prototypes designed with an emphasis on cost-effectiveness, modularity, and adaptability. These grippers were tested in real-world conditions using dual-arm robotic systems, showcasing their suitability for handling high-value crops in unstructured environments.

The research also introduces advanced simulation and modelling techniques to address the inherent complexities of soft actuators. Using methods such as the Sparse Identification of Nonlinear Dynamics (SINDy) algorithm, the thesis accurately characterizes actuator behaviour, minimizing the need for extensive experimental data. Finite Element Method (FEM) simulations were employed to model soft contact interactions and deformation under load, further refining the gripper designs. Virtual representations of objects, combined with real-time sensing, enhanced the development of grip planning strategies, ensuring precision and efficiency in dynamic agricultural tasks.

Additionally, the thesis emphasizes the importance of quality control and standardization in soft robotics. Novel methodologies for performance assessment were

developed, including computer vision-based techniques and tools for measuring displacement and contact forces. These efforts aim to establish benchmarks for the reliable integration of soft robotics into commercial and agricultural systems.

In summary, this thesis bridges the gap between industrial soft robotics and agricultural needs, contributing innovative designs, methodologies, and control strategies for soft grippers. By addressing key challenges in material selection, modelling, and practical implementation, the research lays a foundation for advancing soft robotics in agriculture and other sectors that demand safe and adaptable robotic solutions.

Resumen

Esta tesis tiene como objetivo principal investigar el potencial de la robótica blanda en aplicaciones agrícolas, con un enfoque específico en el diseño, modelado y control de pinzas blandas para tareas de cosecha y operaciones pick-and-place. Se busca reducir la brecha entre los desarrollos en robótica blanda industrial y las necesidades particulares del entorno agrícola, caracterizado por su variabilidad y la manipulación de objetos delicados.

Se desarrollaron tres diseños de pinzas blandas utilizando materiales como elastómeros termoplásticos (TPE) y polidimetilsiloxano (PDMS), mediante técnicas de fabricación como impresión 3D y moldeo. Los prototipos fueron evaluados en escenarios reales con sistemas robóticos de doble brazo. Para el modelado dinámico se aplicaron algoritmos de identificación como SINDy (Sparse Identification of Nonlinear Dynamics) y simulaciones mediante el Método de Elementos Finitos (FEM) para estudiar la deformación y las interacciones de contacto. Además, se integraron sensores y representaciones virtuales de objetos para mejorar la planificación del agarre. Se implementaron técnicas de visión por computador y herramientas de medición de desplazamientos y fuerzas para evaluar el desempeño de las pinzas.

Los diseños propuestos demostraron una manipulación eficaz de cultivos de alto valor en entornos no estructurados, validando su funcionalidad en condiciones reales. El uso de SINDy permitió modelar el comportamiento dinámico de los actuadores con menor dependencia de datos experimentales. Las simulaciones FEM contribuyeron a optimizar la geometría de las pinzas. Las estrategias de planificación basadas en datos sensoriales en tiempo real mejoraron la precisión en tareas dinámicas. Las metodologías de evaluación establecieron parámetros cuantitativos útiles para estandarizar el rendimiento de sistemas de robótica blanda en agricultura.

La investigación evidencia que la robótica blanda, mediante el uso de materiales y estrategias de control adaptables, puede ofrecer soluciones viables para tareas agrícolas que requieren manipulación segura y eficiente en entornos no estructurados. Los avances en diseño, modelado y evaluación desarrollados en esta tesis constituyen una base sólida para su integración en sistemas agrícolas comerciales y sientan las bases para futuras aplicaciones en otros sectores con requerimientos similares.

Dedication

"Nicht wirklich Wichtiges ist ohne Leidenschaft erreicht worden"

(Nada realmente importante se ha conseguido sin pasión)

Georg Wilhelm Friedrich Hegel

Acknowledgements

A mi padre, Gaspar, por ser el principal ideador de que yo realizara esta tesis y quien, junto a mi madre, Teresa, me ha dado fuerzas durante todo este tiempo.

A mis hermanos, Carlos y María, por ser una fuente de apoyo continuo.

A Roemi Fernández, por ser una directora de tesis implicada y una trabajadora incansable, que ha permitido, con esfuerzo, lograr la publicación de cada artículo y patente. A ella, mi más sincera admiración.

A Gregorio Sainz, por su constante disposición y atención incondicional.

A Pablo González-de-Santos, por inculcarme en mis primeros pasos en la investigación el lema que me acompaña hasta hoy: ’Sin prisa, pero sin pausa’.

A Manuel Ángel Armada, alias Chicho, por ser una fuente de inspiración para la continuidad de mi carrera investigadora y porque, gracias a escuchar sus ‘batallas’ me ayudan a afrontar retos futuros en este sector tan cambiante y complejo como lo es la investigación en el campo de la robótica.

A la Universidad de Valladolid y a todo su personal, en particular a la Escuela de Doctorado (EsDUVa), por resolver de forma rápida y eficaz cada duda o cuestión que ha ido surgiendo durante el transcurso del doctorado.

A aquellos que trabajaron conmigo en el Centro de Automática y Robótica (CAR) CSIC-UPM en Arganda del Rey y en el ‘Leibniz-Institut für Agrartechnik und Bioökonomie’ (ATB) en Potsdam, con quienes tuve la suerte de compartir mi tiempo, tanto en España como en Alemania.

Contents

List of Figures

List of Tables

Abbreviations

DEAs	Dielectric Elastomer Actuators
DoFs	Degrees of Freedom
FEAs	Fluidic Elastomer Actuators
FEM	Finite Element Method
IPMCs	Ionic polymer-metal composites
MR	Magnetorheological
PCBs	Printed Circuit Boards
PDMS	Polydimethylsiloxane
ROS	Robot Operating System
SINDy	Sparse Identification of Nonlinear Dynamics
SMAs	Shape-Memory Alloys
SPAs	Soft Pneumatic Actuators
STL	Standard Triangle Language
ToF	Time of Flight
TPEs	Thermoplastic Elastomers
TPU	Thermoplastic polyurethane
URDF	Unified Robot Description Format

Part I

INTRODUCTION

Introduction and Objectives 1

1.1 Introduction

The concept of manipulation, understood as the interaction of an entity with its environment—whether involving living beings or inanimate objects—plays a crucial role in the evolution of species. The type of manipulation skills that a living entity possesses shapes its behaviour and influences how it interacts with its surroundings. A complex capacity for manipulation, with a wide range of movements and fine dexterity, has led humans to become what they are today. The ability to handle small objects without causing damage and manipulate items in unstructured environments, where objects are not arranged in a predictable order, has endowed humans with such intellect that enables them to perform tasks requiring precision and agility, significantly contributing to their evolutionary progress.

While all living beings possess some degree of manipulation ability, replicating this complexity in an artificial entity or robot if highly challenging. Since the inception of robotics, there has always been a strong motivation for robots to acquire this skill, enabling them to interact with their environment through what is known as an end-effector. An end-effector is defined as a tool located at the end of a robot, typically a robotic arm, which allows interaction with the surrounding environment. The first approaches by early robotics researchers involved the use of rigid materials, actuated in various ways, either by means of servomotors or pneumatic actuators. These types of approaches continue to exist and evolve today. New rigid materials, smaller actuators, and more complex sensing and control systems are increasingly being used. This latter sentence is a common denominator in 21st-century robotics.

The difficulties that arise from using rigid materials and linear movements produced by the actuators, as well as the challenges in control and the high cost of sensors, have led to the development of alternative approaches focused on creating adaptable, cost-effective, and easily controllable robotics. This new branch of robotics, known as soft robotics, involves the use of soft, deformable, and flexible materials to create robots that can interact with their surroundings in a safe yet firm manner, whether the environment is structured or not. Within soft technology, there is a field of research focused on the development of soft end-effectors or soft grippers, which studies how this new type of robotics can interact with the environment with certain advantages over traditional rigid robotics.

1.2 Overview of soft grippers and motivation

The expansion of robotics across various productive sectors has rapidly accelerated over the last decade. Initially, classical rigid robotics dominated industrial applications, featuring large robotic arms constructed primarily from rigid materials such as steel or aluminium. At the time, sensing and control technologies were not advanced enough to enable these robotic systems to operate effectively in dynamic or unstructured environments, confining them to controlled settings where the objects to be manipulated were always consistently positioned. Furthermore, these robots were typically enclosed in safety cages to protect workers, as their rigidity and lack of advanced safety features posed significant risks.

With advancements in sensing, control technology, and the development of more efficient and compact motors and actuators, robotics reached a new level of development at the beginning of the 21st century. Today, many robotic companies offer a range of solutions, including robotic manipulators that can safely collaborate with humans. However, there is still a pending challenge related to the implementation of robotics in unstructured environments. Overcoming this challenge could enable robotics to expand into other sectors, such as services and agriculture.

To address this demand, two main lines of research in robotic manipulation are currently being investigated. The first approach focuses on adapting robotics to unstructured environments using complex and adaptive control systems. These systems help interpret the work environment and provide viable solutions to complete the tasks efficiently and safely, minimizing potential damage during interactions. This line of research requires a wide array of diverse sensors to monitor the work environment, along with focused efforts to develop trajectory planning algorithms that solve the various proposed tasks while avoiding collisions and their associated consequences.

On the other hand, a second approach that has gained traction in recent years takes inspiration from biological systems to address the challenges posed by unstructured environments. This emerging field, known as soft robotics, involves the use of soft and flexible materials that can safely adapt to these environments, simplifying interaction control. Soft robotics allows the execution of various tasks while ensuring the safety of both the robot and the environment.

Within this context, one particular branch of soft robotics that has received special attention is the design of soft grippers. These end-effectors are seen as a promising solution for handling delicate and irregularly shaped objects, thanks to innovative actuation technologies and design geometries. Among the most notable actuation technologies are pneumatic actuators, tendon-driven systems, and electroactive materials, all of which allow for flexible and adaptive control while ensuring safe interaction with the environment. In terms of the geometries of soft grippers, they can be grouped into bio-inspired designs, which mimic natural forms, and functional designs, focused on performing specific tasks to maximize the adaptability and grip offered by soft technology. In summary, all these advancements aim to push the boundaries of manipulation robotics, particularly in areas traditionally dominated by rigid robotics or where rigid technology has struggled due to the inherent limitations of stiff materials and the complexity of controlling them in unstructured environments.

Soft robotics thus addresses the critical issue of robot-robot, robot-human, and robot-environment interaction. Thanks to the materials used, as well as the diverse forms of actuation, this type of robotics allows for integration into any sector, whether structured or unstructured. Additionally, the cost-effectiveness of these materials and the simplicity of their manufacturing process enable rapid and inexpensive adaptation to variations that may arise in the environment. However, we are still in the early stages of developing this technology. While soft robotics is well-known in the industrial sector, as evidenced by the emergence of companies offering various solutions, it remains relatively unknown in the medical and agricultural sectors. Therefore, soft robotics holds the potential for implementation in these sectors, offering solutions for tasks where classical robotics cannot reach.

This is the context in which this thesis is framed, aiming to provide solutions in the form of soft robotic grippers specifically designed for the agricultural sector. The deliberated selection of agriculture as the focus of this thesis reflects the sector's unique challenges and opportunities. The advancement of soft robotics within the industrial sphere, in what is now known as Industry 4.0, and its success, particularly in the food industry, is well-documented. However, these soft solutions have the potential to be exploited in other sectors, introducing robotics into areas where its implementation has been minimal. The agricultural sector presents specific challenges that makes it a compelling area for the implementation of new technologies. Firstly, the unstructured and ever-changing environment poses significant difficulties for robotics, requiring systems that can adapt to unpredictable and adverse conditions. Secondly, there is a clear need for automation within the sector, driven by labour shortages and population growth. Thirdly, there is a demand for robotics that can safely interact with the environment, perform various tasks related to the sector, and coexist with humans in the workplace. These factors create a perfect breeding ground for the introduction of a new type of robotics that, with its unique advantages, can address these challenges and contribute to the modernization of the primary sector, which is key to any society.

1.3 Objectives

The overall objective of this doctoral thesis is to design multifunctional end-effector systems based on the principles of soft robotics, capable of grasping objects in unstructured environments and manipulating them while ensuring their stability. To accomplish this overarching goal, the research is focused on the modelling, control and assessment of various mechanisms and actuators for soft robotic end-effectors that exhibit enhanced adaptability and dexterity across a wide range of applications. In this context, the specific objectives of this thesis are the following:

1. Propose a design methodology for multifunctional grippers based on deformable structures and materials. To that end, a comprehensive analysis of the various geometries and materials explored in the literature is conducted, focusing on their mechanical properties, deformation behaviours, and adaptability to different tasks. In addition, biomimetic data collected through motion-tracking gloves is used to explore nature-inspired movement patterns for specific applications. The proposed methodology aims to achieve designs with capability to adapt to various shapes, ensuring damage-free grip while maintaining firm manipulation.

2. Establish a theoretical and practical framework for the modelling of soft end-effectors. This framework entails developing mathematical models that accurately capture the unique behaviours and deformations of soft materials under varying operational conditions. Unlike traditional rigid robotic systems, soft end-effectors require a modelling approach that accounts for their flexibility, non-linear responses, and continuous shape changes. By establishing this theoretical foundation, the research aims to provide a robust basis for predicting and controlling the motions of soft grippers, enabling their effective application in dynamic and unstructured environments where precise manipulation and adaptability are crucial.

3. Explore advanced motion control methods for soft end-effectors. While various approaches for motion control have been proposed in the literature on soft

grippers, many either fail to accurately capture the gripper's trajectory or demand extensive datasets for modelling. This research proposes leveraging novel data-driven models combined with vision-based techniques for data collection, offering a reliable alternative by requiring smaller amounts of high-quality calibration data. By utilizing these vision-based techniques, the study aims to enhance the precision and adaptability of soft grippers, allowing for more effective manipulation in complex and non-structured environments.

4. Develop devices and quality control methodologies for the characterization of soft robotic grippers. One of the key challenges in soft robotics is the lack of standardized methods for measuring the characteristics of various soft actuators designs. In rigid robotics, it is common to evaluate parameters such as maximum load capacity or gripping force. However, measuring these and other values presents a significant challenge in soft robotics, as no concrete method exists for this purpose. To address this, specific tools for measuring displacement and contact forces, as well as methodologies based on computer vision to ensure the quality control of soft actuators are proposed, aiming to establish a standard that enables the comparison of different designs and facilitates the transition of this technology to the market.
5. Evaluate and validate the proposed solutions through simulations and experimentation. The initial phase involves analysing the interaction between the object and the soft actuator, along with virtualizing the manipulated object to gain critical insights into the grippers' behaviour prior to physical testing. The simulated results will then be validated in real-world settings, encompassing tangible objects and unstructured agricultural environments, to rigorously assess the advantages of soft robotics in these challenging scenarios.

1.4 Methodology

The first crucial step in undertaking this doctoral thesis was to conduct an extensive analysis of the existing literature on soft robotics, with a particular focus on soft end-effectors. This comprehensive review aimed to assess the current state of the art, identify key developments, and uncover gaps in knowledge that could be addressed through further research.

During this study, a clear need for the development and implementation of soft robotic technology within the agricultural sector was identified. Recognizing this, an in-depth analysis was carried out to explore the potential for integrating soft robotics into various agricultural applications. This analysis specifically focused on the automation of tasks related to different fruit crops, with an emphasis on the advancements in soft robotics that could be applied to fruit harvesting. The study highlighted the pressing need for innovative solutions to automate these labour-intensive processes, which are currently constrained by the limitations of traditional rigid robotics.

Building on these insights, the overall objective of this thesis was defined: to contribute to the development of multifunctional robotic end-effectors based on deformable materials, specifically designed for use in agricultural environments to automate the harvesting of fruit crops. In addition to agricultural applications, the research also aims to extend the use of these soft grippers to other field of applications, such as the industrial sector, where they can be employed for pick-and-place tasks involving delicate objects.

Therefore, the methodology for achieving the specific objectives outlined in this thesis involves the following key phases:

- **Problem definition:** The research begins with an in-depth synthesis of existing literature in soft robotics, particularly focusing on soft end-effectors. This phase identifies key gaps in current knowledge and technology, specifically highlighting the need for advanced robotic systems in unstructured environments such as agriculture. This critical analysis helps refine the problem statement and guides the subsequent research phases.

- **Conceptual design and theoretical modelling:** Based on the insights gained from the literature review, the next phase involves the conceptual design of innovative soft grippers. Here, the focus is on translating the theoretical principles of soft robotics into practical designs. A theoretical framework is developed to model the kinematic and dynamic behaviour of these grippers, accounting for their unique material properties and the demands of real-world applications.

- **Technology development and system integration:** In this phase, the research advances from theory to practice. Vision-based motion control systems and data-driven algorithms are explored and integrated into the soft gripper designs. The aim is to develop robust and adaptive systems capable of precise manipulation in dynamic environments. This phase also includes the refinement of the grippers' mechanical design, ensuring they meet the required specifications for multifunctional use.

- **Simulation and preliminary testing:** Before full-scale experimentation, the developed grippers and control systems undergo rigorous simulation and preliminary testing. These activities validate the theoretical models and allow for early detection of potential issues. The simulations provide valuable data that guide further refinements in design and control strategies.
- **Experimental validation in relevant conditions:** Following successful simulations, the proposed end-effectors are subjected to experimental testing in both controlled and real-world environments. This phase is crucial for evaluating the performance, adaptability, and reliability of the developed systems in practical applications, such as agricultural harvesting and industrial pick-and-place tasks. The experimental results are systematically analysed to assess the effectiveness of the proposed solutions.
- **Optimization and iterative enhancement:** Based on the outcomes of the experimental phase, an optimization process is conducted to further improve the performance and versatility of the proposed solutions. This involves refining the design, control algorithms, and integration processes to ensure that the final systems are not only effective but also practical for adoption in their target sectors.
- **Cross-sector exploration:** The final phase explores the potential for adapting the developed soft end-effectors beyond their initial agricultural focus. Preliminary studies assess the applicability and impact of the technology in new contexts, providing insights that could guide future innovations and applications.

1.5 Structure of the thesis

This doctoral thesis is organized as follows:

Chapter 2 reviews the state of the art in soft robotics, focusing on the design, manufacturing, sensing, and control of soft grippers, as well as the soft actuators that constitute them. This chapter provides an overview of current advancements, emerging trends, and future perspectives. It also discusses the application of soft end-effectors across several sectors, including industrial, medical and agricultural fields.

Chapter 3 offers a detailed analysis of the design, fabrication, modelling and control of different soft gripper designs, including both modular and reconfigurable options.

The proposed solutions are targeted at addressing tasks such as harvesting in the agricultural sector and pick-and-place operations in the industrial sector.

Chapter 4 delves into the sensing, simulation and control mechanisms of soft actuators, as well as the modelling of a reconfigurable hybrid gripper's grasping capabilities using the Sparse identification of non-linear dynamics (SINDy) algorithm and virtual object representation.

Finally, Chapter 5 summarizes the principal findings of the research, highlighting the contributions made to soft gripper design and modelling, sensor integration, simulation and control systems. A schematic Figure (1.1) provides a visual overview of the thesis's key achievements, including published articles, international conference presentations, and patents generated during this doctoral work. Additionally, this chapter outlines potential future research directions in these areas, providing a roadmap for continued exploration and innovation.

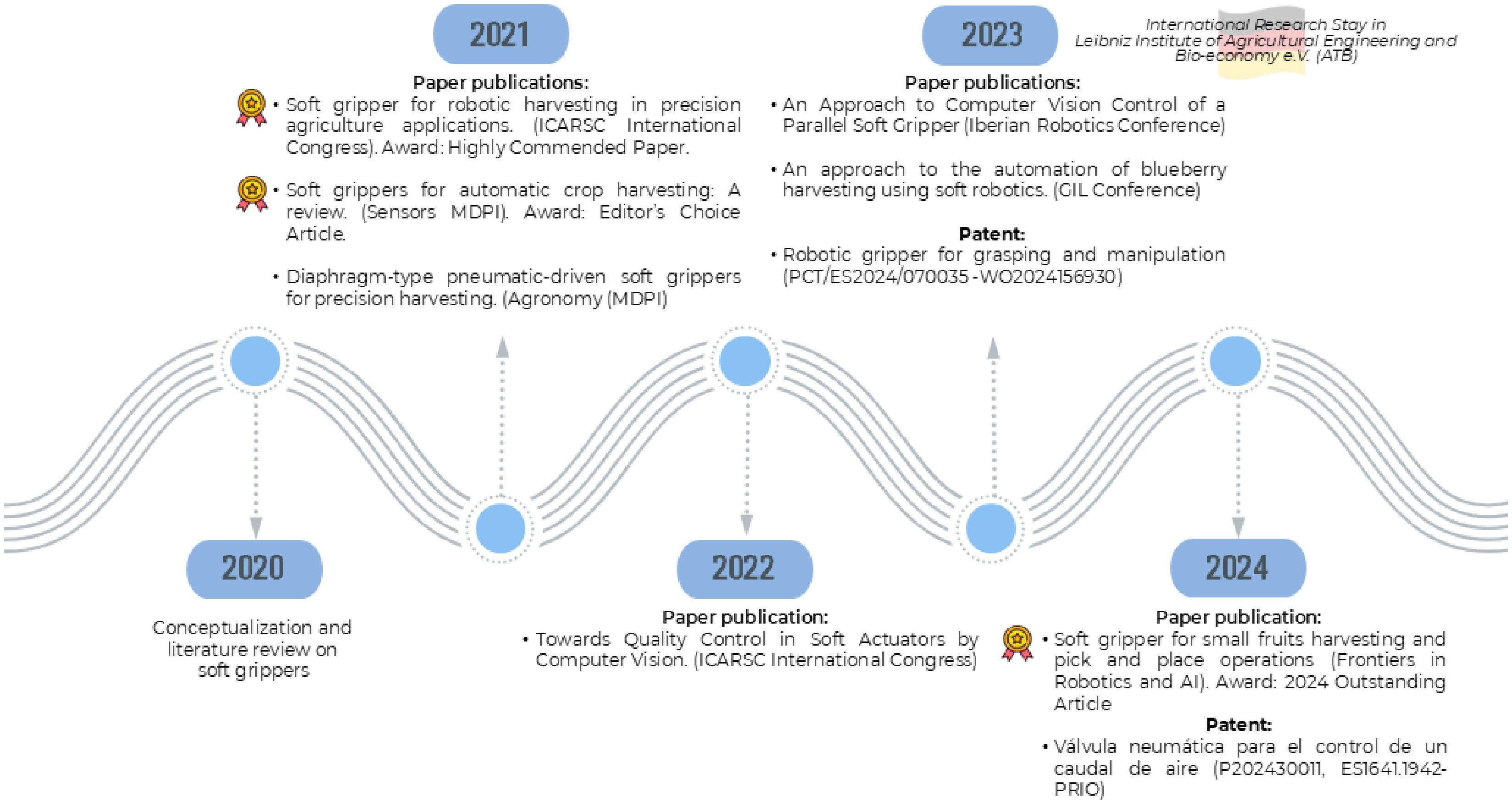

Fig. 1.1.: Timeline summary of Ph.D. achievements.

Part II

STATE OF THE ART

2 State of the Art

Soft robotics is an emerging field within robotics that focuses on the use of flexible and deformable materials to emulate the adaptability and softness found in natural systems. This approach offers significant advantages in applications requiring safe and gentle interaction with various environments, particularly in manipulation tasks. Soft grippers stand out in manipulating objects of various shapes, sizes, overcoming the limitations of traditional rigid actuators. Their design involves intricate geometries and advanced materials, while integrating sensing and control systems requires solutions that provide accurate feedback and enable adaptive handling.

The production of soft devices also presents unique challenges, leading to advances in 3D printing techniques and the development of custom moulds. Despite its promising potential, soft robotics faces considerable challenges, including material durability, precise control of complex motions, and effective sensor integration. However, the range of applications is rapidly expanding, covering sectors such as healthcare, industry, and even agriculture. This trend marks a shift in how machines interact with their environments and facilitates the adoption of robotics in areas where it was previously more challenging.

The following chapter provides a comprehensive review of the current literature, highlighting recent advancements in soft gripper design, sensing, control and manufacturing. It also explores the challenges faced and the emerging applications in this growing field.

2.1 Soft robotics: A conceptualization

The concept of soft robotics has been described in multiple ways within the literature, yet a common definition can be identified. Soft robotics is understood as a multidisciplinary area that merges mechatronics, materials science, automation, and biomechanics. This field focuses on the use of flexible and deformable materials and systems, aiming to create robots capable of operating in unstructured environments

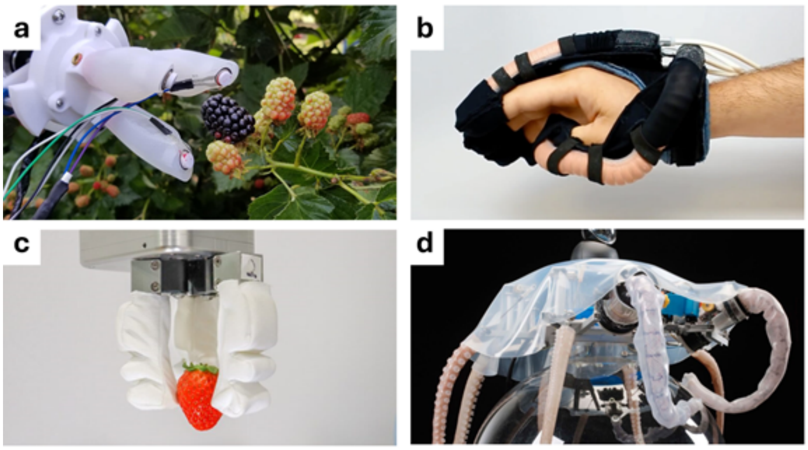

Fig. 2.1.: Soft robotics applications. **(a)** Robotic harvesting grippers [71]. **(b)** Rehabilitation gloves [160]. **(c)** Robotic gripper for pick-and-place operations [9]. **(d)** Mobile robotics [180].

and interacting safely with humans. It also integrates novel manufacturing technologies, such as 3D and 4D printing, which enable the creation of structures with intricate shapes, diverse functions, and varied properties. Currently, soft robotics has applications in a wide range of domains, including industry, healthcare—particularly in surgical procedures and rehabilitation—as well as agriculture. Some of these applications are shown in Figure 2.1.

2.1.1 Soft grippers

Soft grippers are end-effectors that utilize soft, flexible, and compliant materials, along with specific actuation methods, enabling them to effectively hold and manipulate objects. Their adaptability, robustness, and ability to interact gently are inspired by natural organisms, making them ideal for dynamic tasks and safe interactions in unstructured human environments [82]. Soft grippers rely on various technologies and actuation methods to achieve these capabilities, with soft actuators forming a fundamental component of their design.

Soft technologies refer to the theories, techniques, and procedures that enable the primary functions of soft robotic grippers, including actuation, gripping, and shape control. Although numerous authors have proposed different classifications of soft technologies [98, 107, 123, 172, 203], their main objective is to ensure safe interaction with humans and the environment by employing materials with mechanical properties similar to biological tissues [200]. Various reviews on soft grippers [23, 82, 98, 108, 109, 172, 203, 232] offer distinct classification methods.

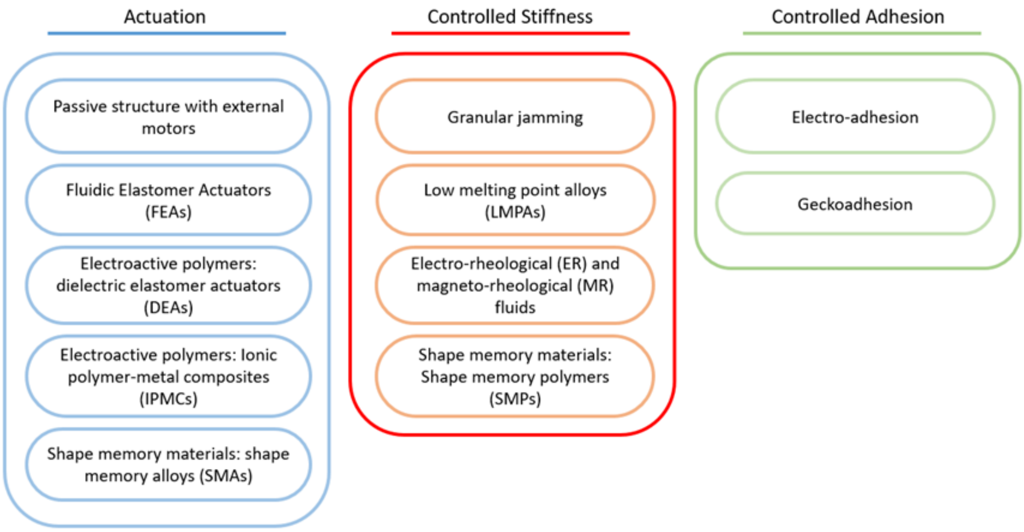

Fig. 2.2.: Soft gripping technologies classification proposed by [184].

A common approach divides soft gripping technologies into three categories [40, 184]: (*i*) actuation, (*ii*) controlled stiffness, and (*iii*) controlled adhesion. However, many designs integrate features from multiple categories. Figure 2.2 presents a classification of current soft gripping technologies based on these principles.

Despite the relatively recent advent of soft robotics, various soft grippers are already available, evolving from traditional rigid gripping tools. These early designs, such as electromechanical grippers, marked the initial step toward soft robotics. Over time, advancements in materials and actuation technologies, particularly soft actuators, have enabled the development of more adaptive and versatile grippers. For instance, pneumatic actuators have become a key actuation method, allowing soft grippers to deform in response to changes in internal pressure. Additionally, technologies, such as tendon-driven systems, shape-memory materials, and electro-adhesion, have further expanded the capabilities of soft grippers, enabling them to handle a wide range of tasks [82, 203, 232].

2.1.2 Soft actuators and actuation methods

At the core of any soft gripper lies the soft actuator, the fundamental component that enables movement and interaction with the environment. Soft actuators are deformable structures that, when activated, can bend, stretch, twist, or contract, depending on the type of actuation employed. These actuators are essential not only for robotic grippers but also for mobile robots, medical devices, and assistive

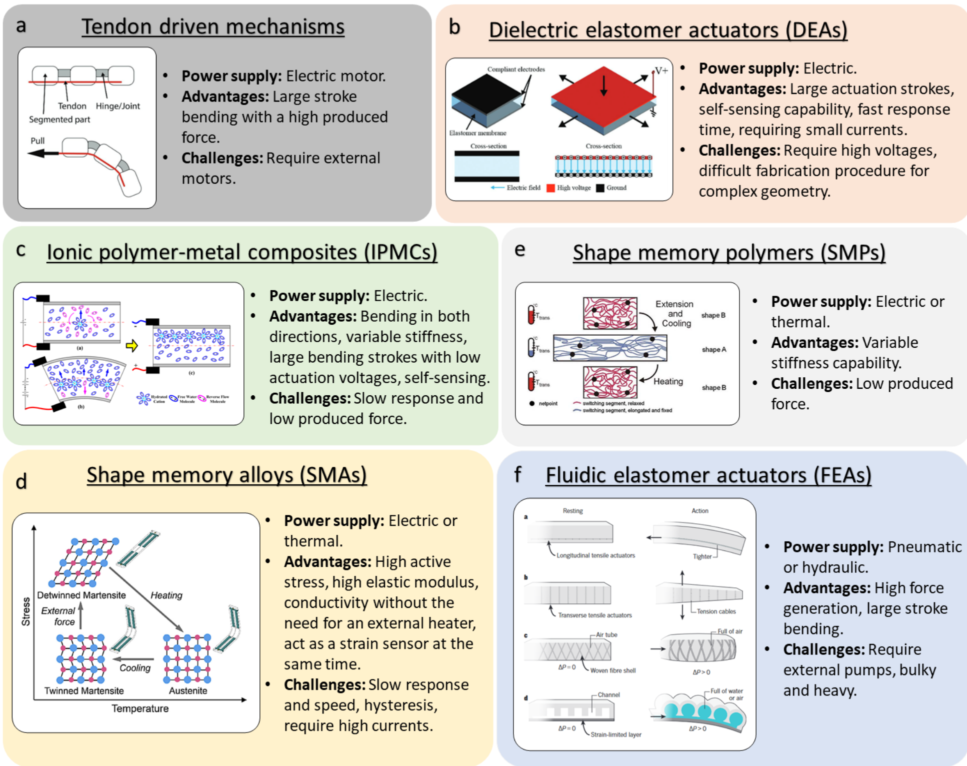

Fig. 2.3.: Different soft actuator types [154, 184].

technologies. Their versatility is driven by the various actuation methods available, each offering its own advantages and challenges, as shown in Figure 2.3.

Among the many actuation technologies used in soft robotics, fluidic elastomer actuators (FEAs) are particularly prominent. These actuators, made from flexible materials like silicone, can generate significant forces and deformations by adjusting internal pressure. Their ease of fabrication and cost-effectiveness make them well-suited for a wide range of applications, including gripping, mobility, robotic manipulation, and even medical technologies [10, 19, 35, 36, 45, 59, 134, 159, 168]. Along with FEAs, other actuation systems like dielectric elastomer actuators (DEAs), magnetorheological (MR) fluids, and shape-memory materials, are frequently integrated into hybrid designs to enhance robotic capabilities and performance across diverse environments [48].

2.2 Design and manufacture of soft grippers

2.2.1 Soft grippers design

In the literature, various designs of FEAs can be found. These designs utilize anisotropic structures specifically engineering to achieve different movements, such as extension, contraction, bending, and twisting. The two predominant types of FEAs are fibre-reinforced actuators and pneumatic network actuators, commonly referred to as PneuNet. Each type of movement is examined below.

- Fibre-reinforced actuators

  These actuators consist of an elastomeric membrane with inextensible fibres strategically embedded in its surface. When air pressure is applied, the membrane expands in regions where the fibres do not restrict movement, resulting in a specific motion dictated by the orientation of the fibres.

  - Extension Movement: This design typically incorporates a cylindrical air chamber with fibres wrapped around its circumference, restricting radial expansion and guiding axial elongation when pressurized [38].

  - Contraction Movement: Contraction can be achieved using a configuration similar to extension actuators but by reversing the air supply direction. Alternatively, some actuators use a bellows structure with fibres arranged to pull the top of the bellows inward when pressurized [38].

  - Bending Movement: Bending actuators typically feature a cylindrical air chamber with fibres embedded on one side of the membrane. When pressurized, the non-reinforced side expands, causing the actuator to bend away from the reinforced side. The direction and degree of bending can be further controlled by varying the fibre angle and applied pressure [161].

  - Twisting Movement: Twisting actuators often use helical or asymmetric designs to generate rotational motion. Helical actuators consist of air chambers with fibres arranged in a helical pattern, causing twisting when pressurized. Asymmetric designs may incorporate offset air chambers or asymmetric shapes that generate a torsional moment when pressurized [38].

- Pneumatic Network Actuators (PneuNet)

  Unlike fibre-reinforced actuators, PneuNet actuators operate based on the principle of individual air chambers embedded within an elastomer body. When air pressure is applied, the shape of these chambers changes, resulting in actuator movement.

  – Bending Movement: PneuNet bending actuators commonly consist of multiple air chambers arranged in layers or in a radial configuration within an elastomer matrix. When specific chambers are pressurized, the actuator bends toward the side of the inflated chambers. Slow PneuNets, which consists of a block of silicone rubber with embedded air chambers, are suitable for applications requiring high force and slow speeds. In contrast, fast PneuNets, which feature gaps between the inner walls of each chamber, exhibit faster response times, making them suitable for dynamic applications [135].

  – Other Movements: Although bending is the most common movement achieved by PneuNet actuators, extension, contraction, and twisting can also be achieved through the strategic design of the air chamber shapes, sizes, and arrangements) [206, 215].

- Novel and unconventional designs

  In addition to conventional designs, there are various novel and unconventional SPAs (Soft Pneumatic Actuators), as illustrated in Figure 2.4 of the article. These innovative structures, including bellows, origami, and membrane-based designs, further expand the capabilities of SPAs, enabling multidirectional movements, stiffness changes, and enhanced dexterity [54, 67, 86, 92, 128, 186, 208, 217, 218, 229, 230, 233].

  In conclusion, while there are various types of soft pneumatic actuator designs, the literature shows a clear predominance of PneuNet actuators. PneuNets are favoured due to their faster response times and ease of manufacture. Unlike fibre-reinforced actuators, PneuNet actuators do not require an additional manufacturing step to place fibres, which helps avoid potential complications during production. Additionally, PneuNet geometries can be more complex, as fibre reinforcement requires symmetry in the actuator design to enable a continuous spinning process around the actuator body.

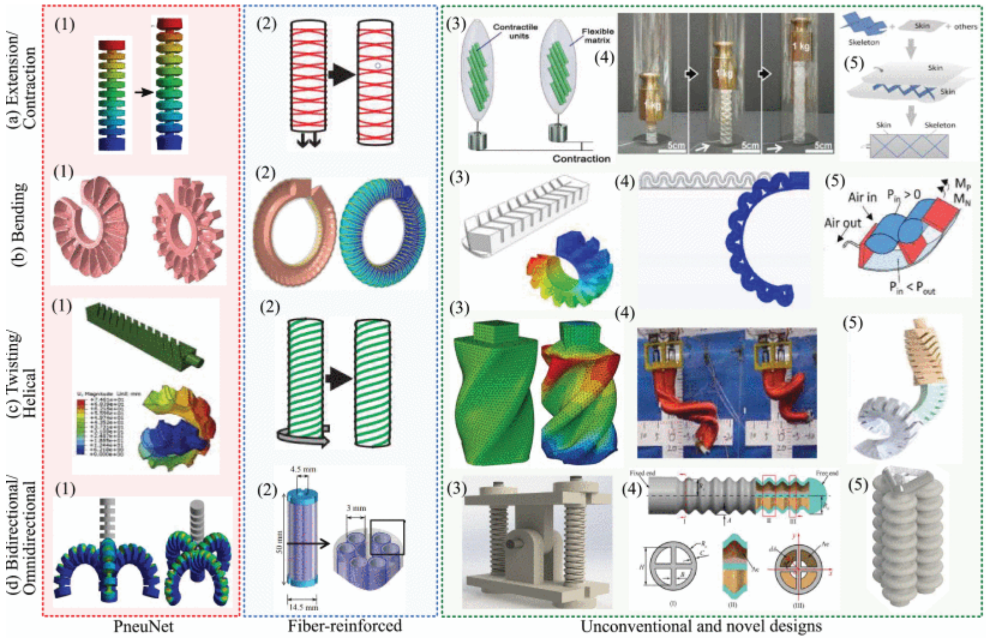

Fig. 2.4.: Soft pneumatic actuator designs reviewed by [216]. **(a)** Extension and contraction SPAs: (1) [215], (2) [38], (3) [208], (4) [128] and (5) [229]. **(b)** Bending SPAs: (1) [135], (2) [161], (3) [233], (4) [67] and (5) [54]. **(c)** Twisting and helical SPAs: (1) [206], (2) [38], (3) [217], (4) [230] and (5) [86]. **(d)** Bidirectional and Omnidirectional SPAs: (1) [215], (2) [1], (3) [186], (4) [218] and (5) [92].

2.2.2 Modelling

Modelling of FEAs can be categorized into three main groups:

- Analytical methods: These methods employ principles from mechanics, such as Euler-Bernoulli beam theory, to model the behaviour of SFAs. They are effective for SFAs with simple, symmetrical structures but are less accurate when dealing with hyperelastic materials like silicone, which undergo large deformations. Examples of these models include the backbone curve approach and the constant curvature model (CCM) [33, 90, 222].

- Numerical methods: The most commonly used technique is the finite element method (FEM), which is particularly effective in modelling the nonlinear behaviour of SFAs. FEM enables the definition of material properties, geometry, boundary conditions, and the compressibility effects of the pneumatic cavity. Various hyperelastic material models, such as Mooney-Rivlin, Ogden, Yeoh, and Neo-Hookean, are typically utilized in FEM to characterize the mechanical properties of silicone and other elastomers used in soft actuators. However, offline FEM methods can be computationally intensive, which limits their application in real-time scenarios [14, 61].

- Model-free methods: These approaches do not rely on an explicit physical model but instead use sensor data-driven techniques, such as machine learning or vision-based systems, to estimate the behaviour or response of the actuator. Sensor data, such as the actuator's tip position or deformation, is used to train algorithms that learn the actuator's behaviour through real-world interaction. These methods are particularly useful when the system dynamics are too complex or nonlinear to be accurately captured by traditional physical models. However, their performance heavily depends on the quality and quantity of the training data [109, 112].

Each modelling approach has its own strengths and weaknesses. Analytical methods are simple but less accurate when applied to hyperelastic materials. Numerical methods, such as FEM, offer higher precision but are computationally expensive. Model-free methods show potential but depend heavily on the quality of the training data. The choice of modelling method depends on the complexity of the SFA, the required precision, and any computational constraints.

2.2.3 Materials and Manufacturing

As mentioned above, a wide variety of soft grippers have been proposed. Soft components typically used in the actuators of these grippers include urethanes, hydrogels, braided fabrics, hydraulic fluidics and polymers, such as silicone elastomers [39]. However, actuators based on silicone elastomers have attracted strong interest due to their low cost and ease of manufacture, as they do not require complex machinery or highly skilled labour. In addition, these compliant materials offer advantages in terms of safety when interacting with biological products, making them appropriate candidates for agricultural applications. Figure 2.5 presents a bar graph showing the commercially available materials (silicone elastomers and other polymers) most frequently reported in the soft robotics literature and commonly used for implementing soft grippers.

Several of these soft materials, particularly silicone elastomers, can be modelled as rubber elastomeric membranes that are hyperelastic and nearly incompressible. Various approaches using free energy density functions have been developed to describe the phenomenological constitutive models of rubber-like materials, such as the Neo-Hookean, Mooney–Rivlin [133, 165], Ogden [151] and Gent models [63].

As shown in Figure 2.5, the five most commonly used materials are Dragon Skin, Ecoflex, polydimethylsiloxane (PDMS), Elastosil M4601 and Smooth-Sil, all of

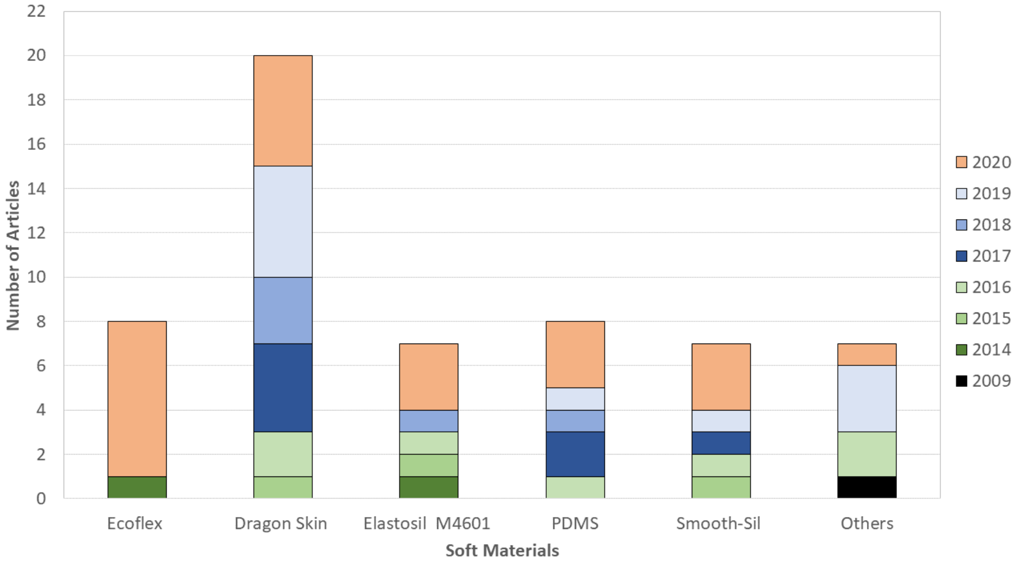

Fig. 2.5.: Silicone elastomers and other polymers used in soft robotics literature, as well as the corresponding number of citations. For this graph, 45 articles were examined: Ecoflex [41, 53, 69, 79, 89, 100, 135, 148], Dragon Skin 10/20/30/FX-Pro [11, 15, 32, 38, 42, 59, 75, 77, 105, 110, 113, 126, 182, 211–213, 224, 228, 239, 240], Elastosil M4601 [59, 69, 80, 135, 161, 174, 195], PDMS [24, 58, 79, 169, 182, 207, 242], Smooth-Sil [38, 42, 53, 59, 113, 126, 195] and Other Polymers [4, 5, 78, 122, 190, 225, 226].

which are silicone elastomers. Other polymers include Agilus30/VeroClear, ultra-high molecular weight polyethylene, electrostatic discharge (ESD) plastic sheet, thermoplastic elastomers (TPEs) and thermoplastic polyurethane (TPU).

Although no specific studies categorically confirm the suitability of these materials for agricultural applications, their safety data sheet declare them as non-hazardous substances. However, it would be advisable to conduct studies analysing the life cycle of soft actuators made from these materials to determine whether their degradation could leave particles on the manipulated products.

Dragon Skin, Ecoflex and Smooth-Sil are commonly used for manufacturing objects outside the scientific field, making it difficult to determine their exact chemical compositions. However, these materials are versatile, easy to use and handle, and relatively low-cost compared to other silicones, with hardness ranging between 10 and 50 Shore A. Elastosil M4601 is highly resistant to bending and elongation; it has low viscosity in its uncured form, making it easy to mould, and its hardness is approximately 28 Shore A. PDMS is known for its high elasticity [88], and as a thermoset [58] material, its behaviour can be precisely modelled using FEM analysis due to its well-known chemical composition. Furthermore, the variation in PDMS hardness through different mixing ratios has been extensively studied in the literature [97, 99]. The main advantage of other soft materials, such as TPU and TPE, is their compatibility with 3D printed. Another advantage of TPU-95 is its durability (85A Shore hardness), which makes it suitable for agricultural environments where harmful collisions with objects are frequent [78].

A common advantage of all these silicones is their ability to cure at room temperature without the need for an oven, although an oven can be used to shorten the curing time.

- Manufacturing methods

  Soft grippers are manufactured using a variety of materials and techniques, with the selection depending heavily on the specific application and design requirements. [82] conducted a comprehensive review of the techniques used in soft gripper fabrication and categorized them as follows:

  - Casting and moulding of materials: This is one of the simplest and fastest methods for creating soft grippers. It involves using moulds, often 3D-printed, to shape structures made of silicone or other elastomers. This method enables rapid prototyping and low-cost development, making it ideal for early-stage iterations. It also facilitates the integration of pneumatic chambers for actuation, a common requirement in soft gripper designs. However, this technique can produce flat-structure manipulators, limiting the actuator's overall range of movements and dexterity. Additionally, certain fabrication issues, such as the formation of interstitial bubbles or delamination, can occur, which may reduce the mechanical integrity and lifespan of the actuator, particularly under repeated use.

  - Shape Deposition Manufacturing (SDM): This layered manufacturing method creates 3D objects through cycles of material deposition, partial removal, re-deposition, and the use of support and sacrificial material. This hybrid process allows for the creation of fully three-dimensional solid parts composed of multiple materials with different properties. It enables the creation of complex and intricate geometries, as well as the inclusion of sensors, circuits, or actuators.

  - Soft lithography: This technique, based on principles similar to photolithography, uses soft materials like silicone and PDMS to create stamped or relief surfaces. It is widely used for microfluidic applications and allows for the inclusion of channels for actuation, as well as materials such as fibre, paper, or plastic to provide some inextensibility. However, the layering process limits the ability to produce fully three-dimensional structures.

- Lost wax casting: This manufacturing method relies on the design of a wax core that defines the internal cavity of the soft actuator, enabling the creation of complex channels and intricate shapes that would be impossible to achieve with other methods. By eliminating the need for seams, whose most common associated problem is delamination, a monolithic body is guaranteed, significantly improving the actuator's durability and strength. Additionally, this technique facilitates the integration of heterogeneous components, such as multi-material layers or pneumatic conduits, achieving greater functionality and ease of connection to other systems.
- 3D printing: Advances in 3D printing have enabled the development of materials with softer and more elastic properties, making it a key technology for the rapid design and fabrication of soft robots, including soft actuators. This method allows for the creation of fully 3D-printed actuators using a mix of materials with different properties to achieve varying rigidity, flexibility, friction, or elasticity. However, the materials used in 3D printing, while flexible, can be relatively fragile compared to moulded rubbers, limiting their suitability for certain actuation methods. Spray deposition is another 3D printing method that can be used to develop soft elastomeric actuators by spraying uncured silicone onto a surface.

The latter manufacturing method is particularly promising due to its ability to eliminate the need for several moulding stages, simplifying the fabrication and reducing overall production time. Additionally, it enables the design and direct printing of more complex inner chambers or pneumatic networks, which are difficult or impossible to achieve with traditional moulding techniques. This allows for greater flexibility in the customization of actuator properties, leading to enhanced performance in applications requiring precise, intricate internal geometries.

2.3 Sensorization and control of soft grippers

Soft grippers, like other soft robotic systems, are characterized by their intrinsic deformability and compliance [125]. These features offer significant advantages in terms of adaptability and safety when interacting with dynamic and unpredictable environments. However, they also present challenges in terms of sensorization and control due to their high inherent number of Degrees of Freedom (DoFs). The complexity of soft actuator control is compounded by the need for precise feedback on parameters such as force, deformation, and position during operation.

Sensorization could play a crucial role in addressing these challenges. By integrating soft sensors into the actuators, the system can monitor and adapt to various conditions in real time. Recent innovations in soft sensing technologies, such as liquid metal-filled microchannels and 3D-printed resistive sensors, have demonstrated significant potential for enhancing soft grippers' functionality and versatility [183, 204]. These developments are particularly relevant for applications requiring precise interaction with delicate or irregular objects.

In addition to sensor-based approaches, sensorless techniques have emerged as a promising alternative for simplifying system designs while maintaining adequate force and displacement estimations. Sensorless systems leverage intrinsic properties of soft actuators—such as internal pressure and volume changes—to estimate outputs like force and position without the need for embedded sensors [91, 166]. These methods reduce fabrication complexity and costs, while maintaining sufficient accuracy for applications where absolute precision is not critical, such as agricultural automation or low-precision industrial tasks.

Following this, different control strategies have been developed to address the nonlinearity and high deformability of soft actuators. Control methods range from model-based approaches, which rely on physics-based simulations, to model-free methods based on pre-existing data from experiments. The subsequent sections will delve into these strategies, emphasizing how sensorization, both sensor-based and sensorless, integrates with control to enable the effective operation of soft grippers.

2.3.1 Soft Sensors and Sensorless Approaches

Soft sensors are increasingly becoming fundamental elements in the field of soft robotics due to their ability to provide enhanced flexibility, adaptability, and sensing capabilities that traditional rigid sensors cannot achieve. These innovative sensors are designed to integrate seamlessly with soft robotic actuators, enabling them to interact more effectively with complex and dynamic environments. As the field of soft robotics continues to evolve, researchers are focusing on developing new types of soft sensors that not only measure physical parameters such as pressure,

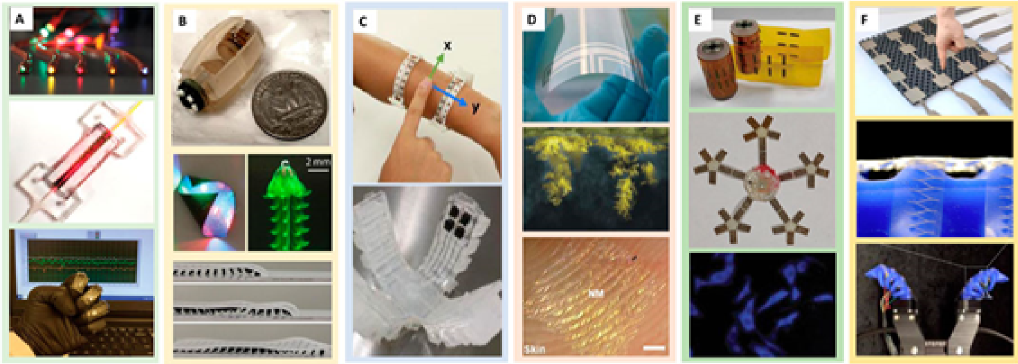

Fig. 2.6.: Overview of typical touchless sensors that have been used in soft sensing reviewed by [185]. **(a)** Photosensitive soft sensors [29, 198, 236]. **(b)** Magnetic-based sensing [70, 101, 164]. **(c)** Adaptive skin with IR sensors [150]. **(d)** Acoustic sensors [21, 60, 93]. **(e)** UV light sensing modules [49] (top and middle). Fluorescence sensor [27] (bottom). **(f)** Capacitive bimodal sensor array made entirely of textiles [227] (top) and multimodal sensor network integrated with a soft robotic gripper [74] (bottom).

deformation, and temperature but also contribute to the control and functionality of soft robotic actuators by providing real-time feedback.

One of the significant advancements in soft robotics is the development of 3D-printed resistive soft sensors that can be co-fabricated with the robot bodies themselves, as demonstrated by [183]. This method enables the creation of integrated, multifunctional soft robotic actuators with enhanced sensing capabilities by incorporating sensors directly into the actuator's structure, providing greater design flexibility and customization. The co-fabrication technique also allows for the production of lightweight and flexible sensors, essential for maintaining the compliance of soft robotic systems.

Additionally, soft sensors utilizing liquid metal-filled microchannels offer unique advantages in terms of compliance and durability. These sensors can stretch and bend with the soft actuator's movements without compromising functionality, making them ideal for dynamic applications [204]. Similarly, embedded barometric sensors can measure internal pressure changes, allowing for the precise control of soft actuators by monitoring deformation and exerted forces. These sensors are cost-effective and provide reliable data, crucial for precise control and feedback in soft robotics. A review by [185], shown in Figure 2.6, illustrates the range of these soft sensor technologies, highlighting their potential and versatility in the field.

In addition to sensorized approaches, recent research has also focused on developing sensorless soft actuators, eliminating the need for embedded sensors while maintaining accurate force and displacement estimation. [91] demonstrated that intrinsic properties like pressure and volume can be used to estimate output force and displacement in pneumatic soft actuators, with errors under 15%. Similarly, [166] proposed a sensorless stiffness control architecture for dielectric elastomer actuators using electrical measurements. [73] introduced a 3D-printed soft actuator with an integrated strain sensor that requires no post-processing or manual fabrication. All these approaches offer advantages such as simplified fabrication, reduced costs, and improved integration possibilities, while still maintaining accurate sensing capabilities for force, displacement, and pose estimation in soft robotic systems.

2.3.2 Control Strategies

Soft actuators present control challenges that differ significantly from those encountered in traditional rigid systems. The large number of intrinsic DoFs in soft actuators, combined with the highly nonlinear dynamics of soft materials, make precise control complex. This complexity is further influenced by the specific type of actuator being used, such as tendon-drive systems, FEAs, or shape memory alloys (SMAs). Low-level control, which is highly dependent on the specific soft material used, can be decentralized to simplify this complexity [223]. Therefore, studying the passive mechanical dynamics of soft actuators during the design phase is essential to achieve the desired deformation behaviour [84]. Nevertheless, as mentioned above, each actuator type poses its own unique challenges. For instance, controlling a servo in tendon-driven technology, managing compressors and pressure regulators in FEAs, and controlling electric charge, electro-adhesion, or thermal stimulus in SMA, all require distinct approaches. Additionally, the geometry of the actuators also has implications for the control system, as it directly influences the number of axes and movements that soft actuators can perform. Among these technologies, FEAs exhibit the widest variety of control strategies, as summarized in Figure 2.7.

Although diverse control strategies have been proposed for FEA-type actuator technology, open-loop control is one of the most frequently used. Several authors [158] report challenges in controlling certain types of FEAs, particularly due to their deflection around object. This issue is especially intricate in anthropomorphic grippers in terms of achieving speed, flexibility and dexterity [40]. These challenges are not limited to FEAs but also occur in passive structures actuated by external motors or tendon motors. This disadvantage can be partially mitigated by incorporating sensors into the actuator or using real-time control with FEM [106, 201]. On the other hand, tendon-driven soft technology has more mature actuators than pneumatic actuators, and therefore, the control of tendon-driven actuators is more straightforward compared to that of FEAs [190].

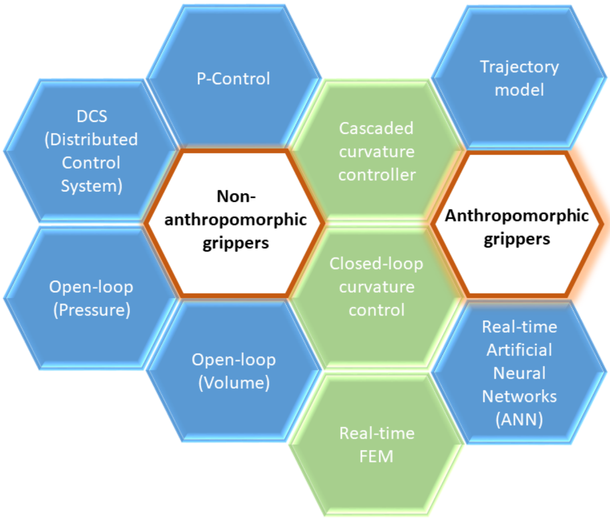

Fig. 2.7.: Several control strategies proposed for FEA-type soft actuators. The control strategies that have been proposed for a particular type of soft gripper (anthropomorphic or non-anthropomorphic) are presented in blue, while those proposed for both types are shown in green.

Control strategies for soft actuators can be broadly categorized into model-based, model-free, and hybrid approaches:

- Model-Based control

  Model-based control is one of the first approaches explored in soft robotics. These systems attempt to capture the complex dynamics of soft actuators' behaviour through physical models that describe the relationships between applied forces, deformations, and interactions with the environment. For instance, in FEAs, these models predict how changes in pneumatic pressure result in specific deformation patterns. A common approach to modelling these systems involves the use of Euler-Lagrange dynamics or equations derived from deformable solid mechanics, such as beam theory or models based on hyperelastic materials theory (e.g., Ogden or Mooney-Rivlin models). However, physical models require deep system knowledge and are highly sensitive to uncertainties and model precision.

  MPC has proven to be particularly effective in applications where precision is essential. However, implementing MPC, especially in FEAs, can be computationally expensive, making it less suitable for real-time tasks where quick response times are critical [83, 171, 187, 191].

- Model-Free control

To address the limitations of model-based control, model-free methods have gained prominence in soft robotics. These approaches do not require explicit mathematical model of the system dynamics. Instead, they rely on strategies that learn directly from interactions with the environment. Among these approaches, feedback control stands out, as it continuously adjusts control parameters in response to real-time data from sensor readings. Another popular model-free approach is fuzzy logic control, which handles the uncertainty and nonlinearity of soft actuators' behaviour through heuristic rules that mimic human reasoning.

Reinforcement learning has also been applied to optimize control policies for soft actuators through trial and error, without needing an explicit mathematical model [12, 131, 177, 197, 205]. Additionally, deep neural networks are being applied to directly learn the nonlinear relationships between input signals and the responses of soft actuators. These networks allow capturing the complex dynamics of soft actuators without extensive modelling, which has been proven especially useful in systems with many state variables and extreme nonlinearities [103]. This application of AI and deep learning helps to overcome the challenge of explicitly modelling highly complex actuator behaviours, offering a data-driven alternative to traditional control methods.

- Hybrid control

  Since both model-based and model-free approaches have advantages and limitations, hybrid control has emerged as a promising trend in soft actuator control. These methods combine physical models with the adaptive flexibility of learning-based or model-free control approaches. For instance, approximate physical models can guide the system during the initial stages of a task, after which a refined learning controller adjusts behaviours according to environmental variations or material deterioration over time [62, 193].

2.4 Characterization and quality control in soft grippers

The growing research interest in soft actuators, particularly soft pneumatic actuators (SPAs), due to their reconfigurability, adaptability, and multifunctionality, has led to the development of numerous design concepts [146]. However, the manufacturing process remains largely artisanal, with limited studies focusing on automating production [16]. Additionally, performance evaluations of these actuators are often tailored to specific designs. Examples in the literature include gripping various non-standardized objects [195], visual assessments [53, 239], and motion-tracking systems [234]. Handcrafted prototypes frequently suffer from manufacturing flaws, such as interstitial bubbles and delamination, which reduce both the durability and effectiveness of the actuators.

Consequently, a reliable process to ensure the actuator's functionality and durability over multiple cycles is necessary, not only for replicating soft technologies but also for their eventual industrial adoption. Such a process is central to what is broadly referred to as quality control, which plays a crucial role in detecting defects and overseeing manufacturing operations to ensure that products meet established quality standards [6]. Quality control can be implemented at different phases: before the manufacturing process, after production, or concurrently with production, known as concurrent quality control. In this concurrent phase, methods utilizing technologies such as machine vision have been introduced, offering advantages like precision, speed, consistency, comprehensive inspection of production items, and cost efficiency [6]. This approach has been applied in industries such as electronics, pharmaceuticals, textiles, printing, and automotive manufacturing [44, 202].

2.5 Soft grippers applications

Soft robotics has already found applications across several sectors, where its advantages are becoming increasingly evident. One key area is the industrial sector, where soft robotics is used in the end-effectors of robotic manipulators for handling small and medium-sized objects. The commercialization of these end-effectors is already underway, with companies such as Soft Robots Inc, The Gripper Company, Rochu Soft Robotic Gripper Group, and OnRobot, offering a range of soft gripper solutions designed for specific needs [37, 68, 153, 188]. These solutions are diverse in their applications.

In the food industry, there is a clear trend towards using this technology for handling food items in pick-and-place operations [19, 20]. Similarly, in the electronics industry, soft grippers are employed for handling electronic components, both for pick-and-place tasks and insertion into printed circuit boards (PCBs) [72]. In all of these applications, soft grippers stand out compared to rigid robotics, particularly in terms of their adaptability to various object shapes and sizes [184].

Soft grippers are also notable for their ability to finely regulate gripping force, which is distributed through the properties of the materials used. This results in a contact pressure that minimizes or eliminates the risk of damaging the objects being manipulated [2, 82, 145, 184]. Additionally, since these grippers are made from materials free from oils and lubricants, they can safely handle food items, complying with food-grade standard and facilitating their introduction into the sector [19, 145].

Another important application area is the medical field, where soft grippers have found a significant role in rehabilitation and assistive devices. Several companies now offer soft gripper-based systems designed for rehabilitating various parts of the body, including hands, shoulders, and legs. These devices are designed to adapt to natural human biomechanics, providing gentle and controlled assistance that facilitates rehabilitation through repeated, adaptive movements. Additionally, soft grippers are being researched for their potential role in minimally invasive surgical tools. Studies, such as the one presented in [168], have explored soft robotics applications in devices like heart wraps that aid in maintaining organ function. While heart wraps themselves may not directly use grippers, the underlying principles of adaptability and gentle contact have inspired the development of micro-grippers for surgical tasks that require precise, gentle manipulation of tissues. Furthermore, the scalability of soft gripper technology opens up possibilities for creating micro-robotic grippers suited to minimally invasive procedures, providing new avenues for precision in surgery and other medical interventions.

Lastly, but no less important, is the agricultural sector. Which has often been left behind in terms of technology adoption. A testament to this is the fact that technologies widely implemented for decades in the industrial sector are only now being incorporated into agriculture. While the reasons for this delay are beyond the scope of this thesis, they undoubtedly have to do mostly with a combination of social and economic factors. Social factors, such as the low qualification requirements to access this sector, and economic factors like low-profit margins, have contributed to the sector being overlooked in term of technological innovation. This is why the main goal of this thesis is to explore innovative technologies, such as soft robotics, to drive development in the agricultural sector. For all these reasons, the following section is dedicated to discussing the application of soft grippers in agriculture.

- Soft grippers in the agricultural sector

  Currently, driven by the momentum of what is known today as Industry 4.0 and the support of the European Union, concepts like Smart Agriculture or Agriculture 4.0 have gained prominence. These terms essentially refer to the application of widely-used industrial technologies in the agricultural sector. With support from European aid and various countries, such as the United States and China, we are witnessing a paradigm shift in the sector. In the past, agriculture relied primarily on human labour combined with relatively simple machinery, a practice with just over a century of history. Today, in industrialized countries, it is entirely feasible to talk about a mechanized agricultural sector equipped with technologies like GPS guidance and crop analysis through IoT and Big Data.

However, there is still much to be done, particularly regarding the widespread implementation of robotics. While robotics is well-established and widely used in the industrial sector, its application in agriculture is still emerging. Despite significant advances in agricultural robotics, particularly in areas like harvesting, soils analysis and weed management, widespread adoption remains a challenge due to the complexities of natural environments. Nevertheless, with the rise of mechanization and the increasing demand for precision farming, discussions about the real-world application of robotics in farming have become more common. As the sector faces lack of labour and the pressure of population growth, the demand for increased productivity in the sector is almost an obligation, acknowledged and funded by various governments to address these challenges.

The application of robotics in this sector can help compensate for the lack of personnel while also increasing process efficiency. However, this does not come without challenges. Tasks such as harvesting or pruning require extensive knowledge of each crop, as there are few, if any, similarities between different types of crops. For example, harvesting coffee in Ecuador in a highly humid and mountainous environment is vastly different from harvesting eggplants in a greenhouse in Spain. Similarly, tasks such as pruning almond trees differ significantly from those for grapevines, necessitating tailored solutions for each crop.

Soft grippers have the potential to bridge these gaps by providing a versatile solution adaptable to multiple crops and environmental conditions. Unlike traditional robotic end-effectors, which may struggle with the variability and fragility of agricultural products, soft grippers are better suited to natural environments with variable factors like humidity, and plant structures. Unlike rigid grippers, soft grippers provide compliant handling that can accommodate the irregular shapes and delicate textures of agricultural produce, which is essential for minimizing damage during tasks like harvesting. Made from flexible materials, these grippers can conform to the shape of objects, distributing pressure evenly and reducing bruising on fruits and vegetables. This makes them particularly valuable for handling delicate crops like tomatoes, strawberries, and grapes, where traditional rigid grippers might cause damage. The study of movement patterns, particularly for harvesting, in the case of manipulation, is then crucial to unlocking the potential for automation in each crop. Table 2.5 presents a review of soft grippers applied to the agricultural sector

Tab. 2.1.: Literature review of food soft grippers.

Soft Technology	Reference	Grasped Object	Object size or weight	Gripper type	Gripper size	Lifting ratio	Scalability	Controllability	Response Time	Surface Condition	Mechanical Compliance	Lifetime (cycles)
FEAs	[17] *	Lettuce	250x250 mm	Two pneumatic actuators and a blade	8000 g, 450x450x300 mm	-	✓	Close-loop with force sensor feedback	31.7 s	-	✓	-
	[78] *	Apple	-	Three soft finger design	Two fingers length: 95,25 mm One Finger length: 152,4 mm	-	-	Open-loop	7.3 s	-	✓	-
	[58]	Mushroom	-	Three soft chambers in circular shell	Chamber height: 20 mm Chamber arc angle: 60^o	30	✓	-	-	Any surface	-	-
	[157]	Apple, Tomato, Carrot, Strawberry	69 mm, 5-150 g	Magnetorheological gripper	-	-	-	PID	0.46 s	Any surface	✓	-
	[210]	Cupcake liners filled with peanuts	34-64 g	Three soft finger design	Finger size: 82x16x15 mm	-	✓	FE analysis	-	-	✓	-
	[214]	Cupcake liners filled with red beans, higiki, ohitashi	75.2 g	Soft fingers	Finger length: 97 mm	1805	✓	Open-loop	10 s pick and place (total procedure)	-	-	1,100
	[211]	Defrosted broccoli	33.54x23.94 mm, 3.8 - 7.0 g	Two soft fingers	Actuator size: 50x20 mm	-	-	-	3 s for inflation and deflation of chambers	-	-	-
	[105]	Granular kernel corn, Chopped green onion, Boiled hijiki	0.77 - 26.6 g	Four soft fingers	Finger size: 43x61,5 mm	-	✓	Open-loop	-	Any surface	-	-
	[213]	Orange	1000 g	Soft fingers	Finger size: 95x20x18 mm	-	✓	Open-loop	-	Any surface	-	-
	[212]	Tomato, Kiwifruit, Strawberry	45 to 76 mm	Four soft chambers in circular shell	Internal diameter: 46 mm Height: 30 mm	-	✓	Open-loop	2 - 5 s	Any surface	✓	-
Tendon-driven	[31]	Tomato	500 g	Three soft finger design	-	-	✓	Preprogrammed rotation of motors	-	-	✓	1,000
	[57]	Tomato, Cucumber (slices) Avocado (Strips) Cherry Tomato, Olives, Pineapples cubes, Broccoli	-	Quad-Spatula design	-	-	✓	-	-	Flat surfaces	-	-
FEA-Tendon-driven	[194]	Banana, Apple, Grapes	2700 g	Three soft finger design with a suction cup	389.69 g	7.06	✓	Teleoperation Control	0.094 s (Rise time)	Any surface (irregular shapes and sharp corners)	✓	26 - 120
Topology optimized soft actuators	[118]	Apple, Grapefruit, Guava, Orange, Kiwifruit	1400 g	Two compliant fingers	-	-	✓	Open-loop (Arduino)	-	-	✓	-

* Soft Gripper for harvesting purposes. - Data not provided.

2.6 Current challenges in soft grippers development

Soft robotics, and soft grippers in particular, hold great potential for broader integration into fields such as medicine, agriculture and industry. However, they still face several challenges that limit their widespread adoption [2, 154, 216]. The following is a summary of the key general and specific challenges that need to be addressed for the continued advancement of soft robotics technologies.

- General challenges in soft robotics:
  - Limitations in simulation and design: Soft robots, including soft grippers, exhibit continuous deformation that requires high-dimensional models or a greater number of DoFs for accurate representation. This complicates the development of precise simulation and design tools.
  - Manufacturing complexity: The fabrication of soft actuators involves flexible materials and complex designs that can be difficult to mass-produce. The lack of standardization for components, coupled with limited knowledge of new materials, further exacerbates this challenge.
  - Control complexity: The high number of DoFs in soft robots, often exceeding the number of available actuators, complicates the implementation of effective control strategies. Additionally, the highly deformable nature of these soft robots makes it difficult to predict their movements and apply traditional control strategies. Therefore, the high dimensionality and nonlinear behaviour of soft actuators present barriers to developing robust control systems that are both efficient and reliable.
- Specific challenges in gripping and manipulation:
  - Limitations in load capacity: Increasing the gripping force and load capacity of soft grippers remains a challenge, mainly due to the difficulty of generating high stresses in soft materials and the need to distribute force evenly across the object being gripped.
  - Object manipulation: Soft grippers must be capable of gripping objects of varying sizes, shapes, textures, and stiffnesses. Adapting to these variations, especially in the case of deformable objects, presents a significant challenge for designers and engineers.
  - Sensor integration: Incorporating sensors into soft grippers without affecting their flexibility or compromising performance is crucial for precise

perception and control. This challenge involves developing flexible and stretchable sensors that can be seamlessly integrated into the soft gripper's structure.

- Speed and robustness: Improving the response speed and robustness of soft grippers is essential for their deployment in real-world applications. This requires optimizing materials, designs, and actuation mechanisms to achieve faster and more durable performance.
- Commercialization barriers: Although some companies are starting to produce soft grippers, large-scale industrial adoption is limited by factors such as controllability, cost, and a lack of knowledge about potential applications.

2.7 Challenges of soft grippers in the agricultural sector

Although numerous soft actuator technologies have been developed for various applications, soft grippers for robotic crop harvesting have yet to receive adequate attention. This gap is mainly due to the complexity and unpredictability of the agricultural environment, the inherent challenges of working with soft materials, and the need to demonstrate the economic viability of robotic harvesting within the industry. The following are some of the major barriers that soft robotics, especially soft grippers, must overcome to be effectively applied in agricultural contexts.

- Design process: Current soft gripper designs focus on general improvements in soft robotics rather than solving specific agricultural challenges. For robotic crop harvesting, grippers need to be modular, easy to repair, and capable of handling different types of crops and foods.
- Repeatability: Standardizing the manufacturing process is essential to ensure the production of reliable soft grippers. Issues like delamination and bubbles in actuators affect their performance, and current manufacturing methods struggle to maintain consistency. Solutions like 3D printing and vacuum chamber techniques are being explored to address these issues [56, 117, 163, 195].
- Control system design: Most existing soft grippers use open-loop control, which lacks precise control over deformation. This makes it difficult to handle fruits at various stages of ripeness without causing damage. New control algorithms that consider the stiffness of the objects are necessary for agricultural use.

- Energy source systems: The power requirements for soft grippers in agriculture, such as electrical sources or air compressors, need to be optimized for efficiency. Current energy solutions are designed for controlled environments like labs, which are unsuitable for the unpredictable agricultural field.

- Economic viability: There is a lack of economic studies on the profitability of robotic crop harvesting [121]. Automation could reduce labour costs, which account for about 30% of the total cost in certain crops, such as tomatoes and peppers, making soft gripper-based harvesting a potentially viable alternative [25, 121, 138].

Another challenge, such as the relatively slower actuation speed, is being partially addressed through the use of pneumatic channels (PneuNet actuators) [135] or low-pressure actuators [181]. Furthermore, hybrid gripper technology [189], which combines the advantages of both soft and hard robotics, presents a potential solution, providing a soft grip and a structural strength capable of withstanding external agents or objects in unstructured environments.

2.8 Future opportunities for soft grippers

Despite the current challenges, the future of soft grippers is highly promising. Advances in materials science, additive manufacturing (3D printing), simulation, and control techniques promise to overcome existing limitations. The following are key areas where future research and development can significantly enhance soft gripper technology.

- Novel Materials: Continued research into novel soft materials with enhanced properties, such as increased strength, durability, and self-repair capabilities, will be crucial for improving the performance, reliability, and lifespan of soft grippers. Such materials would allow soft grippers to handle a wider range of tasks, especially in harsh or demanding environments [52].

- Additive Manufacturing: 3D printing allows for the creation of complex and customized designs, making it easier to produce soft grippers tailored to specific applications. The ability to rapidly prototype and test new designs will accelerate innovation in the field [18, 219]. Furthermore, advances in additive manufacturing and the integration of functional materials could also enable the development of actuators that can self-regulate. In such systems, the material itself can act as both a sensor and an actuator, thereby eliminating the need for external sensors. These self-sensing actuators are key to realizing decentralized control, where different sections of the actuator autonomously manage their own deformations. This reduces reliance on complex centralized control systems and increases scalability, allowing soft devices to adapt to their environments independently [8, 28, 30, 192].

- Advanced Simulation: The development of more accurate and computationally efficient simulation models is crucial. Such models will enable researchers to better predict and optimize the behaviour of soft grippers before the manufacturing phase, reducing time and cost. These simulations will need to account for the non-linear, deformable nature of soft materials. Improvements in this area could significantly advance soft robotics design methodologies [42].

- Intelligent and adaptive control: The application of machine learning and adaptive control techniques can improve the ability of soft grippers to learn from experience and adapt to dynamic environments [76]. Moreover, the integration of data-driven and model-based approaches, coupled with the use of smart materials, present new opportunities for developing adaptive control systems that can operate effectively in unstructured environments. Collaborative robotics or human-robot interaction could benefit greatly from the flexibility and adaptability of soft grippers, particularly as more intuitive, low-cost computational control algorithms are developed.

- Tactile and haptic feedback systems: An emerging trend in soft gripper control is the use of tactile and haptic feedback systems, which leverage the integration of soft sensors distributed throughout the actuator. These sensors gather real-time data on force, pressure, and position, enabling the gripper to adapt its control strategies dynamically during interactions with complex objects and in highly dynamic environments. By continuously measuring and responding to deformation, these feedback systems allow for more precise and adaptable control in physical interactions. This could be particularly valuable in applications such as agriculture or human-robot interaction [124].

2.9 Discussion

As highlighted in the literature, various actuation methods for soft grippers have been explored. However, FEAs stand out from other actuation technologies due to their cost-effectiveness, ease of manufacturing, and their ability to generate significant force. Moreover, FEAs allow for more complex designs, ensuring a firm but secure grip on objects [2]. Based on these factors, the decision to employ uniaxial and biaxial pneumatic actuators in this thesis is driven by their suitability in addressing the specific challenges of soft robotic manipulation in agricultural applications.

Uniaxial actuators, such as diaphragm-type actuators, are advantageous for tasks requiring controlled and firm gripping, which is crucial for handling delicate objects like fruits or plants without causing damage. Their simple design allows for precise linear motion, making them suitable for repetitive pick-and-place operations that require consistent force application. On the other hand, biaxial actuators offer more complex manipulation capabilities and enhanced dexterity, which are essential for handling irregularly shaped objects and performing tasks that require multi-directional movement. This dual approach of uniaxial and biaxial actuators provides a balance between control and flexibility, aligning with the sector's need for robust, adaptable solutions tailored to specific agricultural tasks [241].

On the sensorization front, the selection to implement a sensorless approach for pneumatic actuators is derived from recent advances in soft robotics that emphasize reducing complexity and cost without compromising performance. Sensorless techniques estimate force and displacement by leveraging intrinsic actuator properties, such as pressure and volume, thus eliminating the need for embedded sensors. Studies by [91] and [166], demonstrate that this method achieves sufficiently accurate estimations for practical purposes, with errors below 15%, which is acceptable for agricultural applications where absolute precision is not critical. This approach significantly reduces fabrication costs, simplifies the actuator design, and improves the system robustness by removing fragile sensor components, making it ideal for agricultural environments where maintenance simplicity is crucial [91, 166]. On the other hand, computer vision-based techniques will be also explored to enhance the gripper's functionality by enabling object detection and identifying optimal contact grasping points.

Finally, the adoption of two complementary modelling approaches — FEM and data-driven models — provides a comprehensive framework for understanding and controlling pneumatic actuators. FEM allows detailed physics-based simulations of actuator behaviour, providing insights into material deformations and force distributions under different conditions. The challenge of selecting an appropriate mathematical model to simulate hyperelastic materials is relevant during the design phase, as it optimizes actuator structures for specific tasks [244]. In contrast, the data-driven approach focuses on real-world performance, enabling the development of control systems that adapt to the actuators' behaviour based on experimental data. Combining these two approaches allows the system to benefit from FEM's theoretical analysis of complex structures and the precision of data-driven models for control, especially when integrated with virtual objects in a simulation environment, in order to find the optimal path planning for manipulation with soft grippers.

Part III

DESIGN AND STRUCTURAL MODELLING OF SOFT GRIPPERS

3 Design and Structural Modelling of Soft Grippers

The literature on soft grippers presents a diverse range of designs, primarily focused on pick-and-place operations within the industrial sector. These designs tend to offer general-purpose solutions aimed at advancing the broader field of soft robotics, rather than addressing sector-specific challenges. In contrast, this thesis seeks to explore the design of soft grippers that not only contribute to innovations in soft robotics but also provide targeted, practical solutions for automation, with a particular emphasis on applications in the agriculture sector.

To meet the unique demands of agricultural applications, this research focuses on FEAs, a technology widely used in the literature for its ease of fabrication, cost-effective materials, large deformation capabilities, and ability to generate high forces. Additionally, pneumatic systems are favoured in agricultural environment for their straightforward implementation and minimal risk; in the event of a leakage, they pose no harm to the surroundings. Furthermore, designs based on pneumatic network actuators or PneuNet structures have been proposed due to their fast response times and adaptability in creating complex pneumatic chambers configurations.

Beyond these foundational technologies, this thesis incorporates a range of actuator designs, including uniaxial diaphragm-type actuators, which are characterized by their firm and controlled grip on objects, as well as biaxial actuators that allow for more complex manipulation and increased dexterity. By selecting these specific technologies and designs configurations, the proposed grippers align with current advancements in the field while addressing the agricultural sector's unique requirements, such as modularity, ease of repair, and the ability to handle food safely and interact gently with various crops without causing damage.

Therefore, this chapter presents a series of soft gripper designs specifically developed to address the unique challenges of agricultural automation. Each design leverages the inherent adaptability and compliance of soft materials to enable delicate handling, precise control, and versatility in various agricultural tasks. The proposed designs have been manufactured and tested in a controlled laboratory environment and further validated in real-world settings through integration into dual-arm robotic systems. These tests provide practical insights into the efficacy of the grippers under conditions that closely resemble those in agricultural environments. The following sections delve into these distinct design approaches, each with specific advantages for targeted applications within agriculture.

3.1 Diaphragm-type pneumatic-driven soft grippers for precision harvesting

This section presents a new design approach for soft grippers based on modules that combine the use of a pneumatic-driven soft diaphragm actuator and a 3D printed structure. The main advantage of pneumatic-driven diaphragm actuators over other soft actuators is their ease of manufacture. On the other hand, the 3D printed structure imposes a series of constraints on the DoFs of the soft actuator, thereby simplifying gripper control. The proposed modules can be then freely configured to obtain grippers that adapt to products of different diameters. Additionally, a series of easy-to-implement measurement tests are proposed to characterize different types of soft diaphragm actuators, providing a foundation for benchmarking analysis.

3.1.1 Design and structural modelling

To determine the key criteria a soft gripper must satisfy to be fully functional, a review of agricultural processes, particularly harvesting tasks, was conducted [50, 140, 143, 146]. One critical requirement for increasing the profitability of harvesting machinery is the ability to manage different types of crops. Consequently, the objective was to develop a design that is both highly adaptable and modular. The resulting engineered module can be configured in multiple ways to accommodate a wide range of crop diameters and lengths. This flexibility enables a gripper designed under this concept to be reconfigured to suit the harvesting of different kinds of fruits. Another essential criterion in this domain is simplicity, which manifests in systems that are interchangeable and easy to repair. Therefore, the design also focused on single modules that could operate independently and were straightforward to manufacture. Additional requirements relate more to maintaining the quality standards of the fruit than to the harvesting process itself, such as preventing fruit damage, using non-hazardous materials, and employing designs that inhibit the spread of diseases and pests. These important considerations have often been overlooked in the design of new grippers, which frequently suffer from the use of materials that could harm the fruits and complex designs that complicate cleaning. Thus, integrating soft robotics technology with hygienic designs and variable compliance is essential for preventing damage to fruits and crops. Environmental sustainability, durability, and robustness are also crucial for agricultural and industrial applications. Therefore, careful selection of materials for the manufacturing process has been made to satisfy these requirements. Lastly, the modular soft gripper is intended to function as the end effector of a robotic manipulator [143, 145, 176], capable of executing nearly all the movements necessary for harvesting, commonly referred to as picking patterns in the literature [81, 115, 136, 221]. These picking patterns sometimes involve combinations of basic movements, such as twisting, pulling, lifting, and bending.

The following subsections will discuss the choice of soft materials and the modelling process used in developing the proposed pneumatic-driven soft diaphragm actuators. Additionally, the design's strengths, rooted in its geometry and modularity, will be highlighted. Finally, the manufacturing and assembly process for the soft gripper modules will be presented.

- Soft actuator design: The designed grippers feature a geometric shape based on single-channel diaphragm-type actuators. A key advantage of this design is the straightforward manufacturing process, which can be broken down into two primary steps. The first step involves filling the moulds for both the diaphragm and the cover, which simplifies the moulding process compared to other multi-channel actuators. The second step is the assembly of these two parts, where the same material as the rest of the components is used to join them together. Another benefit of this type of soft actuator is its ease of control. This is because the soft diaphragm actuators are engineered to move primarily along one axis, with movements in other axes being minimal. This design choice simplifies the control of the gripper's DoFs.

  The proposed soft diaphragm actuator also incorporates the bellows concept, which offers distinct inflation behaviour compared to other geometries. In designs like cylinders, cubes, or spheres, inflation typically causes not only forward elongation but also force dissipation along the side walls. This radial expansion reduces forward movement in cylindrical and cubic geometries. Spherical geometries, while exhibiting better inflation behaviour, present significant challenges due to the complex moulding required for manufacturing. However, the bellows-based geometry, especially the proposed bellows-cylinder design, combines aspects of cylindrical and spherical shapes. This approach addresses the problem by utilizing the forces generated by radial inflation to contribute to forward elongation, thereby extending nearly the entire length

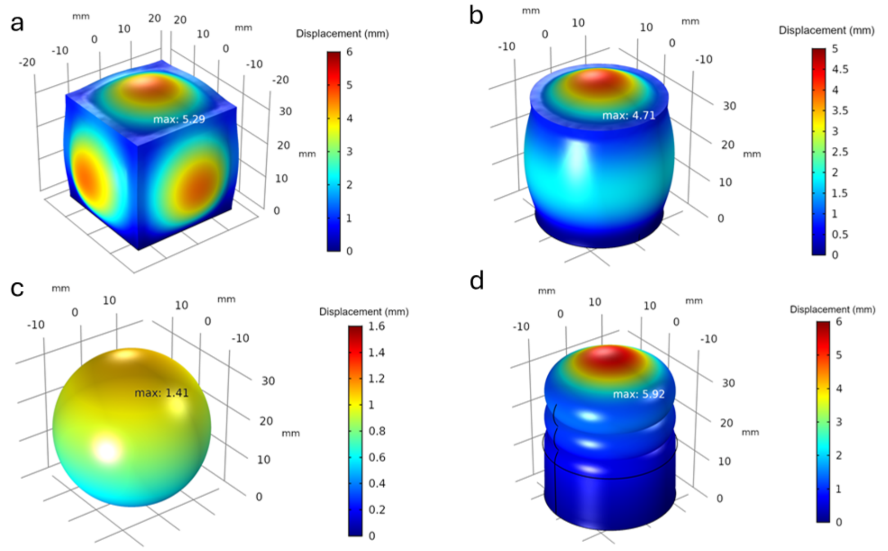

Fig. 3.1.: An example of the inflation behaviour of 30 mm geometries with 3 mm walls under an internal pressure of 50 kPa. **(a)** Cubic geometry. **(b)** Cylindrical geometry. **(c)** Spherical geometry. **(d)** Bellows-based geometry. As can be observed in (a) and (b), part of the air flow is wasted on the expansion of the walls to different degrees depending on the geometries, which does not contribute to the forward displacement. This method does not seriously affect sphere-based geometry, but due to manufacturing criteria, bellows-based geometry is an important option to consider.

of the gripper in that direction. The difference between these geometries can be observed in Fig. 3.1.

To design effective soft grippers for medium- to large-sized fruits, two types of soft diaphragms were considered: one with smaller bellows than the other, though both have the same diameter. To analyse their inflation behaviour, both designs were modelled in COMSOL Multiphysics® using FEM analysis (see Fig. 3.1). For this purpose, PDMS was modelled as a hyperelastic material. Although several mathematical models are available in the literature to describe the behaviour of this type of soft material, the second-order Ogden model has been found to more accurately represent its response compared to the Mooney-Rivlin and Neo-Hookean models [99]. Additionally, the inflation pressure applies equibiaxial tension to the soft diaphragm. Ogden theorized this type of tension in hyperelastic materials like PDMS [152]. This approach considers elastic solids with a strain-energy function and isotropic behaviour relative to the stress-free state, while also assuming that the material is incompressible. Thus, it can be formulated as follows.

$$\sigma_i = \mu_r a_i^{\alpha_r} - p, \tag{3.1}$$

where σ_i, $i \in \{1,2,3\}$, represents the principal Cauchy stresses (σ_1,σ_2,σ_3), the parameters μ_r and α_r are constants obtained experimentally, a_i represents the stretches (a_1,a_2,a_3) and p is an arbitrary hydrostatic pressure introduced because of the incompressibility constraint. Due to the equibiaxial tension, two out three principal stresses are equal, and the third one is zero:

$$\sigma_2 = \sigma_3 = \sigma, \sigma_1 = 0 \tag{3.2}$$

Moreover, the stretches can be written as follows:

$$a_2 = a_3 = a, \tag{3.3}$$

and due to the incompressibility assumption, it can be considered that a_1=a^{-2}. The substitution of the aforementioned into (3.1) is as follows:

$$\sigma_i = \mu_r a^{\alpha_r} - p, 0 = \mu_r a^{\alpha_r - 2} - p. \tag{3.4}$$

The elimination of p yields:

$$\sigma_i = \mu_r (a^{\alpha_r} - a^{\alpha_r - 2}). \tag{3.5}$$

Finally, Equation 3.5 is inserted into the FEM software together with the values of μ, α and bulk modulus, which have been obtained from [99]. The PDMS mix ratio used was a 15-part base elastomer and a 1-part curing agent. The data obtained from the FEM software is shown in Fig. 3.2 for the soft actuators, and in Fig. 3.3 for a gripper with hexagonal configuration. All cases have been analysed under an air pressure of 50 kPa.

As can be seen in the figures above, the FEM analysis yields a larger displacement for the 2-bellows actuator than for the 4-bellows actuator, with values of 10 and 9 mm, respectively. Regarding the stresses, both actuators have a tensile strength of approximately 6.7 MPa, which is the value indicated by the manufacturer.

- Design of the rigid structure: One of the biggest challenges in agricultural automation is designing a versatile gripper that can serve multiple purposes, meaning it can harvest various types of fruits with minimal modifications. When it comes to soft robots, particularly soft grippers, this challenge becomes even more complex because these robots require a specific design for the

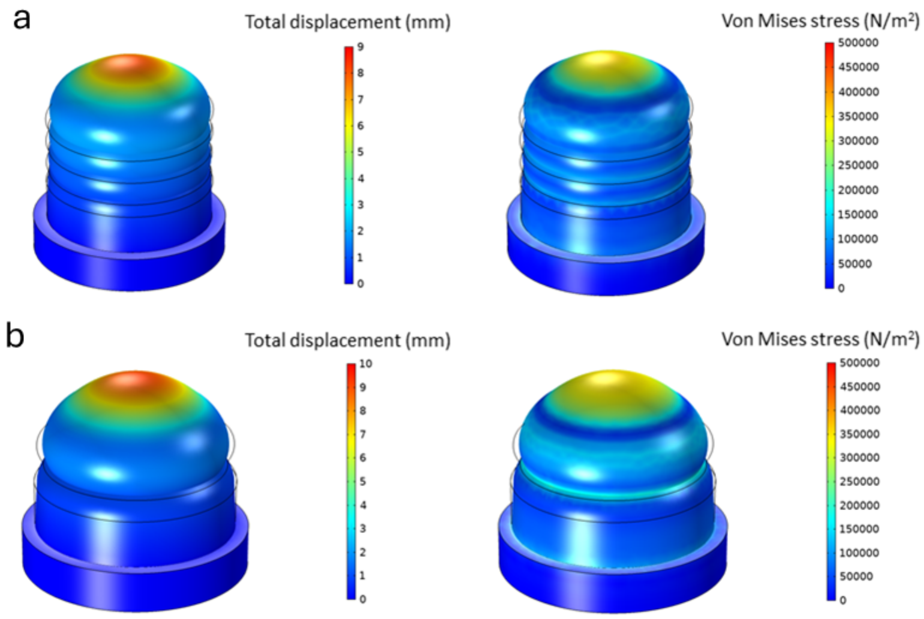

Fig. 3.2.: Model showing displacements reached and von Mises stress under 50 kPa pressure. **(a)** 4-bellows soft actuator. **(b)** 2-bellows soft actuator.

gripper, which inherently limits their versatility. Although some studies in the literature explore modularity and scalability, these are often limited in scope. For example, the soft gripper described in [58] features a modular design but is specifically intended for handling small fruits and edible fungi. Additionally, its computational modelling is simplified, and it achieves relatively less displacement at the same inlet pressure compared to the proposed soft actuator.

The design proposed here aims to advance modularity and scalability further to develop a near-universal gripper concept adaptable to various fruits. To achieve this, a 3D-printed module made from polylactic acid (PLA) was developed. PLA is a widely recognized synthetic biodegradable polymer known for its good mechanical strength and low toxicity. Its faster degradation rate makes it a more environmentally friendly alternative to traditional plastics [196]. As greater toughness is needed for durable applications, recent review articles have discussed advancements in toughening PLA through plasticization, copolymerization, and melt blending with different tough polymers, rubbers, and thermoplastic elastomers [7, 96, 104, 120, 149, 162, 231]. Moreover,

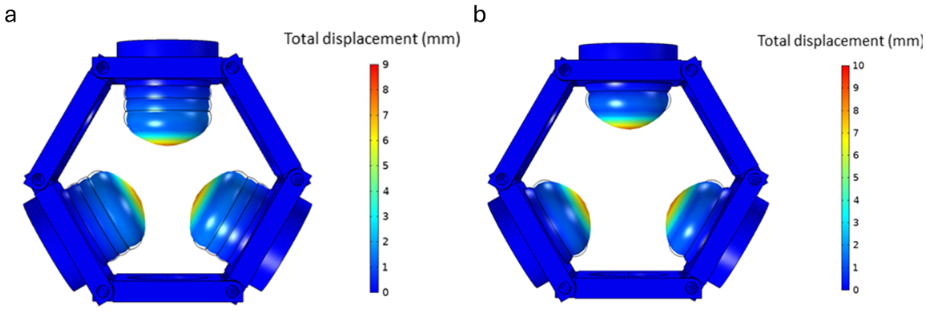

Fig. 3.3.: Model showing the displacements reached on the actuators of the soft gripper with hexagonal configuration under constant pressure. **(a)** 4-bellows soft actuator. **(b)** 2-bellows soft actuator.

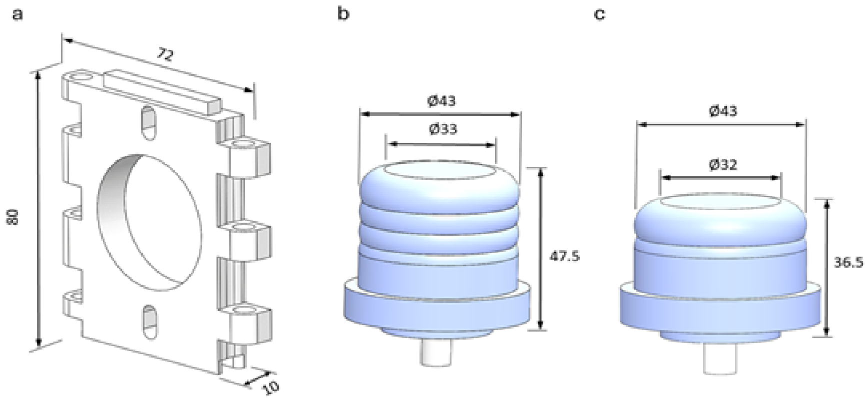

Fig. 3.4.: Main parts of a single soft gripper module with the two types of actuators. **(a)** Rigid structure. **(b)** 4-bellows actuator and **(c)** 2-bellows actuator. All dimensions are in mm.

many PLA formulations with enhanced toughness are available on the market for durable applications, as summarized in [137].

The proposed PLA structure offers several advantages. First, the module is independent of the gripper, meaning it can function on its own, allowing the gripper to adapt to a wide range of tasks. Second, the gripper is interchangeable, which enhances its reliability. This innovative feature provides an edge over other soft grippers, typically designed as a single unit. In those cases, if a failure occurs, the entire gripper must be replaced. Third, this module is fully replicable; both the rigid components and the mould for the soft components can be easily 3D-printed. The materials used in its manufacture are readily

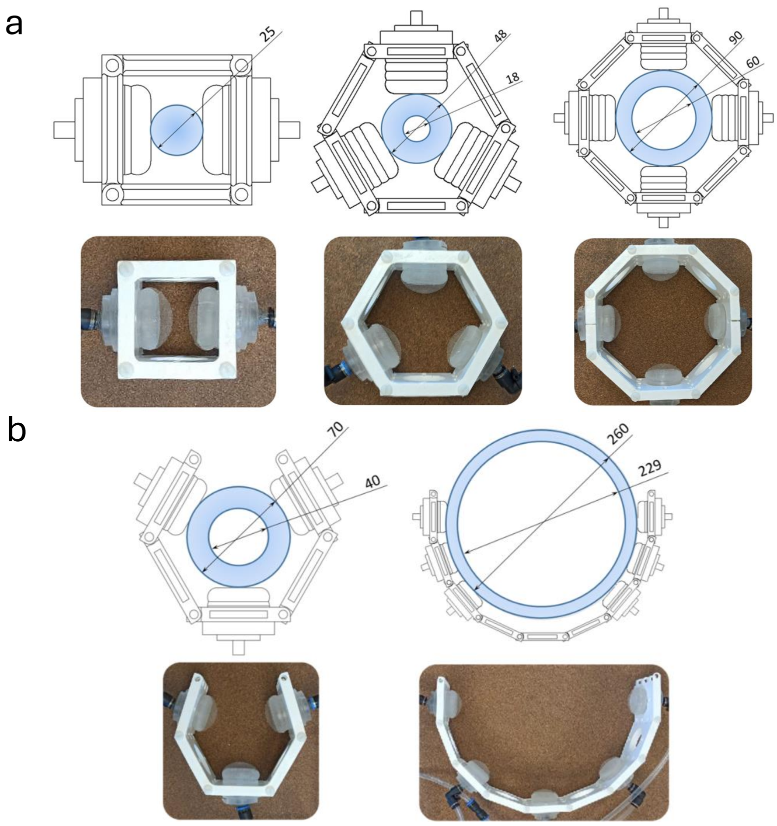

Fig. 3.5.: Examples of soft grippers obtained from the proposed design approach. **(a)** Closed gripper configurations. **(b)** Open gripper configurations.

available and inexpensive, and no post-processing of the parts is required. The main parts of the soft gripper module can be seen in Fig. 3.4.

Finally, the proposed design concept enables the soft grippers to be configured into a variety of shapes, allowing them to adapt not only to different types of fruits and vegetables but also to various handling techniques. Figure 3.5 illustrates several examples of soft grippers formed from different arrangements of the proposed modules. In Figure 3.5a, multiple closed gripper configurations are shown. These closed setups are ideal when multiple contact points are required, providing better control over the object and enabling the execution of nearly all necessary harvesting movements or picking patterns. Conversely, the proposed modules can also be arranged in an open configuration, as depicted in Figure 3.5b. Unlike closed chain configurations designed for harvesting fruits that always hang vertically, open chain configurations are recommended for medium to large fruits that typically rest on the ground, such as watermelons, melons, or pumpkins.

It's also important to note that the interaction between the soft components and the rigid structure was analysed using FEM, confirming that no significant load values were observed in the structure.

3.1.2 Materials and manufacturing methods

Various materials, including Ecoflex [79, 135], Dragon Skin [38, 43, 182, 213], and Elastosil M4601 [59, 135, 174, 195] are frequently employed in the field of soft robotics. While these materials are recognized for their ultra-smooth characteristics, which make them highly valuable in manufacturing, their precise chemical composition can be difficult to ascertain, as they are primarily intended for use outside the scientific domain. On the other hand, polydimethylsiloxane (PDMS), commercially known as Sylgard 184, has been extensively used in research [58, 79, 132, 169, 182, 207]. PDMS offers not only the ability to determine its mechanical properties, such as high elasticity [88] and thermosetting behaviour [58], but also allows for precise mathematical modelling of its behaviour through FEM analysis.

One significant advantage PDMS shares with other commonly used materials in soft robotics is its ability to cure at room temperature, which simplifies the manufacturing process of soft gripper modules and reduces costs. If necessary, this curing process can be accelerated in industrial settings by using ovens, which can decrease curing times from 24 hours to just 10 minutes at 150ºC [88]. Moreover, according to its safety data sheet, PDMS is classified as a non-hazardous substance, ensuring safe interaction with biological products and making it suitable for agricultural applications. Additionally, PDMS is relatively resistant to fatigue and does not age quickly, making it ideal for both agricultural and industrial applications. Recent studies have also proposed PDMS composites that exhibit low energy dissipation during cyclic loads (low hysteresis), while demonstrating high toughness and fatigue resistance, which makes them well-suited for prolonged cyclic use [209].

For the production of the gripper actuators, a moulding process that is widely recognized and discussed in the soft robotics literature is employed [75, 128, 240]. A visual overview of the moulding process is provided in Figure 3.6.

The process is outlined as follows: (*i*) The mould is first created using a 3D printer, with PLA being the plastic material used. (*ii*) Once the mould is assembled (Fig. 3.6a), PDMS is poured into it (Fig. 3.6b). (*iii*) The two moulds filled with PDMS are then placed in a vacuum chamber (Fig. 3.6c) to remove any internal air bubbles. After this vacuum treatment, the entire setup is allowed to cure at room temperature

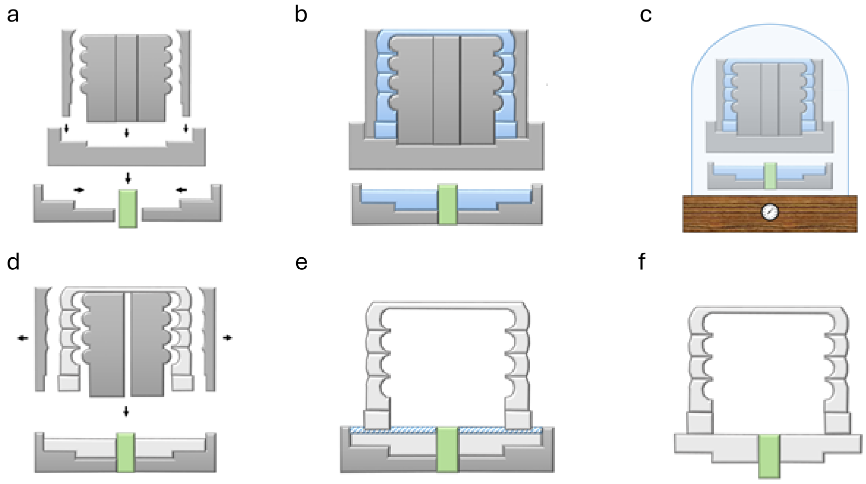

Fig. 3.6.: Moulding process. The PLA mould is shown in dark grey, the fresh PDMS soft gripper is represented in blue, the precured PDMS is in striped blue, the cured PDMS soft actuator is displayed in light grey and the PUR pipe is in green. **(a)** Mould assembly. **(b)** Pouring of the PDMS on the mould. **(c)** Vacuum process. **(d)** Demoulding. **(e)** Gluing with PDMS of the two resulting parts. **(f)** Fully assembled soft actuator.

for one to two days, depending on the ambient conditions. (*iv*) Next, the demoulding process is performed (Fig. 3.6d), and the two resulting PDMS parts are bonded together (Fig. 3.6e). (*v*) Finally, after an additional day of curing, the soft actuator is ready for use (Fig. 3.6f). In some cases, a silicone sealant like Loctite 5699 is applied to prevent air leaks between the polyurethane (PUR) tubing and the PDMS in the soft actuator.

While the simplicity of the manufacturing process is notable, it is important to consider the need for studies on repeatability and precision, especially to address common issues in soft actuators, such as delamination or interstitial bubbles, which can arise from manufacturing defects. Several solutions have been proposed to tackle these issues, such as the use of vacuum chambers [56, 117, 163, 195], which have shown positive outcomes. However, the literature lacks methods that, for instance, control variables such as pressure or time relative to volume to ensure consistency in the process. Future methods, including 3D printing of soft materials or lost-wax casting, may offer promising alternatives for improving repeatability and accuracy in the manufacturing process.

Once the soft actuator is fabricated and the rigid components are 3D printed with a 10% infill, the soft component is inserted into the hole of the rigid structure and secured with a screwed clip. At this stage, the standalone module is fully assembled. For different gripper configurations, nylon threaded rods, washers, and nuts can be

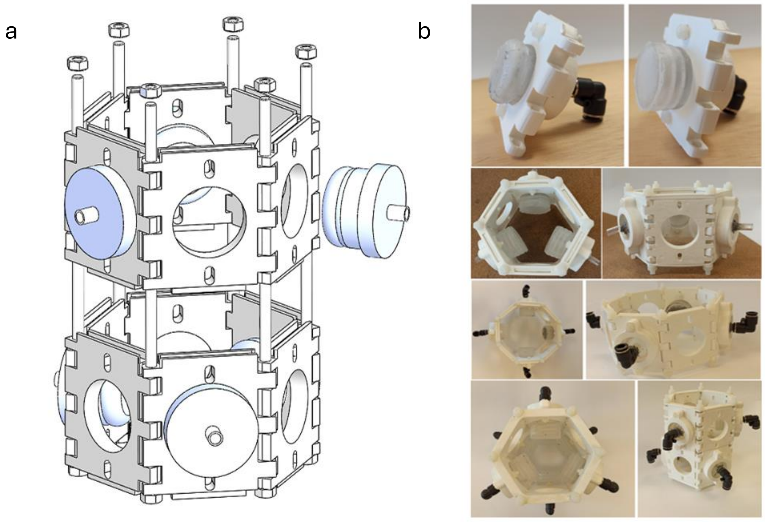

Fig. 3.7.: Modules, assembly process and various configurations. (a) Assembly of the modules. (b) Fully assembled modules and several soft grippers configurations.

used for assembly (see Fig. 3.7a). Nylon fasteners are preferred due to their low density, making them ideal for lightweight robotic manipulators. However, steel fasteners can be used if the application requires greater strength. A fully assembled module and several examples of soft gripper configurations are shown in Fig. 3.7b.

One of the key benefits of the proposed design approach is that it enables the rigid structures of the modules to be assembled in various geometries, allowing for optimal positioning of the soft actuators. This ensures sufficient contact areas that provide stable grips for different types of fruits. Figure 3.8 demonstrates that the design supports a variety of gripping scenarios, including those where the fruit is not ideally centred (i.e., positioned at the midpoint of the gripper). If the object (represented by the blue areas in Fig. 3.8) and the closed-configuration gripper are concentric, all actuators will participate in the grasp. However, if the target is located elsewhere, as shown with the oranges, the grip might involve only two actuators.

As illustrated in Fig. 3.8a, the closed configurations provide a larger gripping area compared to the open configurations shown in Fig. 3.8b, since the object can be positioned between the rigid part, which acts as a fulcrum, and the soft actuators. Additionally, it can be inferred that the number of gripping points on an object in closed configurations can range from 2 to n, where n is the total number of soft actuators on the gripper, depending on the fruit. In contrast, with an open configuration, it is necessary to adjust the pressure of each actuator independently,

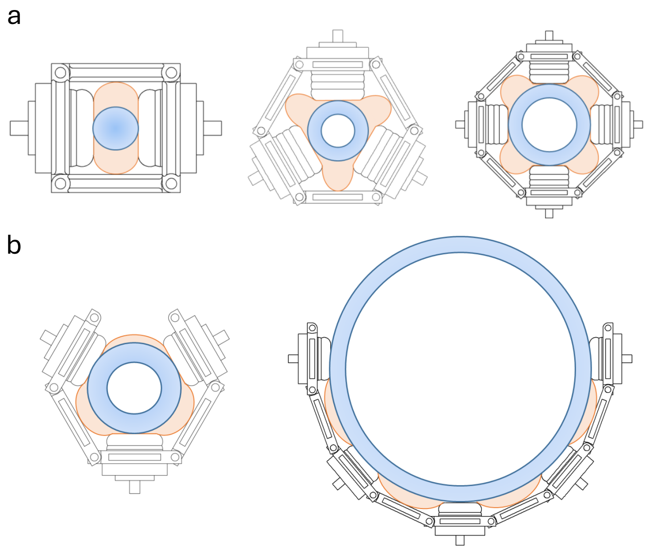

Fig. 3.8.: Feasible grip areas. **(a)** Closed gripper configurations. **(b)** Open gripper configurations.

as the actuators at the ends generally bear the load of the target, while those in the middle help prevent rotation during the grip.

Another significant advantage of the proposed design approach is that the 3D-printed structure imposes certain constraints on the DoFs of the soft actuator, which simplifies the control of the grippers.

3.1.3 Characterization of uniaxial soft actuators

One of the key gaps in the development of soft actuators is the lack of a standardized method for characterizing their performance and mechanical properties. There is, however, a clear need for a reliable approach to quantify the features of soft actuators. Such a method would enable comparative studies between different models, facilitate the creation of distinct categories based on their performance, and provide a basis for establishing an index to guide improvements in soft robotics technology.

A crucial aspect of a soft gripper is the contact force it can apply to an object and how effectively that force is controlled, as this directly determines its ability to handle objects with varying levels of sensitivity. Several research studies, such as those in [43, 58, 59], utilize different methods for measuring contact force. In [58], the contact pressure (P_c) is found by means of FEM software, while the contact area (A_c) is measured by analysing the "fingerprint" left by the soft gripper on a Styrofoam surface. The contact force (F_c) is then calculated using the well-known Equation:

$$F_c = P_c \cdot A_c \tag{3.6}$$

While the method used to determine contact pressure provides a reasonable approximation, its reliability is limited due to its dependence on the mathematical model implemented in the FEM software. Specifically, the Mooney-Rivlin model, which is commonly used to describe PDMS behaviour, is not very accurate in this context [99].

In [43], the measurement process is divided into three tests. Two of these involve a trial-and-error approach, while the third uses the Takei Physical Fitness Test. However, this test is only suitable for humanoid hands and cannot be applied to diaphragm-type grippers. Another interesting approach is described in [59], where a pressure map is employed. In that case, the pressure map is wrapped around a tube with a radius tailored to the specific curve of the soft gripper.

Despite these efforts, there is still no standardized method for testing the properties of soft grippers. To address this gap, this thesis proposes a measurement process using two devices that enable an objective analysis of soft grippers, with a particular focus on diaphragm-type models.

Figure 3.9 shows the two devices used in the proposed process to measure key features of soft actuators, including the relationship between forward displacement, contact force, contact area, contact pressure at the centre of the soft actuator, and the inlet air pressure.

The first parameter, forward displacement, is measured in a press using a dial gauge with an accuracy of 0.01 mm, as shown in the schematic in Fig. 3.9a. The other parameters, which are the contact force, the contact area and the contact pressure, are measured using a press, such as the one outlined in Fig. 3.9b, with an Entran ELW-D1-500N compression load cell, whose technical specifications are listed in Table 3.1. This load cell was selected because its measurement range aligns with the expected load values for this type of pneumatic actuator.

To conduct the measurement process, a basic understanding of geometry is required, which is visually clarified with the graphic description shown in Fig. 3.10.

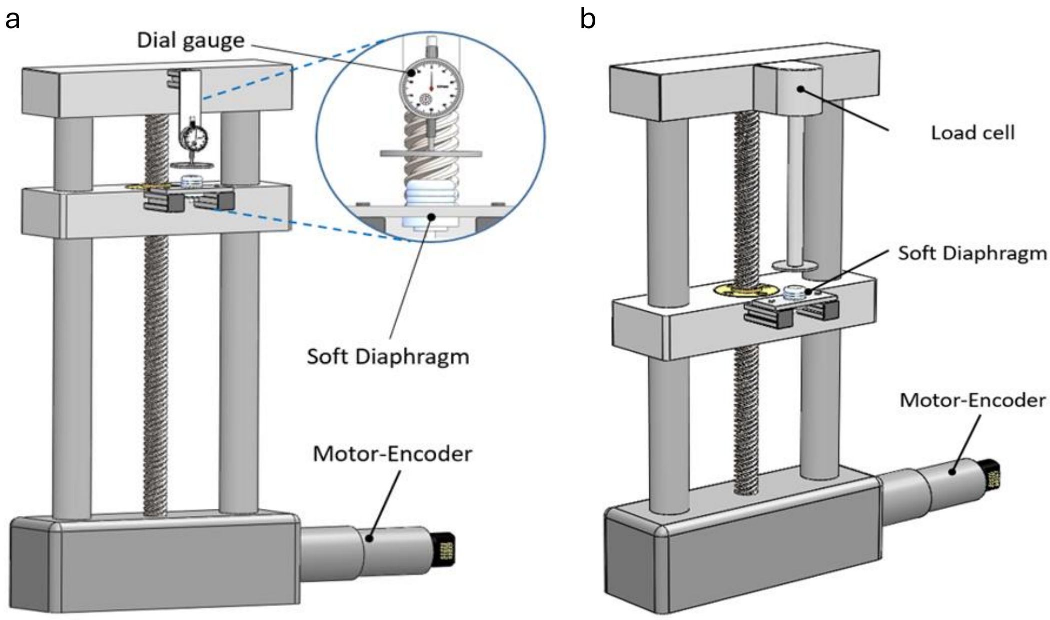

Fig. 3.9.: Devices for measuring the soft actuators features. **(a)** Assembly of the dial gauge to measure the displacements in the soft diaphragm. **(b)** Assembly of the load cell to measure the contact force in the soft diaphragm.

Therefore, taking into account the diverse cases, the contact area can be stated as follows:

$$A_c(x) = \begin{cases} \pi r^2, & \text{x=0} \\ 0, & x > 0; h < x \\ \pi r_c^2, & x > 0; h > x \end{cases} \tag{3.7}$$

Tab. 3.1.: Main technical specifications of the compression load cells.

Nonlinearity	$\pm 1\%$
Hysteresis	$\pm 1\%$
Thermal Zero Shift	$\pm$2.5mV/50^{o}C
Thermal Sensitivity	$\pm 2.5\%$/50^{o}C
Deflection at "FS"	<0.013 mm nom.
Operating Temperature	(-40 to 120)^{o}C
Thickness	3.81 mm
Diameter	25.4

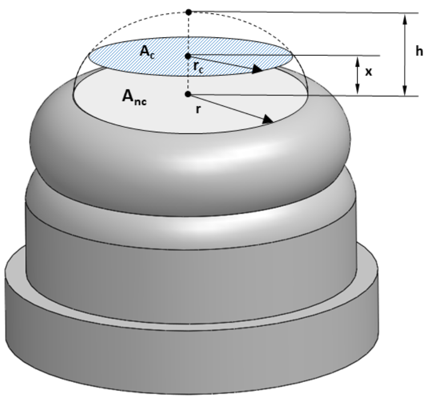

Fig. 3.10.: Graphic description of the contact area and the non-contact area, where *r* is the actual radius of the soft actuator, r_c is the radius of the contact area, *x* is the distance between the actuator and the object and *h* is the relative longitudinal distance between the soft actuator at rest and its maximum displacement at a given pressure.

where r_c can be expressed through various geometric relationships as: $r^2 - (x + r - h)^2$.

Therefore, the contact area will be accurate for each pressure and displacement. The only assumption made is that the contact area is circular, which has been experimentally determined to be valid for this actuator geometry.

Once the contact area is obtained and the contact force is measured, the contact pressure in the middle of the soft actuator can be obtained by the contact pressure distribution formulated by [220], here presented in Equation 3.8:

$$p(r_v) = C_k \frac{N}{\pi r_c^2} \left[1 - \left(\frac{r_v}{r_c} \right)^k \right]^{\frac{1}{k}} \tag{3.8}$$

where *N* is the normal force, r_c is the contact radius described above, r_v is the variable radius with $\leq r_v \leq r_c$, *k* determines the shape of the pressure profile, and C_k is a coefficient that adjusts the profile of the pressure distribution over the contact area to satisfy the equilibrium condition.

In [114], the author shows that for soft contact, the value of *k* is approximately 1.8. With that, the value of C_k can be calculated as follows:

$$C_k = \frac{3}{2} \frac{k\Gamma\left(\frac{3}{k}\right)}{\Gamma\left(\frac{1}{k}\right)\Gamma\left(\frac{2}{k}\right)} \tag{3.9}$$

Since p_0, which is the pressure in the middle of the actuator, can be a target value for evaluating a soft actuator, r_v is substituted by 0 to obtain the contact pressure in the middle of the soft actuator, leaving Equation 3.10 as:

$$p_0 = p(0) = C_k \frac{N}{\pi r_c^2} \tag{3.10}$$

Based on the aforementioned details, the proposed measurement process has been outlined in order to characterise the soft actuators in terms of forward displacement, contact force, contact area and contact pressure.

3.1.4 Experimental results

To validate the proposed design and manufacturing approaches for diaphragm-type pneumatic-driven soft grippers, as well as the characterization method for their actuators, a series of experimental tests were conducted to evaluate their performance.

First, two types of soft actuators were characterized, following the method described in Section 4: one with four smaller bellows and another with two larger bellows. The goal was to compare their behaviours. The results of these tests are shown in Fig. 3.11.

As illustrated in Fig. 3.11a, both soft actuators demonstrated nearly linear behaviour, closely matching the results of the FEM simulations. The experiments also confirmed that the 2-bellows actuator could exert more force than the 4-bellows actuator (Fig. 3.11b). This suggests that actuators with thicker walls can withstand higher input pressure and thus generate more force. However, while thinner walls allow for greater displacement, they reduce the actuator's reliability. Hence, wall thickness is a crucial design variable and may need to vary across different parts of the actuator to optimize the chosen geometry. Fig. 3.11c shows that the contact area increases almost linearly as the object moves away from the actuator, owing to the larger flat contact surface compared to the actuator head. In Fig. 3.11d, the combined results reveal that contact pressure remains constant under the experimental conditions. The tests also identified slight differences in behaviour among actuators of the same type, likely due to manufacturing inconsistencies, which can introduce air bubbles. It was also observed that actuators with shorter bellows tend to behave more like cylinders, limiting their displacement, while taller bellows allow for greater displacement due to their more spherical-like behaviour.

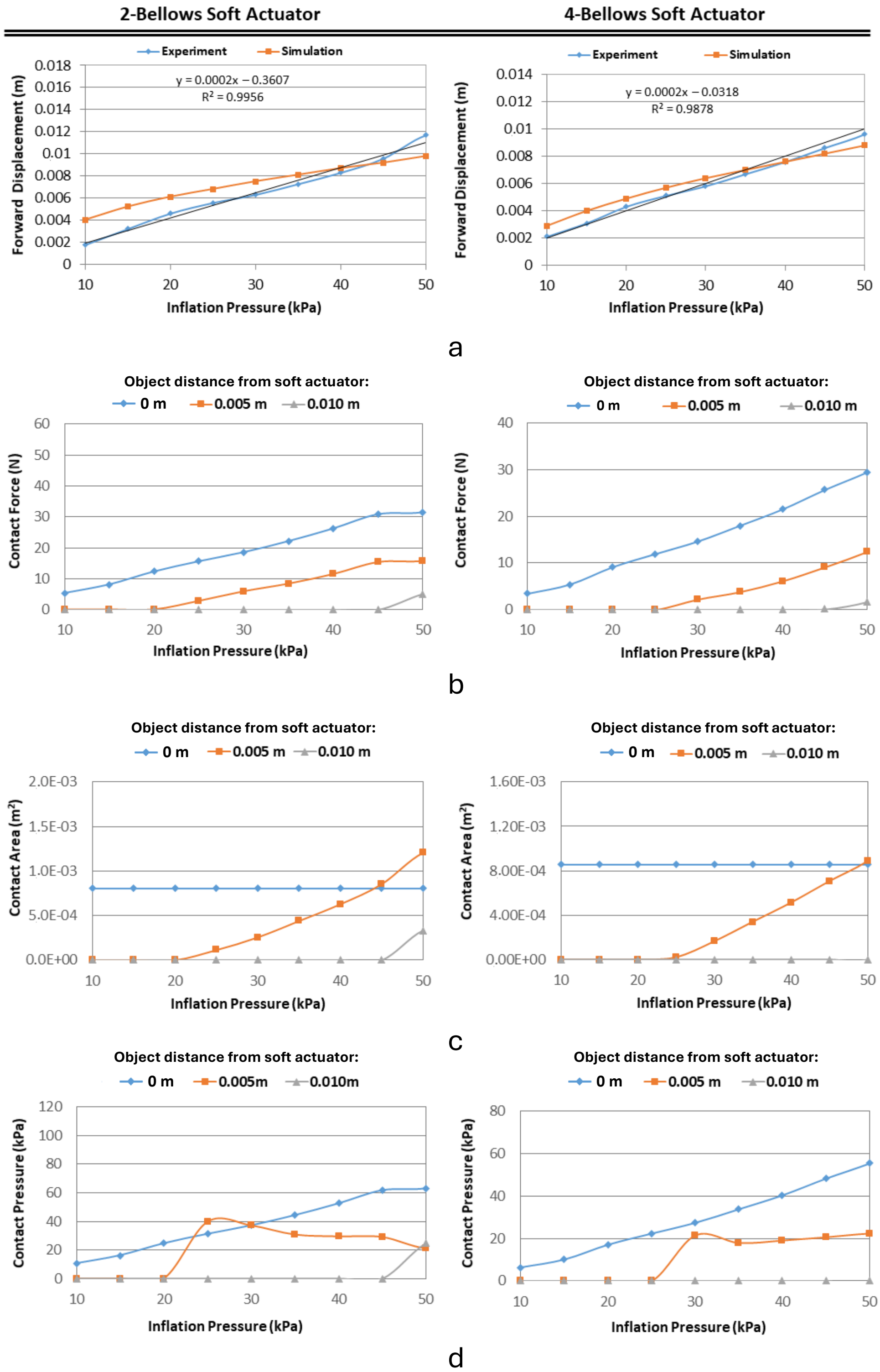

Fig. 3.11.: Experimental characterization of soft actuators. **(a)** Experimental measurement of the forward displacement as a function of the inflation pressure. **(b)** Measurement of the contact force as a function of the inflation pressure. **(c)** Relationship between the contact area and the inflation pressure. **(d)** Relationship between the contact pressure in the middle of the soft actuator and the inflation pressure. Graphic legends show the distance between the soft actuator and the object. In (a),(b) and (c), the value 0 m refers to the initial position of the actuator prior to inflation, which is used as a baseline condition for analyzing the evolution of actuator contact characteristics.

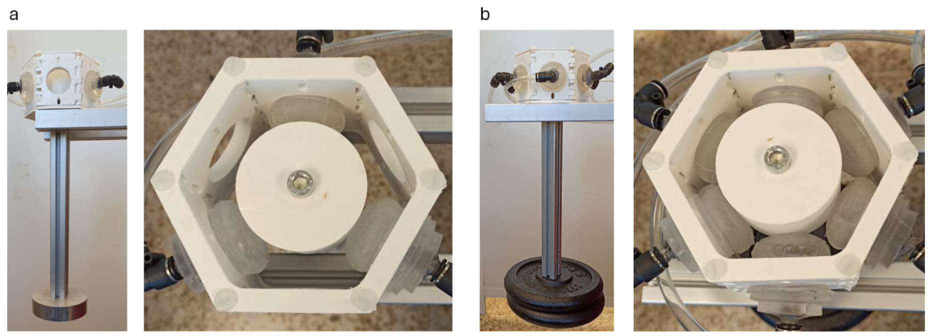

Fig. 3.12.: Slip test setup in a hexagonal configuration. **(a)** Soft gripper with three soft actuators. **(b)** Soft gripper with six soft actuators.

Next, the gripping force of the modular soft gripper was evaluated using a grasping force test [240], also referred to as a slip payload test [58] or pull-off force test [75]. This test, shown in Fig. 3.12, uses a system that applies a downward force while measuring the slip payload. The test was conducted at a constant pressure of 50 kPa, with weight added until slippage occurred or the soft actuator failed. The results showed a limit load of 4.75 kg for a hexagonal configuration with three actuators, and 10 kg for six actuators. This load capacity is sufficient for gripping most market fruits and exceeds the lifting capacity of typical robotic manipulators. The test demonstrated the scalability and modularity of the proposed gripper design, significantly increasing load capacity without comprising its structural integrity.

Additional tests assessed the gripper's performance with real fruits to determine possible damage. For these tests, a hexagonal gripper with three actuators was mounted on a Kinova Mico manipulator [102] within the ROBOCROP dual-arm robot setup [144, 175] (Fig. 3.13a). The gripper was tested on 20 artificial eggplants and 25 real fruits, including sweet peppers, pears, lemons, tomatoes, and kiwis, all at edible maturity. The tests showed that the design provided sufficient contact area for stable grips on various fruits, even when the target wasn't centred on the gripper (Fig. 3.13c). In this case, only two actuators were used for grasping. No surface damage was observed on the fruits after the test or 24 hours later (Fig. 3.13).

Table 3.2 summarizes the key experimental results for both a single soft actuator module and a hexagonal gripper with six actuators.

Finally, Figure 3.14 outlines the optimal gripper configurations for different fruit types, based on factors such as size, mass, shape, and orientation. It also considers the gripper's properties, including grasping range, maximum lifting capacity, and number of contact points.

Fig. 3.13.: Experimental tests to evaluate the grasping performance. **(a)** Soft gripper with hexagonal configuration mounted on one of the Kinova Mico manipulators that make up the ROBOCROP dual-arm robot. **(b)** Example sequence of the harvesting process with the proposed soft gripper. **(c)** Grasping a target that is not centred on the midpoint of the gripper. **(d)** Evaluation of the soft gripper with several real fruits.

As can be seen in Figure 3.14, the square configuration is ideal for small fruits, tested with a pepper weighing $11.6 \cdot 10^{-3}$ kg and a fig of $7.1 \cdot 10^{-3}$ kg. The hexagonal configuration with three actuators is suitable for a broader range of fruits, providing a greater grasping range and higher load capacity. The same configuration with six actuators is best for heavy, asymmetrical fruits, as the increased number of contact points enable it to lift heavier weights.

In testing, the hexagonal gripper with three actuators successfully grasped a 0.11 kg tomato and a $96.6 \cdot 10^{-3}$ kg lemon, while the six-actuators version lifted a 0.38 kg mango and a 0.20 kg pear. The octagonal configuration offers versatility with two to four contact points, making it suitable for medium-sized fruits. It was tested with a 0.49 kg pomegranate and a 0.33 kg red bell pepper. Lastly, the open configuration is recommended for large fruits that lie on the ground. In this case, independent pressure control for each actuator is required, as the outer actuators bear most of the load, while the inner ones prevent rotation. This configuration was tested with a 2.26 kg pumpkin and a 2.15 kg watermelon.

Tab. 3.2.: Characterization of a soft gripper module and a hexagonal configuration gripper endowed with six soft actuators.

Mass of a single module fully mounted	$69 \cdot 10^{-3}$ kg
Max. displacement of the soft actuator (75 kPa)	0.017 m
Max. contact force (75 kPa)	54 N
Operating pressure range	0-75 kPa
Mass of a fully assembled single floor hexagon configuration	0.3 kg
Slip payload test (50 kPa)	10 kg
Mean Response Time	≈ 1 s

3.1.5 Discussion

The proposed modular soft gripper design prioritizes versatility, ease of production and assembly, cost-effectiveness, and adaptability for handling medium- to large-sized fruits, while leveraging the benefits of soft robotics technology. To achieve this, the concept of diaphragm-type soft actuators, particularly the bellows-type design, have been thoroughly investigated through both analysis and experimental validation.

Furthermore, several steps have been outlined to quantitatively assess the characteristics of the soft actuators—a topic that has been somewhat controversial and sparsely addressed in the literature, especially regarding the tools used for such measurements. The importance of accurately characterizing these actuators is essential for their implementation in industries such as agriculture and healthcare, to establish a fair benchmark. Therefore, the proposed diaphragm-type pneumatic-driven soft grippers have been comprehensively characterized, and the measuring instruments employed in this process have been thoroughly described.

3.2 Soft grippers for small fruit harvesting and pick-and-place operations

This section introduces a uniaxial pneumatic diaphragm soft gripper, designed to manipulate objects indirectly through a deformable structure. This design was selected for its simplicity of fabrication, being entirely 3D-printed in thermoplastic elastomer (TPE) using a single-pass additive manufacturing process. The result is a monoblock

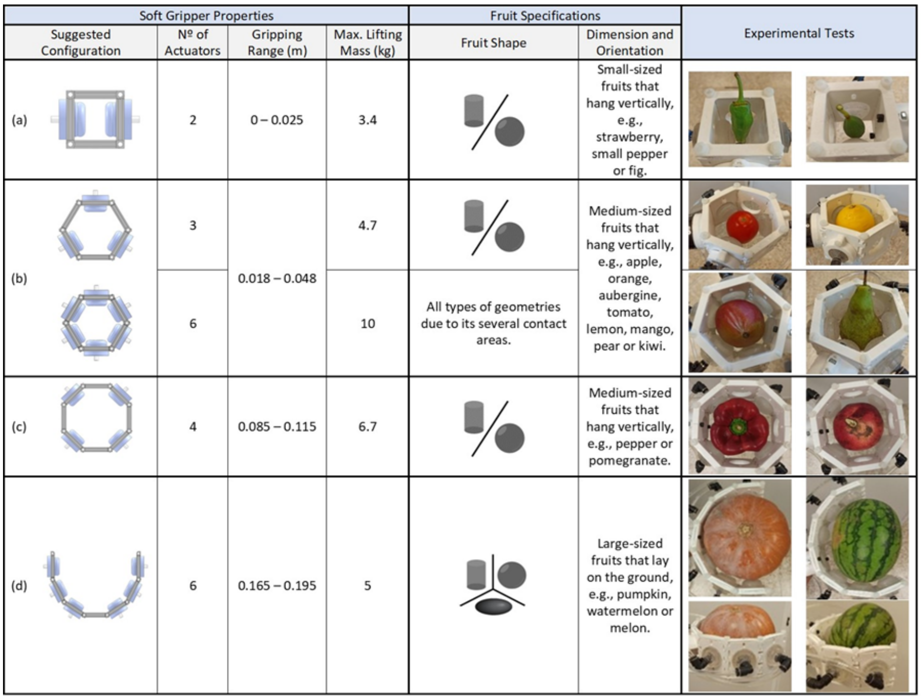

Fig. 3.14.: Preferred gripper configuration based on fruit type. **(a)** Square configuration (two soft actuators). **(b)** Hexagonal configuration (three and six soft actuators). **(c)** Octagonal configuration (four soft actuators). **(d)** Open configuration (six soft actuators).

structure that requires no post-processing. The gripper's geometry enables it to access complex areas, making it well-suited for harvesting small to medium-sized fruits, even in clustered arrangements, which presents a notable challenge in the development of harvesting robotic grippers. Thanks to the combination of materials and its carefully designed geometry, the gripper provides a firm yet delicate grip, preventing bruising of the fruit.

In line with the broader design considerations discussed earlier, this pneumatic diaphragm actuator exemplifies the practical and efficient approach of using FEAs and pneumatic systems in agricultural applications. It not only simplifies the manufacturing process but also meets the agricultural sector's requirements for modularity, ease of repair, and safe interaction with crops. Additionally, human movement data collected through a finger-tracking glove was used during the design to guide the development of the gripper's movement patterns, particularly for agricultural tasks like small fruit harvesting. Rather than fully mimicking the complexity of a human hand, this data inspired a simplified three-point grip mechanism, capturing key aspects of human motion essential for gripping small objects. The resulting design performs targeted opening and closing actions, making it particularly suitable for tasks such as small fruit harvesting and pick-and-place operations.

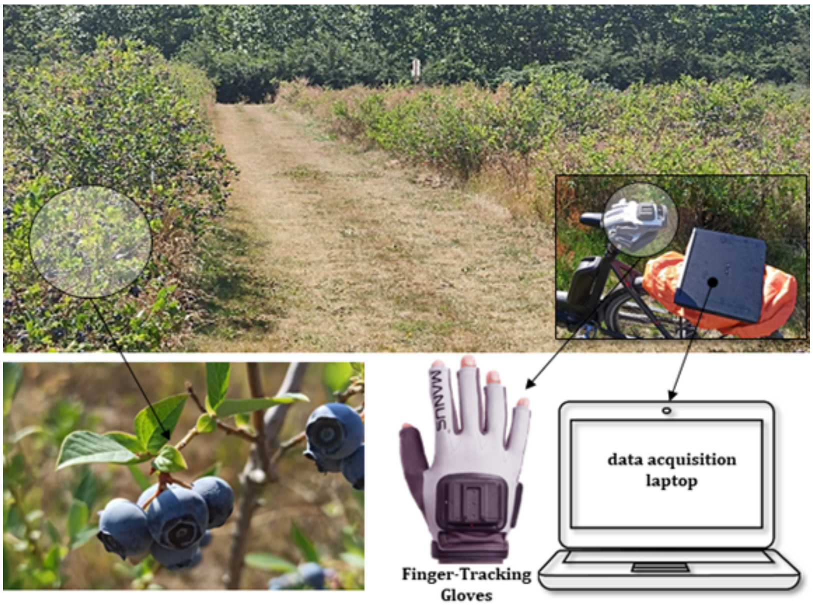

Fig. 3.15.: View of the Blueberry experimental field and data acquisition setup.

3.2.1 Data acquisition

During the design phase, finger-tracking gloves were employed to gain a better understanding of the movement patterns involved in the harvesting process. This data was then applied to tailor the soft gripper's design, enhancing its ability to replicate essential human motions. Using finger-tracking gloves represents an innovative approach to studying fruit harvesting techniques. Traditionally, visual methods have been the most common approach in scientific literature for analysing harvesting movements [47, 237]. However, visual methods often lack the precision needed to capture the complex motion patterns exhibited by humans during fruit picking tasks. Finger-tracking gloves, by contrast, enable accurate monitoring and numerical quantification of these movement patterns, allowing for a more in-depth analysis of different harvesting techniques as part of a broader manipulation study.

The data acquisition trials with the finger-tracking gloves were conducted under natural field conditions at the Leibniz Institute of Agricultural Engineering and Bioeconomy e.V. (ATB) to capture realistic harvesting movements. Blueberries (*Vaccinium corymbosum*), sourced from the ATB Marquardt fields in Potsdam, Germany, were chosen for these tests. The gloves used for data collection, shown in Figure 3.15, were the Manus Prime 2 [127], which are capable of tracking joint angles, as well as the stretch angles between fingers.

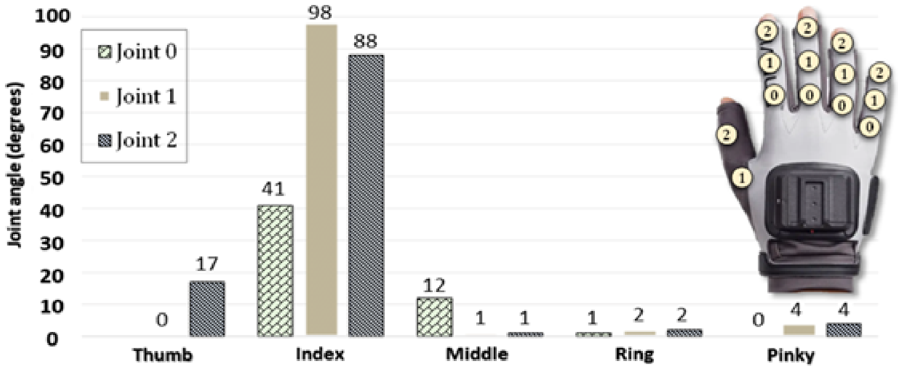

Fig. 3.16.: Maximum angle reached by the finger joints during blueberry harvesting [147].

To assess the characteristics of blueberries, a random sample of 20 berries was selected. The average diameter measured was 13 mm, with sizes ranging from 10 mm to 15 mm. The average weight was 1 g, with individual berries weighing between 0.6 g and 1.4 g. During the harvesting of these 20 samples, finger joint angles were monitored, as shown in Figure 3.16. The thumb and index finger were primarily used, following a pulling picking pattern. A quick analysis was conducted using the maximum joint values to identify the fingers involved in the process. The spread angles for the thumb, index, middle, ring, and pinkie fingers were 39º, 0º, 0º, 0º, and 0º, respectively. Notably, these angles remained constant, with the thumb and index finger in a fixed position, suggesting a strong grip. Based on these observations, it can be concluded that a two-point grip is ideal for harvesting blueberries. However, to accommodate a wider range of small fruits and varying picking patterns, the gripper is designed with three contact elements, ensuring a secure grip and effective handling while offering a versatile solution for diverse harvesting scenarios.

3.2.2 Design, structural modelling and manufacturing

To identify the key requirements for a soft gripper specifically designed for small targets, a review was conducted on agricultural processes involving precise manipulation, with a particular focus on tasks related to harvesting [50, 140, 143, 145] and pick-and-place applications [19]. A critical factor in improving the efficiency and profitability of small fruit harvesting equipment is the ability to adapt the gripper design to handle various types of fruits. With this in mind, the goal was to develop a fully parameterizable and scalable gripper design that could be produced in different sizes, allowing for a range of diameters and lengths. This adaptability enables the gripper to be reconfigured for handling different small fruits effectively. Another important consideration is simplicity in design, resulting in systems that are easy to interchange and repair. To achieve this, the design is based on a compact soft actuator with a flexible gripping structure that can be quickly produced using 3D printing technology, allowing for rapid prototyping and customization.

In addition to functional requirements, other design priorities focus on maintaining the quality of the harvested fruit. These include preventing damage during handling, using food-safe materials, and designing the gripper to minimize the risk of disease and pest transmission. Unfortunately, previous gripper designs often overlooked these critical factors, frequently employing materials that could harm delicate fruits and incorporating complex structures that are difficult to clean. This new design addresses these issues by combining soft robotics principles with hygienic, flexible, and adjustable features to ensure both crop safety and fruit quality.

The modular soft gripper is also designed to function as the end effector of a robotic manipulator [143, 145, 175], enabling it to perform the essential movements required for harvesting, commonly referred to in the literature as "picking patterns" [81, 116, 136, 221]. These patterns include basic actions such as twisting, pulling, lifting, and bending, which can be combined as needed to accommodate different fruit types and harvesting conditions.

The following section outlines the field study conducted to establish a design that meets the demands of small fruit harvesting. This includes an overview of the materials selected for the gripper, with emphasis on their key advantages, as well as the design specifications for both rigid and soft components. The soft parts are modelled using finite element analysis to optimize performance. Finally, the manufacturing and assembly processes of the gripper are described to provide a comprehensive understanding of its development.

- Soft actuator design: Once data on fruit characteristics and picking patterns have been gathered, the design requirements are established. Analysis of these patterns, along with criteria such as simplicity, minimizing fruit bruising, and the ability to handle clustered fruit, defines the key design constraints. Ultimately, the soft gripper is developed not just as an end effector but also as a versatile tool for a robotic arm, capable of executing almost all the picking patterns needed for fruit harvesting [146]. In terms of the geometric design, as illustrated in Figure 3.17, the proposed grippers utilize a single-channel diaphragm-type actuator with a flexible structure. One of the main benefits of this design is its ease of manufacturing, as it can be produced in a single piece via 3D printing. Additionally, it simplifies control, as the diaphragm actuators

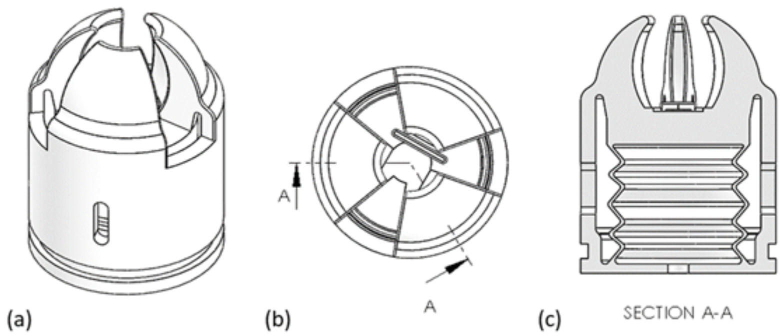

Fig. 3.17.: Soft Actuator. **(a)** Isometric View. **(b)** Top view. **(c)** Section view.

are designed to move primarily along one axis, with minimal motion on other axes, reducing the complexity of managing the gripper's DoFs.

The flexible diaphragm design incorporates a bellows concept, distinguishing it from other shapes in how it inflates. As mentioned in Section 3.1, unlike cylindrical, cubic, or spherical designs, which often lead to inefficient side forces during inflation, the bellows design mitigates this issue. While cylindrical and cubic geometries suffer from reduced forward motion due to radial expansion, and spherical shapes—though superior in inflation behaviour—require complex moulding, the bellows-cylinder combination partially addresses these drawbacks. It effectively uses radial forces from inflation to create forward extension, enhancing the gripper's overall performance.

The actuator's structure includes three contact elements that ensure a firm grip and effective manipulation of objects. These elements provide three points of contact and a stable surface, enabling secure handling. This mechanism is crucial for tasks like harvesting, allowing the gripper to perform a range of picking movements such as pulling, twisting, and bending the fruit's stem, all while maintaining a firm hold. Moreover, these contact elements are reinforced with thicker TPE walls compared to the diaphragm, providing stability for the claw's opening and closing actions.

To develop an optimal soft gripper for handling small fruits, the COMSOL Multiphysics® platform was used to simulate its inflation behaviour using the FEM as shown in Figure 3.18. TPE was modelled as a hyperelastic material. In existing literature, several mathematical models are available to describe the behaviour of 3D-printed thermoplastic elastomers. Among these, the fifth-order Ogden model—compared to Yeoh's, Van der Waals', and Arruda-Boyce's models—offers a more accurate depiction of TPE's behaviour [3].

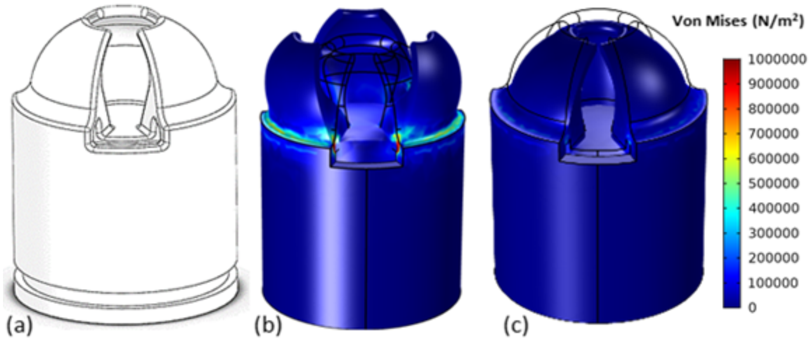

Fig. 3.18.: Model showing the displacement reached on the soft gripper in **(a)** normal position, **(b)** open position, and **(c)** closed position.

Additionally, the inflation pressure on the soft diaphragm induces equibiaxial tension, a phenomenon in hyperelastic materials like TPE. This was first modelled by Ogden [152], applying to elastic solids characterized by a strain-energy function and isotropic stress-free behaviour. The solid's incompressibility was also considered. These parameters, along with values for μ, α, and bulk modulus from [99], were input into the FEM software. The simulation results are shown in Figure 3.18 for the soft gripper.

When determining the working pressure range for the analysis, priority was given to ensuring sufficient working volume for small fruits while maintaining low energy consumption and delivering enough grip force for various manipulation tasks. After an iterative process, a pressure range of 50 kPa to -50 kPa was established.

The soft gripper's structure was designed to achieve varying levels of rigidity by adjusting wall thickness, as some areas need to be rigid for stable gripping, while others require flexibility. The bellows walls, for example, were printed with a thickness of 0.8 mm, a rounding radius of 1 mm, and a wall angle of 90 degrees to achieve the necessary flexibility.

- Design of the rigid structure: After thoroughly analysing the collection patterns of various fruits, it was found that rotational motion is often employed to assist in detaching them from the plant. To integrate this functionality into the designed soft gripper, a rotational degree of freedom around the gripper's axis was added. For this purpose, a rotating base made from PLA, depicted in Figure 3.19a, was incorporated and powered by a Nema 17 stepper motor.

  – Soft materials: 3D printing has proven to be a promising method for manufacturing soft actuators. This technology provides greater precision and efficiency, reducing manufacturing defects and allowing for better experimental reproducibility. Additionally, design changes can be made through software, offering improved control over the actuator's behaviour and performance.

In the field of soft robotics, polymer-based materials like Ecoflex [79, 135], Dragon Skin [38, 42, 182, 212], Elastosil M4601 [59, 135, 174, 195], and polydimethylsiloxane (PDMS), commercially known as Sylgard 184 [58, 79, 132, 169, 182, 207], are commonly used due to their desirable mechanical properties and ease of processing. However, fabricating soft robots with these materials can be time-consuming and complex, involving multiple steps such as mould design and precise assembly to avoid material leakage. Additionally, the process can suffer from issues like interstitial bubbles and delamination, potentially compromising actuator performance or leading to failure.

Thermoplastic elastomers (TPEs) [46, 119], however, have attracted considerable attention in soft robotics due to their ability to create complex geometries that are difficult to achieve with traditional moulding processes. TPEs, which combine the elastic properties of rubber with the processing benefits of thermoplastics, are ideal for use in additive manufacturing methods like 3D printing. Their capability to form intricate shapes has made TPEs a valuable material for developing soft robots, which require flexible structures to perform a wide range of adaptive motions.

Thus, for the soft gripper's construction, a 1.75mm TPE filament produced by Multicomp Pro was selected. TPE offers the dual advantages of elastomeric flexibility and thermoplastic processability, making it well-suited for the creation of compliant soft actuators that can handle diverse motions and adapt to different tasks. Furthermore, TPE's flexibility, durability, and biocompatibility enhance its potential use in agricultural applications.

- Manufacturing and assembly: The soft gripper was fabricated using Fused Filament Fabrication (FFF), specifically with a modified Creality Ender 3 3D printer capable of handling flexible materials. The 3D printing parameters were optimized using Ultimaker Cura software to print an airtight soft pneumatic bellow gripper. The nozzle temperature for the bellow actuator was set at 230°C, with a printing bed temperature of 50°C. A printing speed of 20mm/s was used for the infill, while the

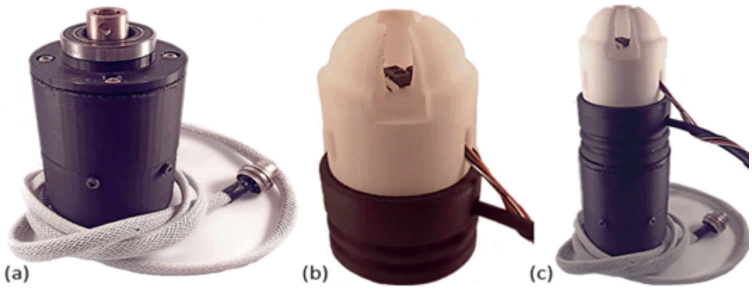

Fig. 3.19.: View of the **(a)** soft gripper rotating base, **(b)** soft Actuator, and **(c)** complete assembly of the soft gripper.

outline speed was reduced to 10 mm/s to ensure high-quality exterior finishes and airtightness. A 20% infill was used for the entire structure, with a perimeter overlap of 30%. The layer height was set at 0.2 mm, and the extrusion width at 0.4 mm for the whole print.

This manufacturing process offers a promising approach for producing soft robotic components, as it enables the creation of complex geometries with high customizability in a cost-effective and time-efficient manner.

The rigid parts of the soft gripper were fabricated using Polylactic Acid (PLA). The soft actuator was attached to the rigid base via a press-fit mechanism, as shown in Figure 3.19b, eliminating the need for screws or other rigid fasteners. The motor was mounted to the gripper claw using screws, and the motor shaft was coupled with the movable part of the gripper through a motor coupling supported by a bearing. The lower section of the claw is designed to be detachable, allowing it to function either as a primary soft gripper or as a soft tool for a robotic arm. Figure 3.19c provides a detailed view of the fully assembled soft gripper.

3.2.3 Characterization and experimental results

To evaluate the performance of the soft actuators and validate the proposed approach, a series of experimental tests were conducted. Initially, several static experiments were performed to assess the physical characteristics of the actuator, including its weight, the range of fruit diameters it could handle, the maximum opening diameter, and the pressure range. Figure 3.20 illustrates the gripper in both its open and closed states. Further experiments were carried out to determine the maximum gripping or detachment force of the gripper for a specific geometry at varying pressures, which is crucial for selecting suitable target fruits. The geometry was based on the

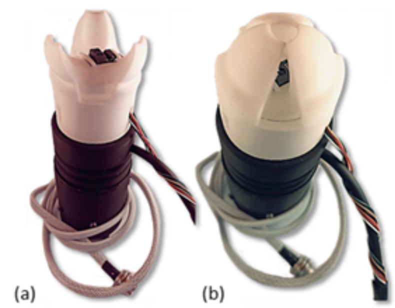

Fig. 3.20.: **(a)** Soft Gripper in open position. **(b)** Soft Gripper in closed position.

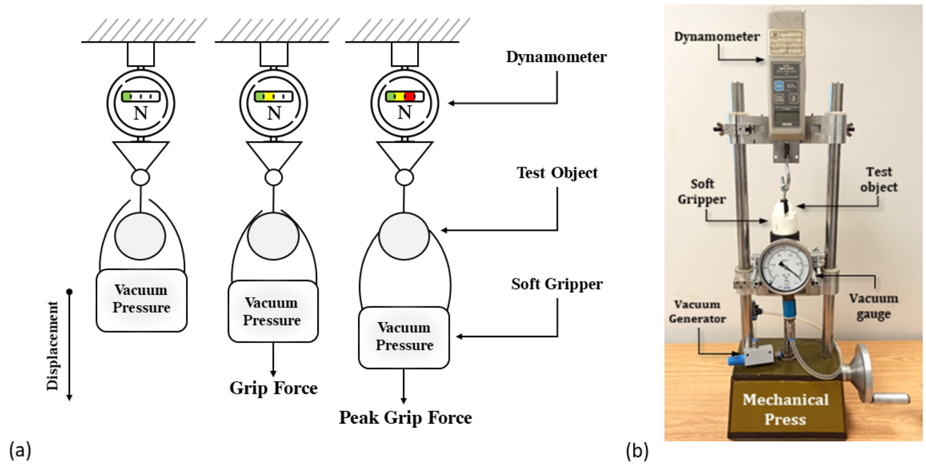

Fig. 3.21.: Slip test. **(a)** Experiment schematic view. **(b)** Experiment setup.

target fruit to be manipulated, represented in this case by a smooth sphere with a 20 mm diameter, 3D-printed using PLA. This experiment, known as a slip test [58] or pull-off force test [75], involved setting up a movable assembly that included: (*i*) the movable base of a mechanical press, (*ii*) the soft gripper, and (*iii*) fixed components such as a dynamometer, a pressure gauge, a vacuum generator, and the object to be manipulated. The experimental setup and schematic are shown in Figure 3.21.

The procedure involved varying the position of the soft gripper, which held the object at a set vacuum pressure, while recording the peak force exerted by the object as it slipped from the gripper. This was repeated at different vacuum pressures.

The results are shown in Figure 3.22, depicting the relationship between the gripping force and the vacuum pressure applied by the soft gripper. As illustrated, the soft gripper achieved a maximum gripping force of 13 N at a vacuum pressure of -52 kPa. The gripping force varied linearly with pressure, with an R^2 value of 0.93, indicating a strong linear relationship. To verify consistency, three soft grippers were tested, with no significant variations observed among them.

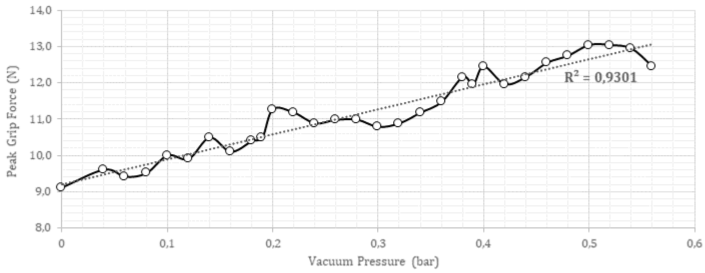

Fig. 3.22.: Plot of the slip test for soft gripper characterization showing peak grip force versus vacuum pressure.

Finally, with all the experiments detailed above, Table 3.3 summarizes the characteristics values of the designed soft gripper.

Tab. 3.3.: Soft gripper characterization.

Soft gripper weight	38.05 g
Weight of the fully assembled gripper	577.55 g
Max. soft actuator diameter (150 kPa)	0.045 m
Min. soft actuator diameter (-52 kPa)	0.007 m
Max. slip force (-52 kPa)	13 N
Operating pressure range	-52 to 150 kPa
Mean Response Time	≈ 1 s

Two additional sets of experiments were conducted to assess the soft gripper's performance in picking tasks. In the first set, the gripper was used as a tool operated by a human, referred to as the soft tool mode. Figure 3.23 shows several sequences of the gripper in this mode. These tests demonstrated the gripper's effectiveness in pick-and-place applications and in harvesting various fruits in clusters, minimizing damage to the products.

In the second set of experiments, the soft gripper was tested in harvesting tasks using an ABB YuMi IRB 14000 dual-arm collaborative robot (see Figure 3.24). The initial step involved recording the surface condition of fruits such as cherry tomatoes, blueberries, raspberries, and grapes. The robot and the operation scenario were then simulated in a virtual environment using CoppeliaSim software. The joint positions obtained from the simulation were sent to the robot to perform the necessary harvesting movements. The test results showed that the fruits were successfully harvested without any visible damage or changes to their surface one week after the test. Although grapes and cherry tomatoes are not typically harvested individually from a bunch, the gripper was able to pick each fruit separately, a challenge in the development of robotic grippers for harvesting [13]. This type of grip is made

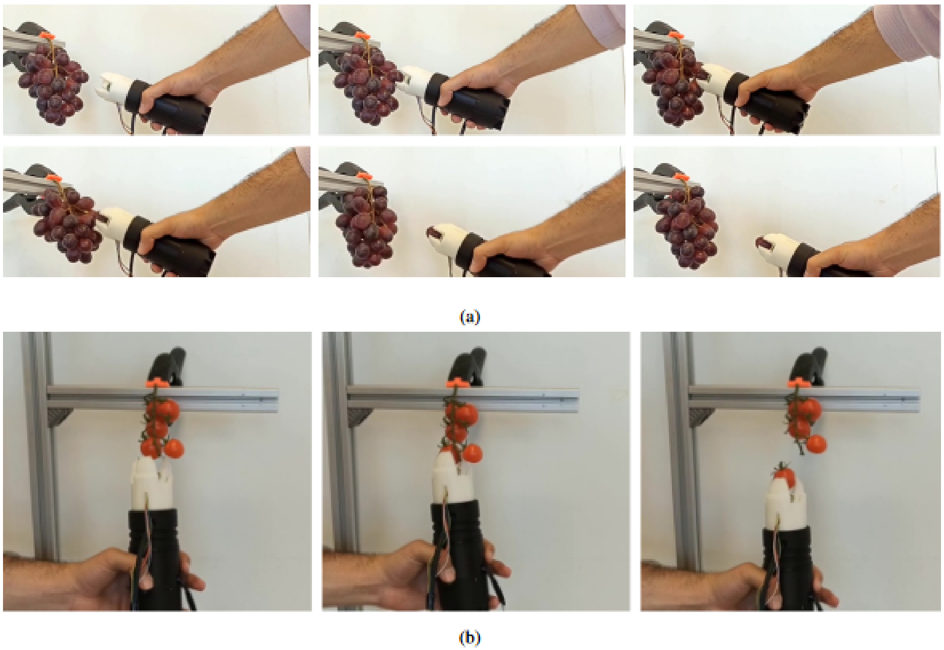

Fig. 3.23.: Evaluation of the designed gripper used as a soft tool for picking operations of clustered fruits such as **(a)** grapes and **(b)** cherry tomatoes.

possible by the design and material of the soft gripper, which allows for the careful selection of fruit without damaging the surrounding produce.

3.2.4 Discussion

The proposed soft gripper design offers several significant advantages, including versatility, ease of production, and cost-effectiveness, making it well-suited for handling small to medium-sized fruits. Moreover, the gripper can efficiently manage agricultural products during harvesting and pick-and-place tasks, even when the fruits are clustered together. By leveraging soft robotics technology, the gripper achieves the delicate balance required for such tasks. The use of 3D additive manufacturing, particularly with flexible filaments, enables the creation of a monoblock design that integrates both flexible structures and pneumatic actuation, simplifying the production process while maintaining functional complexity.

A key innovation in this work is the analysis of movement patterns in blueberry harvesting, using data collected from finger-tracking gloves. This data-driven approach guided the development of a simplified three-point grip mechanism, inspired by essential aspects of human hand movements, to enhance the gripper's adaptability

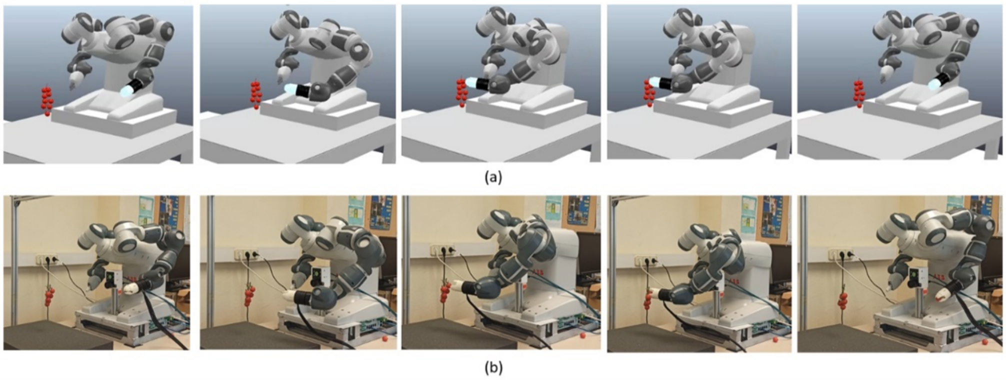

Fig. 3.24.: Evaluation of the soft gripper for tomato bunch harvesting operations. **(a)** Simulation of the process in CoppeliaSim. **(b)** Harvest test in laboratory conditions.

for small fruit harvesting and similar agricultural tasks. Another major contribution is the design of a compact hybrid gripper that combines flexible structural technologies with varying stiffness levels. This hybrid design utilizes pneumatic actuation to enable indirect movement, while incorporating a rotating rigid structure that supports a range of gripping and picking patterns. Importantly, the proposed soft gripper also includes puncture-prevention strategies to protect the pneumatic components from potential failures, which is relevant in agricultural scenarios.

Furthermore, the proposed design simplifies the gripper's control and functionality by employing a uniaxial diaphragm actuator. This actuator is easy to replicate and replace, providing a cost-effective solution ideal for both agricultural and pick-and-place operations. Its uniaxial motion reduces the complexity of the control system while delivering a firm yet delicate grip, allowing the gripper to harvest fruits or objects in clusters without damaging adjacent items. This compromise between efficiency, adaptability and simplicity enhances the viability of the design for real-world agricultural application.

3.3 Reconfigurable hybrid soft grippers

Reconfigurable hybrid soft grippers represent a significant advancement in robotic manipulation, combining rigid and soft components to achieve both precision and adaptability. These hybrid designs, frequently explored in the literature [64, 143, 145, 155, 243], leverage the strengths of both approaches: the precision, stability, and strength of rigid systems with the flexibility, gentle handling, and adaptability of soft robotics. The rigid elements enhance structural integrity and precise control, while the soft components enable delicate manipulation, safer interaction, and adaptability in dynamic or unpredictable environments.

A defining feature of reconfigurable hybrid grippers is their ability to adjust their structure or functionality based on the task at hand. This reconfigurability enables a single gripper to handle object of varying shapes, sizes, and manipulation requirements by modifying its configuration, such as adjusting the position or number of actuators. Such versatility is particularly beneficial in applications like agriculture or manufacturing, where a wide range of shapes and geometries must be managed efficiently, minimizing downtime associated with tool changes.

The combination of rigid and soft elements, along with reconfigurability, significantly enhances the versatility of hybrid soft grippers, enabling them to perform tasks that would typically require multiple specialized grippers. This type of gripper is ideal for multifunctional tasks, such as harvesting and pick-and-place operations, due to its ability to adapt and perform complex manipulations through its hybrid design.

3.3.1 Rigid Structure Design

The proposed patented soft gripper design [141], depicted in Figure 3.25, employs a hybrid approach by integrating traditional rigid robotic components with soft robotics elements. The gripper consists of a soft section, which provides adaptability and ensure safe interaction with objects, and a set of rigid components aimed at enhancing the gripper's dexterity.

The rigid parts are divided into a structural element and two mobile segments. These segments incorporate a bevel gear system powered by two motors with encoders, enabling two of the three fingers to rotate around the gripper's longitudinal axis, with a motion range of 30º to 120º relative to the fixed soft finger. This reconfigurable design allows the actuators to be independently repositioned in a circular layout around the palm's centre, supporting complex movements and manipulations.

Rigid Polylactic Acid (PLA) filament was used for both the structural components and the finger rotation mechanism. The gripper, including its rigid elements, was manufactured using 3D printing technology on a modified Creality Ender 3 3D printer equipped with a direct-drive extruder.

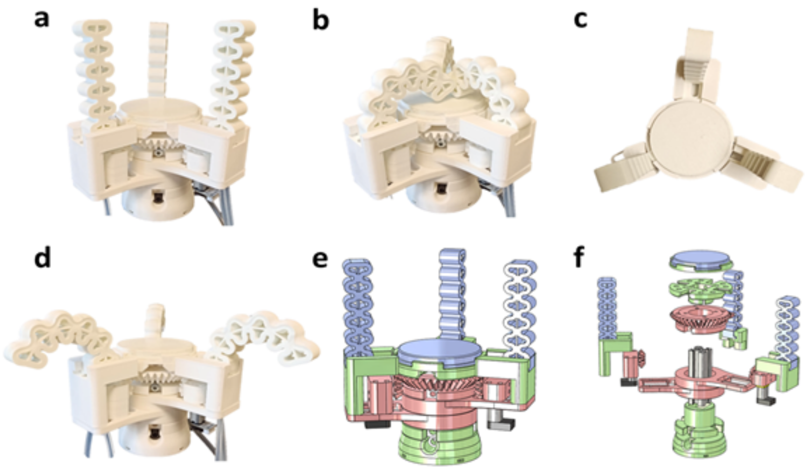

Fig. 3.25.: Proposed soft gripper design. **(a)** Manufactured soft gripper in normal pose. **(b)** Fully close position. **(c)** Top view. **(d)** Fully open position. **(e)** CAD view. In blue, the parts made of flexible filament, in red the rigid parts in charge of the movement of the soft actuators, and in green, the structural parts of the soft gripper. **(f)** Exploded CAD view.

3.3.2 Soft Actuators

The soft portion is made up of three soft actuators. The proposed soft actuator is inspired by the single-channel pneumatic design introduced by [95], which achieves symmetry along its longitudinal axis. This symmetrical configuration enables both gripping and releasing motions by utilizing two opposing pneumatic chambers. The actuator's flexibility can be dynamically adjusted by inflating one channel with positive pressure while applying either vacuum or positive pressure to the other channel to modify its stiffness. Figure 3.26 provides an overview of the actuator's dimensions and manufacturing process.

The three actuators that form the soft gripper are fabricated using additive manufacturing with FilaFlex 60A flexible filament, specifically chosen for its high flexibility. To ensure airtight printing, the following 3D printing parameters were applied: a nozzle temperature of 230°C, a bed temperature of 50°C, a printing speed of 20 mm/s for the infill and 10 mm/s for the outline, 20% infill with 30% perimeter overlap, and a layer height of 0.2 mm with an extrusion width of 0.4 mm.

This flexible Thermoplastic Elastomer (TPE) filament—FilaFlex 60A by Recreus—was used for the soft actuators to provide adaptability and safe interaction with objects. The actuators' design and fabrication were optimized for airtightness, ensuring the soft gripper's ability to perform delicate, complex manipulations.

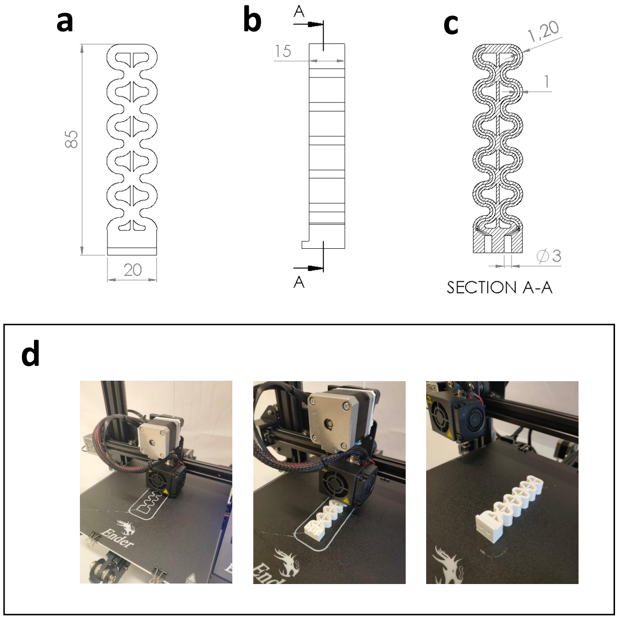

Fig. 3.26.: Proposed soft actuator design. **(a)** Front view. **(b)** Side view. **(c)** Split view of the soft actuator, showing the two opposing pneumatic chambers. **(d)** Soft actuator 3d printing process. Bottom print, air chambers and top printing, respectively.

3.3.3 Characterization and experimental results

To assess the performance of the proposed two-channel soft actuator design, a series of experimental tests were conducted. The initial phase involved several static experiments, as shown in Figure 3.27, to evaluate the physical characteristics of the actuator, including its weight, range of motion along two axes, as well as the force at the tip of the actuator at different pressure levels. For the latter test, where the actuator force is measured, the actuator was placed on a flat surface with a force sensor positioned under one of its tips. As the pressure was gradually increased, the resulting forces were recorded, as shown in Figure 3.27c. This procedure represents the standard method for measuring this parameter [111, 235, 238].

Table 3.4 shows a summary of the soft gripper features.

The proposed soft gripper serves as a foundation for modelling and manipulation control, which will be discussed in detail in the following section. Prior to this, a series of experiments were conducted to evaluate its performance in pick-and-place operations using an ABB YuMi IRB 14000 dual-arm collaborative robot (see Figure 3.28). To validate the design, pre-programmed gripping motions were tested on fruits of varying sizes. The gripper successfully manipulated both small fruits, such as cherry tomatoes (24x24x24 mm, 12.70 g), and larger, heavier fruits, such as

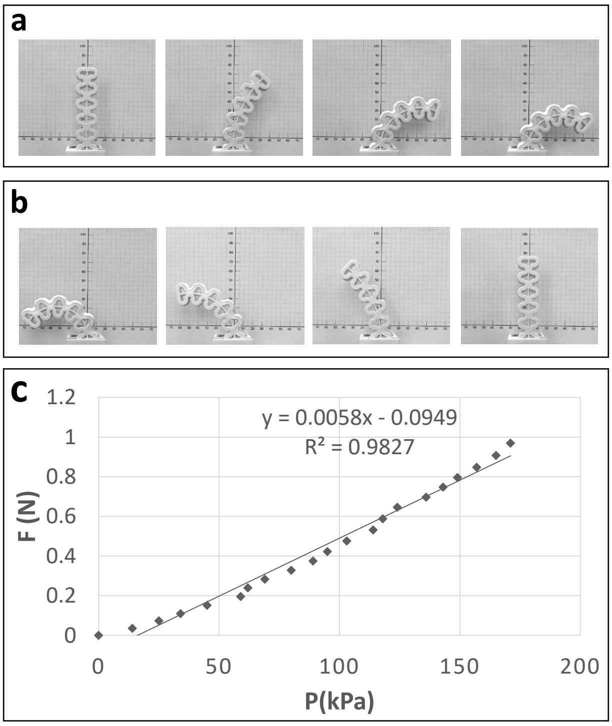

Fig. 3.27.: Soft actuator characterization. **(a)** Rightward movement of the actuator. **(b)** Leftward movement of the actuator. **(c)** Characterization of actuator contact force at various pressures.

mangoes (130x80x70 mm, 372.60 g). The experiments demonstrated its ability to firmly grasp fruits while preventing bruising.

3.4 Conclusion

The development of soft gripper designs in this research has been conducted with a focus on real-world integration, particularly within agricultural environments. To achieve this, key requirements such as modularity, reconfigurability, and the use of affordable, readily available materials, which are essential for adapting to different scenarios, have been thoroughly addressed.

The first soft gripper designed introduced a modular approach, prioritizing its adaptability to various crops of different sizes and weights without compromising its gripping capability. This adaptability is achieved through individual, easily integrable modules that allow for different geometries configurations in the form of regular

Tab. 3.4.: Characterization of the reconfigurable soft gripper.

Soft gripper weight	12.75 g
Weight of the fully assembled gripper	297.7 g
Max. soft actuator diameter (175 kPa in opposite air chamber)	0.090 m
Min. soft actuator diameter (175 kPa)	0.020 m
Max. gripping load (175 kPa)	500 g
Operating pressure range	-80 to 175 kPa
Mean Response Time	≈ 1 s

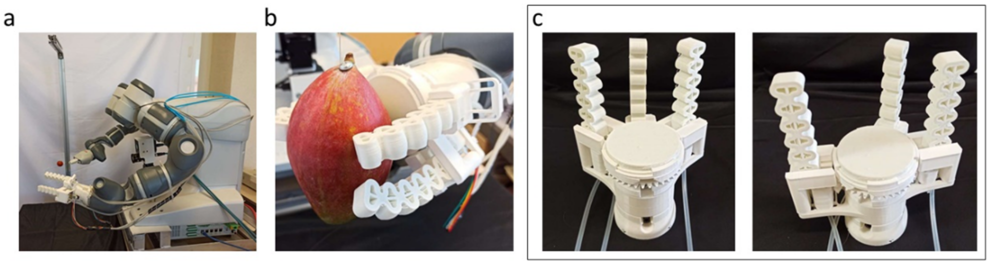

Fig. 3.28.: Evaluation of the proposed reconfigurable soft gripper. **(a)** Experimental setup with suspended fruit to test various manipulation paths. **(b)** Gripping of a heavy object for design validation. **(c)** Testing finger configurations to explore the ability to perform a variety of grip patterns.

polygons. Additionally, its closed design ensures the protection of the fruit during handling, preventing damage throughout the process [87].

The second design focused on a soft gripper tailored for handling small objects, featuring a compact structure manufactured entirely through additive technology. This approach not only facilitates its repair due to the quick replicability of its parts, but also reduces both manufacturing and maintenance costs. This gripper has been successfully tested in real harvesting environments and pick-and-place operations, excelling in hard-to-reach areas and in harvesting clustered fruits, which pose a significant challenge in the development of robotic grippers for agricultural applications. Moreover, the design methodology stood out for its use of finger-tracking gloves to collect data from real-world environments, which guided the gripper's design development to meet the practical requirements observed during field studies.

In the third design, a reconfigurable soft gripper was proposed with the goal of achieving dexterous gripping performance. This gripper features three soft fingers, two of which are capable of rotating relative to the gripper's centre, allowing for versatile reconfiguration. To ensure compatibility, the gripper was designed to be lightweight, meeting the requirements of robotic manipulators that handle up to

500 g. Additive manufacturing was utilized for all components, including the bevel gear system that enables its reconfiguration.

In comparison with existing literature, the three soft grippers developed, exhibit competitive performance. In terms of maximum load, the diaphragm-type pneumatic-driven soft gripper with hexagonal configuration can lift up to 10,000 g at 50 kPa, significantly exceeding most devices reported, with only one reaching 1000 g [213] and another 2700 g [194]. The diaphragm-type pneumatic-driven soft gripper and the reconfigurable hybrid soft gripper also demonstrate notable capabilities, supporting slip forces up to 13 N and gripping loads of 5 N, respectively. Regarding response time, the three proposed grippers have an average of approximately 1 s, outperforming several devices in the literature with significantly higher response times, such as 31.7 s [17] or 10 s [214]. In terms of gripper size, the proposed designs maintain compact and varied dimensions (e.g., the diaphragm-type pneumatic-driven soft gripper with hexagonal configuration with a module mass of 69 g and total configuration of 300 g), aligning with similar setups in the literature while offering advantages in force and control. Lastly, all developed grippers operate within pressure ranges typical of those found in the literature.

Part IV

Sensorization, Simulation and Control of Soft Grippers

4 Sensorization, Simulation and Control of Soft Grippers

4.1 Introduction

The sensorization, simulation and control of soft grippers pose significant challenges in the field of soft robotics, primarily due to the nonlinear behaviour of hyperelastic materials such as silicones, rubbers, and other elastomeric polymers. These materials undergo large deformations that are difficult to model, resulting in a quasi-infinite number of degrees of freedom. This complexity not only affects the design and simulation processes but also complicates the integration of sensorization systems. Providing accurate feedback on deformation, force, and position is particularly challenging due to the highly unpredictable nature of soft actuators. Addressing these difficulties demands the development of innovative approaches capable of capturing the dynamic behaviour of these systems while maintaining their compliance and adaptability.

Another challenge in this field lies in simulating soft contact interactions accurately, where actuators come into contact with objects. Advanced mathematical frameworks, like the Mooney-Rivlin model, are often needed to effectively describe the hyperelastic properties of these materials. Additionally, the adaptability required for soft robotics in dynamic environments further highlights the multidisciplinary nature of this research area. As a result, advancements in sensorization, simulation, and control of soft grippers remain central topics of interest within the field.

To address these challenges, this chapter focuses on three main approaches: sensorless techniques for pneumatic actuators, soft contact simulation using FEM, and a hybrid control method combining hyperelastic simulation and data-driven strategies for grasping.

Sensorless techniques leverage the intrinsic properties of actuators, such as pressure and volume, to estimate force and displacement, eliminating the need for embedded sensors. This approach reduces system complexity, cost, and fragility, making it suitable for applications where absolute precision is not critical, such as agriculture.

In terms of soft contact simulation, FEM is a powerful tool for modelling material deformations during interactions between actuators and objects, offering valuable insights into materials behaviour under load and enhancing the design and control of actuators.

Finally, in terms of control, a hybrid strategy is adopted, combining FEM with data-driven methods. FEM enables detailed simulations to refine actuator design by capturing material deformation dynamics, while data-driven models adapt control systems based on real-world conditions. Together, these approaches create a comprehensive framework for controlling soft grippers, improving their performance through reliable, effective path planning, and precise simulation of contact interactions.

4.2 Sensorization

As outlined in the state-of-the-art chapter, various methods for sensorizing soft actuators have been explored in the literature. These methods can be broadly categorized based on their purpose: (*i*) strategies designed for the control of the actuator, and (*ii*) techniques aimed at facilitating interaction with objects, which depend on the former. This classification enables a systematic decomposition of the grasping task into the conjunction of two stages. The first is a static stage, during which the gripper, through the sensorized soft actuators, interprets contact with the object. The second is a dynamic stage, where the interaction process takes place, requiring the modelling of the actuator displacement through sensors. This two-stage strategy provides a structured methodology for better understanding and improving the grasping process.

- Approaches to actuator control: Controlling soft actuators requires accurate feedback on their operational states, which has led to the common practice of integrating rigid sensors directly into the actuators. In the specific case of pneumatic soft actuators, these sensors are usually fitted into the air chambers or placed on the surface of the actuator, either embedded or adhered to the contact area. Although effective, these approaches compromise the intrinsic advantages of soft robotics. The rigidity of the sensor materials reduces the actuator's flexibility, limiting its ability to adapt its surface or motion to the objects it interacts with. On the other hand, sensorless methods relocate the sensing components outside the actuator's contact and movement range.

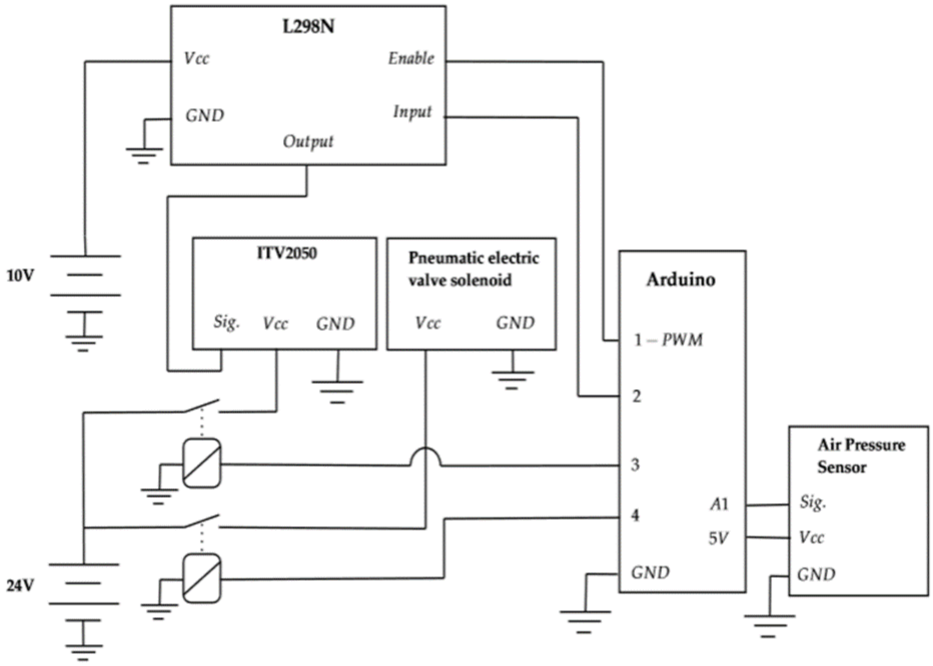

Fig. 4.1.: Electrical schematic commonly used for the control of uniaxial and biaxial soft gripper actuators.

These approaches often rely on pressure and optical sensors, as well as camera-based perception systems, to estimate actuator states, enabling precise control without interfering with the actuator's adaptability.

Following this sensorless methodology, the soft grippers presented in the previous design chapter utilize a combination of pressure sensors, a pneumatic regulation system, and a microcontroller to enable precise modelling and control. These components form the foundation for achieving reliable and adaptive operation of the proposed grippers. The developed electronic system, schematically illustrated in Figure 4.1, integrates these elements to improve both functionality and performance. Designed for scalability, this system can be readily adapted to various pneumatically actuated soft grippers, accommodating different configurations and use cases. At the core of this electronic system lies an Arduino Mega 2560 microcontroller, which manages the operation of the components. The microcontroller communicates with a LabVIEW interface for real-time monitoring and operates under the control of Matlab/Simulink.

To pneumatically actuate the proposed soft actuator designs, the circuits shown in Fig. 4.2 were implemented. A critical aspect influencing the effectiveness of these pneumatic circuit designs lies in the type of exhaust mechanism used,

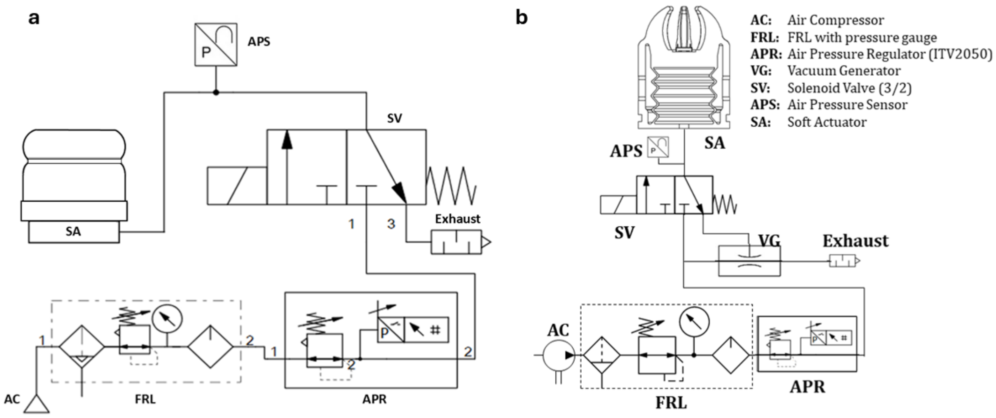

Fig. 4.2.: Several pneumatic schemes for controlling soft gripper actuators. **(a)** Direct actuation and free exhaust. **(b)** Direct actuation and vacuum-assisted exhaust.

as it significantly impacts both the responsiveness and energy efficiency of the system. One option is the use of free exhaust, a cost-effective solution that reduces the expense of pneumatic components and lowers compressed air consumption. However, this method increases the actuator's response time, as air is expelled solely by the pressure differential with the ambient environment. The alternative is vacuum-assisted exhaust, which offers enhanced performance by enabling faster response times, making it particularly suitable for pick-and-place operations. Despite its advantages, vacuum-assisted exhaust requires a vacuum generator, leading to higher compressed air consumption and increased costs due to the addition of these components. In both cases shown, the pneumatic system includes: (*i*) an Abart Start O15 air compressor with a six-liter capacity and 1.1 KW power; (*ii*) pneumatic air treatment equipment; (*iii*) a pneumatic solenoid valve for precise control of airflow; (*iv*) an SMC ITV2050 electropneumatic regulator for adjusting pressure levels; and (*v*) a Honeywell 40PC air pressure sensor with a measurement range of 0 – 100 kPa, an output voltage of 0.5 – 4.5 V, and a measurement accuracy of $\pm 0.4\%$. The features of the air pressure regulator are detailed in Table 4.1.

- Sensors for interaction with objects: Apart from the pressure sensors integrated in the pneumatic circuits, artificial vision is employed to enhance the gripper's functionality by enabling object detection and interaction within the robotic manipulation system. The approach uses RGB and Time-of-Flight (ToF) cameras, with data processing executed in the Robot Operating System (ROS) Noetic [170]. Two parallel processing nodes handle perceptual tasks: (*i*) acquiring synchronized colour and distance data; and (*ii*) registering these colour and distance data within a unified reference frame [55]. This integra-

Tab. 4.1.: Main features of the pneumatic elements of the system

Pneumatic Element	Main Characteristic	Value
Air Compressor	Compressed air deposit	6 L
	Power comsumption	1.1 kW
FRL unit	Standard nominal flow rate	1600 L/min
Pneumatic solenoid valve	Type	3/2-Way Normally Close
Air pressure regulator	Pressure range	0.005 - 0.9 MPa
	Power comsumption	4 W
	Max. Flow rate	1500 L/min
	Repeatability	±0.5%
	Response time	0.1 s
Air pressure sensor	Pressure range	0 - 100 kPa
	Measurement precision	±0.4%
Vacuum generator	Max. Vacuum pressure	80 kPa

tion enables the system to interpret visual information, providing the spatial and contextual data required for precise manipulation tasks.

In order to detect the objects to be manipulated, the YOLOv8 convolutional neural network [66] was employed, trained specifically for the identification of objects relevant to the manipulation task, such as fruits in agricultural applications. This model enables real-time recognition, with object centroids calculated from bounding box coordinates to inform path planning and manipulation algorithms. The specifications of the perception system are summarized in Table 4.2, and the camera arrangement is depicted in Figure 4.3.

Tab. 4.2.: Perception system characteristics

Component	Main Characteristic
Colour Camera: Triton TRI016S	Sensor model & Sony IMX392 CMOS
	Resolution: 1.6 MP (1440 x 1080 pixels)
ToF Camera: Helios2	Sensor model: Sony DepthSense IMX556PLR CMOS
	Pixel size: 10.0 μm (H) x 10.0 μm (V)
	Resolution: 0.3 MP (640 x 480 pixels)
	Depth Range: 0.3 m to 8.3 m
	Field of view (horizontal): 69°
	Field of view (vertical): 51°

The calibration processes for both intrinsic and extrinsic parameters, as well as distance measurements, followed the approaches outlined by Bouguet [22] and [34], ensuring the reliability of the perception system.

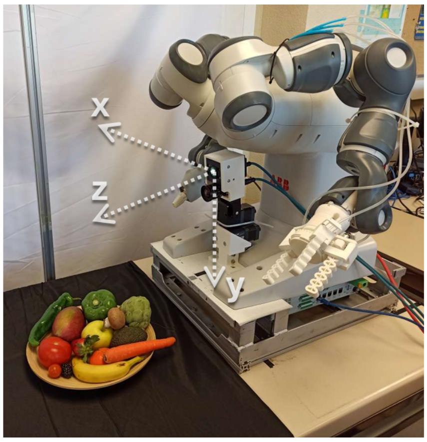

Fig. 4.3.: Perception system consisting of a Triton TRI016S RGB camera and a Helios2 ToF camera.

The combined artificial sensing and perception system not only enable object identification and manipulation but also provide essential insights into the dynamic behaviour of soft actuators during interaction. This data is vital for improving the simulation of soft actuators, as it captures how soft materials respond to different conditions. By integrating perception data, it becomes possible to refine simulations of contact between the actuator and the manipulated elements, laying the groundwork for the next step in the process: soft contact simulation and the selection of appropriate mathematical models to represent the hyperelasticity of actuator materials. Furthermore, in Section 4.5 of this Chapter, the detected objects will form the basis for a virtualization process, which is essential for identifying the achievable grasping points during the planning stage.

4.3 Soft contact simulation

A critical step in controlling soft actuators is accurately modelling their behaviour when they are in contact with the objects to be manipulated. The modelling of this contact is particularly challenging due to the complex interactions involved and the need to select an appropriate mathematical model to describe the hyperelastic behaviour of the material used in the fabrication of the soft actuator. For the soft actuators developed in the multifunctional reconfigurable soft gripper (see Figure 4.4), the Mooney-Rivlin model was selected. This model is widely recommended in the literature for the thermoplastic elastomers, the material used in the fabrication of these actuators [154].

To understand the application of the selected model for hyperelastic materials, it is important to provide context regarding its derivation. This model is a generalization of the Rivlin model, which itself is an expansion of the strain energy density function used for hyperelastic materials. The strain energy density function is typically expressed in terms of the invariants of the right Cauchy-Green deformation tensor, C. These invariants represent key quantities used to describe the material's deformation:

- $I_1 = tr(C)$, the first invariant (sum of the diagonal elements).
- $I_2 = \frac{1}{2}[(tr(C))^2 - tr(C^2)]$, the second invariant (related to the principal stretch products).
- I_3=det(C), the third invariant (the determinant of C).

For an incompressible material, $I_3 = 1$, so we only need to consider I_1 and I_2. Then, the generalized Rivlin model can be written as an infinite series expansion in powers of the invariants:

$$W = \sum_{i,j=0}^{\infty} C_{ij}(I_1 - 3)^i (I_2 - 3)^j \tag{4.1}$$

Here, C_{ij} are material constants determined experimentally, and the terms

$$(I_1 - 3)$$

and

$$(I_2 - 3)$$

are included to maintain the correct stress-free reference state. Building on the generalized Rivlin model, the Mooney-Rivlin model is a simplified version that assumes the strain energy density function depends linearly on the first two invariants, I_1 and I_2, which represent the first and second invariants of the Cauchy-Green deformation tensor, respectively.

For an incompressible material like Filaflex 70A, used in the manufacture of the proposed soft actuators, the third invariant, I_3, remains constant and equal to 1. This indicates that the material volume does not change during deformation, satisfying the incompressibility condition:

$$det(F) = 1 \tag{4.2}$$

where F is the deformation gradient tensor. This constraint must be enforced by adding a Lagrange multiplier, typically denoted as p, to account for the incompressibility. However, in the formulation of the strain energy function itself, we are primarily concerned with I_1 and I_2 only. Thus, the series expansion is truncated to just the first two terms, giving:

$$W = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) \tag{4.3}$$

Here, C_{10} and C_{01} are material constants determined experimentally related to the material's stiffness, and the terms $(I_1 - 3)$ and $(I_2 - 3)$ are included to maintain the correct stress-free reference state. This equation represents the potential energy stored in the material as a function of the deformation invariants, capturing both shear and extensional stiffness.

For the implementation of this model, FEM analysis was used. While several commercial software options support this type of analysis, not all of them provide the capability to handle the complexities of hyperelastic materials, particularly the large deformations that occur under applied loads. To develop the soft contact simulation, the chosen software had to support complex geometries, adapt meshing appropriately, describe the material based on a specific mathematical model, define boundary conditions, and perform finite element analysis effectively. To meet these requirements, three different software tools were used. First, the geometry of the soft actuator was designed using CAD software. Next, meshing adjustment were performed using Gmsh software [65]. Finally, the Python package Felupe [51], was used to carry out the soft contact simulation with various object geometries.

As shown in Figure 4.4, voxelization is first performed, segmenting the complex geometry of the soft actuator into small discrete portions. Subsequently, the load is applied, allowing the degree of deformation for a force of 25 N and the resulting displacement to be observed.

By simulating the behaviour of soft actuators through FEM and evaluating their response under various forces and deformations, this model provides a solid foundation for developing precise control strategies. Understanding the actuator's hyperelastic response and deformation characteristics enables the implementation of control systems that effectively manage both the applied forces and contact interactions. The following section discusses specific control approaches used to achieve precise and adaptive manipulation of various objects with soft grippers based on uniaxial and biaxial soft actuators.

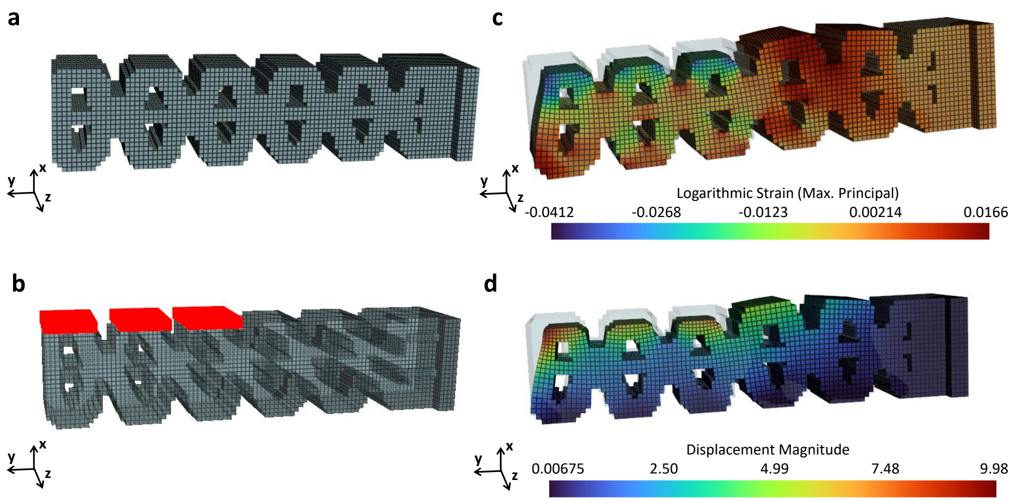

Fig. 4.4.: Soft contact simulation. **(a)** Voxelization. **(b)** Load distribution. **(c)** Stress analysis. **(d)** Displacement.

4.4 Contact control of uniaxial and biaxial motion soft actuators

This section presents control strategies for uniaxial and biaxial pneumatic actuators in hybrid soft grippers. The soft grippers concept proposed in Section 3.2 can be seen as a specific example of hybrid grippers, which have emerged over the past few decades as a fusion of soft and rigid robotics [130, 156]. This integration not only involves the physical combination of the two technologies but also leverages the rigid structure to constrain the degrees of freedom (DoFs) of the soft actuator, thereby simplifying the control of the gripper. At the low level, the soft actuators of these modular grippers are controlled either teleoperated through a LabVIEW interface or operated autonomously using a proportional-integral-derivative (PID) system combined with sensorless techniques for contact monitoring. The LabVIEW interface enables precise regulation of pneumatic electrovalves and pressure levels, ensuring the grippers achieve desired performance.

On the other hand, the proportional-integral-derivative (PID) control system uses the feedback provided by the internal pressure measurements from a sensor located at the soft actuator's inlet. As shown in Fig. 4.5, this controller samples pressure changes at a frequency of 50 Hz, and if the rate of pressure change exceeds that caused by the electropneumatic regulator, it indicates that the soft actuator has contacted the object. This is confirmed by corresponding reduction in the gripper's volume and the subsequent increase in internal pressure (see red point in Fig. 4.5).

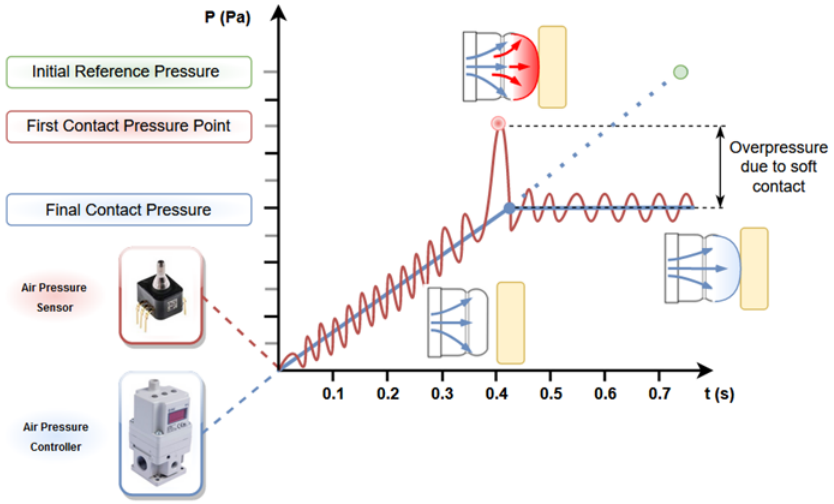

Fig. 4.5.: Diagram of the control method for the soft actuator without embedded sensors.

Therefore, this setup provides effective monitoring of soft actuator contact without the need for embedded sensors, preserving its intrinsic adaptability and flexibility.

Although the soft grippers are conceived to operate with a bimanual robot utilizing computer vision for object recognition [175], they can also incorporate optical infrared sensors, such as the GP2Y0E03 model. This sensor, with a measurement range of 40-500 mm and an output voltage of 2.7-5 V provides position feedback to the vision system, enhancing the accuracy and success of grasping operations. Algorithm 1 outlines the steps involved in this process.

Additionally, at the high level, a Unified Robotics Description Format (URDF) model of soft grippers was developed within the Robot Operating System framework to streamline integration with dual-arm robotic platforms. This model facilitates seamless communication between the robotic grasp planning module and the gripper's low-level controller. Figure 4.6 presents one of the designed soft grippers visualized in 3D using the RVIZ software.

The control strategies described for uniaxial and biaxial soft actuators provide the stability required to address grasp planning and actuator behaviour modelling in complex manipulation scenarios. The integration of various sensors, along with the incorporation of a URDF model, enables efficient coordination between the robotic planning module and the actuator controllers. This integration lays the foundation for implementing an effective grasping strategy.

The following section outlines the actuator model and grasp planning strategy for the reconfigurable hybrid soft gripper proposed in Chapter 3. These components are

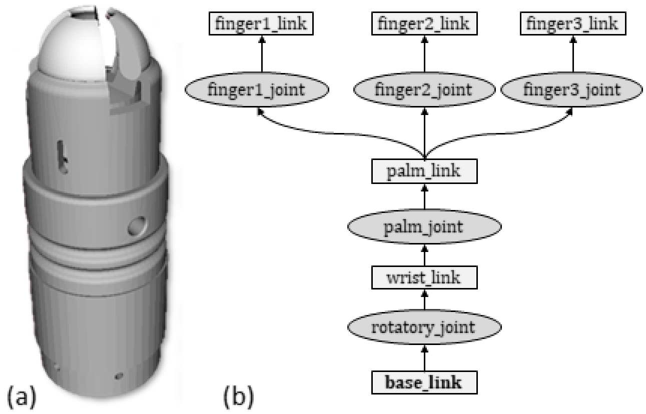

Fig. 4.6.: URDF model of the soft gripper designed for small objects implemented in ROS. **(a)** Soft gripper displayed in RViz; and **(b)** URDF specification. The links and joints are visualized by boxes and ellipses, respectively.

essential for accurately determining contact points and pressure adjustments during interactions between the soft actuator and the object, ensuring both efficiency and safety in manipulation tasks.

4.5 Grasp planning and control modelling for the reconfigurable hybrid soft gripper

To effectively leverage the full potential of the reconfigurable hybrid soft gripper proposed in Chapter 3, a robust grasp planning and control strategy is essential. The inherent complexity of soft actuators, marked by nonlinear deformations, high degrees of freedom, and material compliance, renders traditional control methods inadequate, particularly when no constraints are applied to their degrees of freedom. Furthermore, the reconfigurability of the hybrid design introduces additional variables, such as the positioning of rigid components, which must be carefully configured to ensure successful manipulation of diverse objects. In light of these challenges, this section presents a structured approach that integrates advanced modelling, perception, and control strategies to enhance the gripper's adaptability and precision. By combining data-driven actuator modelling, virtual object analysis, and iterative simulation-based control, the proposed strategy addresses the unique demands of hybrid soft grippers in dynamic and unstructured environments.

Therefore, the approach outlined in this section consists of three main stages. First, the soft actuators are modelled using experimental data and the SINDy algorithm

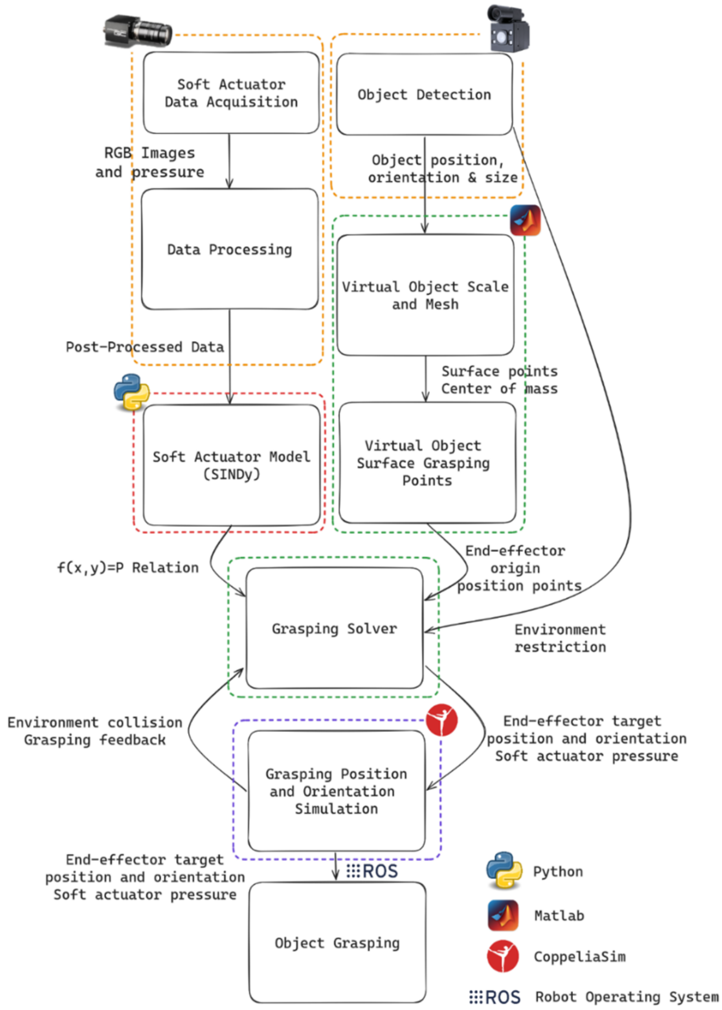

Fig. 4.7.: Outline of the proposed grasp planning strategy.

[26]. This technique provides an accurate predictive model of the actuators' positions, ensuring effective grasping. Second, the object to be manipulated is detected, followed by its scaling and reorientation through a virtual model. This virtual model incorporates a highly detailed mesh, allowing for a comprehensive analysis to determine reachable grasping points. Finally, the model of the soft actuators and the identified grasping points are fed into a solver, which computes the required pressure to move the soft actuators and establish contact with the object. The solver then iteratively runs simulations to converge on a feasible solution. Figure 4.7 schematically illustrates the system's operation. The following subsections provide a detailed description of the steps involved in the proposed strategy.

- Data Acquisition and Modelling of Soft Actuators

The modelling method for the designed soft actuators employs the SINDy algorithm [26]. This modern technique leverages datasets to develop sparse models that capture the key characteristics of the system dynamics, allowing for predictions and analyses without requiring an in-depth understanding of the system's underlying physics. To parameterize and calibrate the relationship between spatial coordinates and pneumatic pressure in the soft actuators, data was collected using computer vision techniques (see Figure 4.8). The dataset was obtained with a Prosilica GC2450C camera, which provides high-resolution 5.0 megapixel colour images, excellent sensitivity, low noise, and a full-resolution frame rate of 32 fps.

During data acquisition, the soft actuators were subjected to varying pressures profiles, both in terms of growth and decay. These tests aimed to investigate the non-linearity of the actuators while minimizing potential variations introduced by the material or air regulator used in the experiments. To locate the contact areas of the soft actuator on the plane, circular-coloured markers were strategically placed, and K-means clustering was employed to automatically detect these markers in the captured images. The Hough transform was subsequently applied to identify each circle and determine its centroid. The coordinates of these centroids were then converted into the reference frames of their corresponding actuators, denoted as O_{SF1}, O_{SF2}, and O_{SF3}, as shown in Figure 4.9. For clarity, the origins of these reference frames were also marked with a red label, as illustrated in Figure 4.8. Consequently, from these spatial transformations, a pair of coordinates (x, y) was obtained for each $SF_{i,j}$, where i refers to the finger number and j represents the marker on each finger. The reference frames of the actuators, O_{SFi}, were defined on a plane tangent to the object's surface, aligned with the origin of the gripper's reference frame, O_{SG}. This arrangement allows for the transformation of coordinates from the O_{SFi} reference frames to the gripper's reference frame, O_{SG}. This transformation takes into account the distance $\overline{O_{SFi}O_{SG}}$ and the angles α (ranging from 35º to 120º) and β (ranging from -35º to -120º). These angles are measured between the fixed actuator segment $\overline{O_{SF1}O_{SG}}$ and the rotating bases of the mobile actuators $\overline{O_{SF2}O_{SG}}$ and $\overline{O_{SF3}O_{SG}}$, respectively. Thus, the markers of each soft actuator are mapped to the absolute coordinates of the soft gripper as follows:

$$\begin{bmatrix} O_{SF_{i,j}}^{SG_X} \\ O_{SF_{i,j}}^{SG_Y} \\ O_{SF_{i,j}}^{SG_Z} \end{bmatrix} = \begin{bmatrix} (\overline{O_{SFi}O_{SG}} - SFx_{i,j}) \cdot cos(\theta) \\ SFy_{i,j} \\ (\overline{O_{SFi}O_{SG}} - SFx_{i,j}) \cdot sin(\theta) \end{bmatrix} \tag{4.4}$$

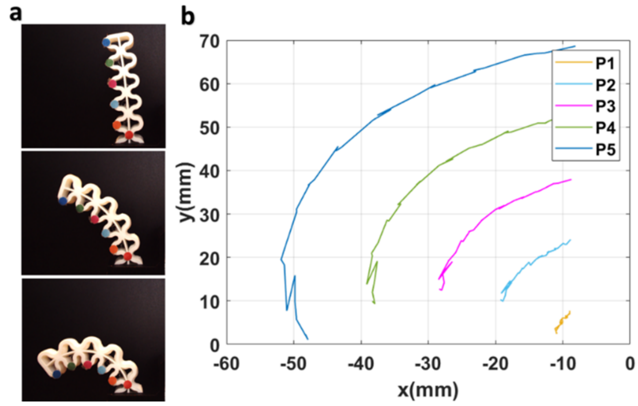

Fig. 4.8.: Data acquisition for modelling. **(a)** Test carried out to obtain the relationship between the spatial coordinates of the actuator contact points and the pneumatic pressure. **(b)** Soft actuator trajectory points acquired during experimental testing.

where θ is equal to α or β for i=2 and i=3, respectively.

Once the datasets are obtained, the modelling approach is applied. This method relies on the principle that most physical systems are influenced by only a limited number of significant terms, making the governing equations sparse within a high-dimensional nonlinear function.

In the two-dimensional (2D) case, where each soft actuator's position is determined by its biaxial movement, the dynamic system can be represented in the following form:

$$\frac{d}{dp}SFx_{i,j}(p) = f(SFx_{i,j}(p)) \quad \frac{d}{dp}SFy_{i,j}(p) = f(SFy_{i,j}(p)) \tag{4.5}$$

Therefore, it is possible to achieve a more accurate approximation by decomposing the actuator motion into its axial components; thus, vectors $SFx_{i,j}(p), SFy_{i,j}(p) \in \mathbb{R}^n$, denotes the system states at pressure p, while the dynamic constraints defining the equations of motion of the system are denoted by $f(SFx_{i,j}(p))$ and $f(SFy_{i,j}(p))$. Since for many systems of interest, f comprises only a few significant terms, the potential functions in the space are sparse and can be written as linear combinations of basic functions, with the majority of coefficients being equal to 0:

$$\begin{aligned} f(SFx_{i,j}) &= \xi_1\theta_1(SFx_{i,j}) + \xi_2\theta_2(SFx_{i,j}) + ... + \xi_n\theta_n(SFx_{i,j}) \\ f(SFy_{i,j}) &= \gamma_1\theta_1(SFy_{i,j}) + \gamma_2\theta_2(SFy_{i,j}) + ... + \gamma_n\theta_n(SFy_{i,j}) \end{aligned} \tag{4.6}$$

To determine the function f from the data, it is crucial to collect a dataset that includes pressure values along with the corresponding $SFx_{i,j}(p)$, and $SFy_{i,j}(p)$

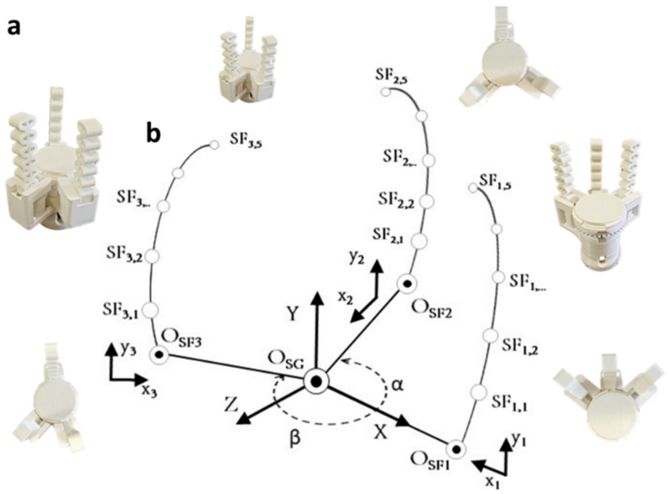

Fig. 4.9.: Soft gripper reconfiguration. (a) Different reconfiguration positions. (b) Placement of markers and reference frames associated with the actuators.

states. Next, the derivatives $S\dot{F}x_{i,j}(p)$ and $S\dot{F}y_{i,j}(p)$ can be numerically approximated from $SFx_{i,j}(p)$ and $SFy_{i,j}(p)$ (p) using either the Kalman derivative method or the Spline method. These approximations are then organized into the matrices $\dot{X}$ and $\dot{Y}$. By applying each method, the most appropriate fit for the dataset can be identified. After defining the matrices $\Theta(X)$ and $\Theta(Y)$ that include potential candidate functions, as well as the matrices Ξ and Γ containing the coefficients for these candidate functions, the problem can be solved as follows:

$$\dot{X} \approx \Theta(X)\Xi \qquad \dot{Y} \approx \Theta(Y)\Gamma \tag{4.7}$$

Given that $\dot{X}$, $\dot{Y}$, $\Theta(X)$ and $\Theta(Y)$ are known, it is possible to determine the functions governing the motion of the soft actuator along the x and y axes.

For the application of the SINDy algorithm, the PySINDy package [94] was utilized with various datasets. All training data were collected with the soft actuator in an unloaded state, as the main objective of the proposed modelling was to accurately characterize the actuator's behaviour for establishing contact with objects. The focus was on achieving firm and safe manipulation by identifying the maximum number of contact points between the soft actuator and the object's surface. A comprehensive study of the interaction between soft actuators and different objects is beyond the scope of this thesis.

Figure 4.10 presents the SINDy approximation compared with the actual data, displaying the modelling equations for the soft actuator. The coefficient of de-

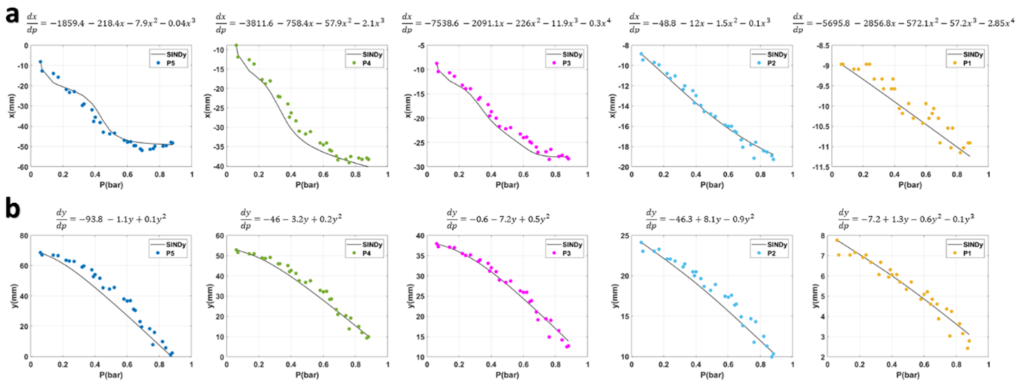

Fig. 4.10.: SINDy model approximation for soft actuator points. (a) X-axis displacement. (b) Y-axis displacement.

termination R^2 consistently exceeds 0.9 across all approximations, ranging from a minimum of 0.92 to a maximum of 0.98, demonstrating the robustness of the model.

- Virtual Object Representation

The process begins with object detection using the perception system described in Section 4.2. This system includes a Helios 2 ToF camera, featuring a 0.3 MP Sony DepthSens IMX556 CMOS sensor and a resolution of 640×480 pixels, alongside a Triton RGB camera equipped with a 3.2 MP Sony IMX265 CMOS sensor with a resolution of 2048×1536 pixels. Due to the differing resolutions and fields of view of these cameras, their data is aligned through a registration process to ensure direct correlation between the colour information and the point cloud, with all data referenced in a unified coordinate system [173]. A segmentation algorithm is then applied to the registered data, enabling object detection and the extraction of size and orientation information.

Following this, to develop an optimal manipulation strategy, particularly for fruits, and to identify the Optimum Object Surface Grasping Points, a fruit library in Standard Triangle Language (STL) format was created. This library allows for meshing and a detailed evaluation of potential grasping points on the object's surface. The mesh is scaled and reoriented based on dimensions obtained from the detection system described earlier.

Next, the geometric centre of the object is calculated from its detected dimensions, with the working assumption that the centre of mass aligns with the geometric centre of the object, which holds true in most cases. Once this centre is established, the distance from each mesh point to the centre of mass is calculated. Based on this, objects are then classified by their geometry as either quasi-cylindrical, where the major axis is more than twice the minor axis, or spherical, where the ratio between major and minor axes is less than two. For quasi-cylindrical objects, the optimal grasping points are those nearest to the centre of mass to ensure stable handling and minimize torque during manipulation. For spherical objects, the largest circular section of the geometry is identified, and contact points along this circle are prioritized using two soft actuators to balance the load. For smaller objects with a radius equal to or smaller than the curvature of the soft actuator, a single-finger grip is employed.

- Grasping Solution

In the next phase, a Grasping Solver specifically developed for this thesis is used, integrating both the model of the soft actuators and the identified grasping points of the object. The solver also accounts for the constraints imposed by the environment, such as proximity to the floor, walls, or surrounding objects, to calculate feasible positions for the gripper's origin in space. These calculations prioritize energy efficiency by aiming to use the lowest possible pressure while maximizing the contact area between the gripper and the object. The results are further affected by the limitations and singularities of the robotic manipulator used. When positioning the gripper's palm, priority is given to direct contact with the object to ensure a firm and stable grip, consistent with the controller's primary objective. Nonetheless, the controller is also capable of executing more complex grips for diverse manipulation tasks. The number of potential positions for the gripper's origin is determined by the resolution of the object's mesh and is categorized into zones based on feasibility and energy efficiency. These zones are grouped into more or less optimal regions, defining different grasping areas for the object, as illustrated in Figure 4.11.

Since the initial contact points in space are determined by the object's mesh characteristics, two specific criteria are applied to identify which of these points are optimal for grasping.

The first criterion focuses on physical feasibility, excluding points that the robotic arm cannot reach due to singularities, range limitations, or potential collision with the environment. Points obstructed from the robot's perception system are also eliminated. Additionally, points associated with high energy consumption are discarded, particularly those demanding excessive torque in the manipulator's joints or comprising the efficiency of the soft gripper's operation. In the latter case, inefficiency is assessed based on the pressure required to maximize the contact area between the soft actuators and the object. These less efficient zones are often

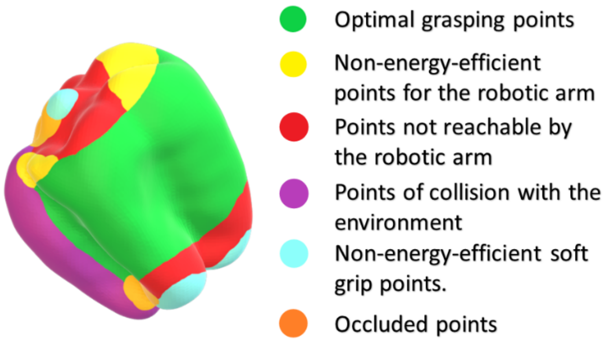

Fig. 4.11.: Visual representation of the grasping zones based on energy efficiency analysis.

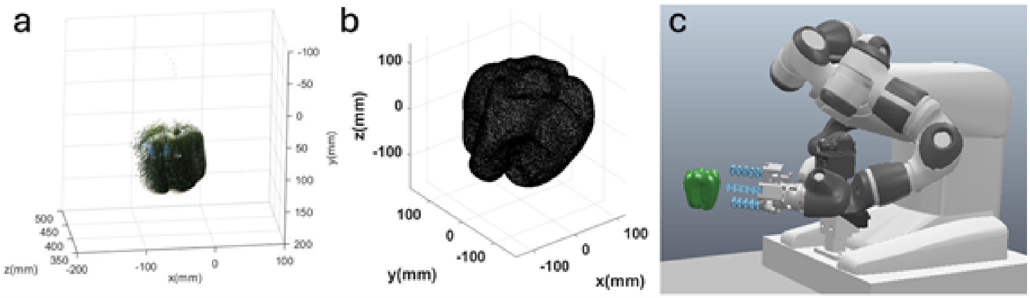

Fig. 4.12.: Vision system data acquisition and processing. **(a)** Registered image. **(b)** Detected fruit oriented and scaled in STL format. **(c)** Simulation of grasping position and orientation.

characterized by sharp-edged regions, where the soft actuators would need higher pressures (and thus greater energy) to achieve a secure and firm grip.

Building on this approach, the proposed grasp planner begins by detecting the fruit and producing a registered image in which the colour data from the RGB camera is aligned with the ToF camera's point cloud within the same reference frame (see Figure 4.12a). Next, the object's dimensions are extracted to adjust its size and orientation, after which the corresponding fruit model is retrieved from the virtual object library in Standard Triangle Language (STL) format (see Figure 4.12b). The object is subsequently positioned in a virtual environment to simulate the gripping process, as illustrated in Figure 4.12c.

After resizing and reorienting the object, grip points are determined in MATLAB according to the previously mentioned criteria, as shown in Figure 4.13a. The object is then iteratively intersected with planes representing the soft actuators (see Figure 4.13b). These planes are able to rotate around the central axis to simulate the reconfiguration of the gripper's fingers accurately. The solution is defined by the rotation angles of these planes and the position of the palm centre, which serves as

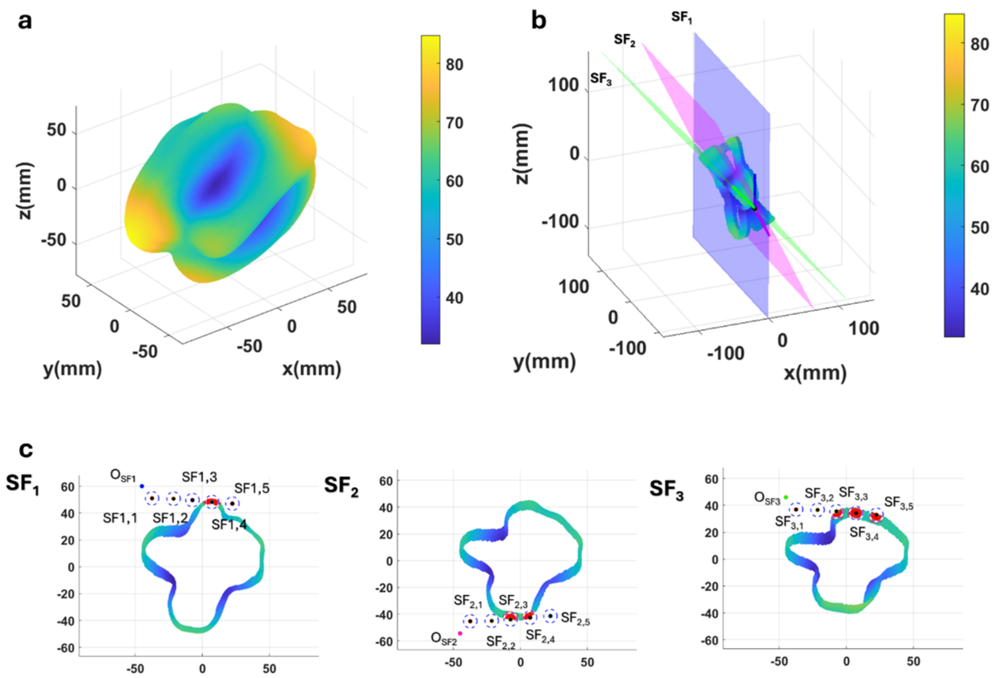

Fig. 4.13.: Grasp solution overview. **(a)** Mesh points sorted by colour according to their distance from the fruit's centre of mass. **(b)** Intersection planes of the soft actuators with the point cloud and soft gripper position and orientation. **(c)** Contact points for each soft actuator with the object mesh in the intersecting plane.

the origin of the end-effector. The provided solution, which is not necessarily unique, indicates the number of contact points for each finger. In the example shown in Figure 4.13c, each actuator is divided into five sections, representing its contact areas with the object's surface.

Once the Grasping Solver identifies a feasible solution for positioning the gripper, it is sent to the CoppeliaSim simulator to safely execute the manipulation in a virtual environment. To improve the simulation's accuracy, the MuJoCo kernel [199] is used to model the flexible and deformable elements of the soft gripper, ensuring realistic behaviour for subsequent real-world application.

Finally, the grip is executed through communication between CoppeliaSim and the ABB cobot using ROS. This framework sends the target point for the end-effector to reach, followed by a command to the gripper's microcontroller to initiate closure based on the values provided by the Grasping Solver. The final control of the grip is achieved using a PID closed-loop control system that relies on pneumatic pressure sensors installed at the soft actuators' inlets. These sensors detect object contact by identifying sudden change in the actuator chamber volumes.

4.6 Experimental evaluation

To evaluate the performance of the reconfigurable soft gripper and the proposed grasp planning strategy, the YuMi – IRB 14000 collaborative robot from ABB [167] was selected. This robot is equipped with a humanoid torso and two arms, each with 7 DoFs. The arms have a reach of 559 mm and are capable of handling payloads of up to 500 g. With high repeatability and a positional accuracy of 0.02 mm, this robot facilitates a detailed analysis of manipulation techniques and grip optimization. The manipulation study concentrated primarily on homogeneous objects, where the centre of gravity aligns with the geometric centre. This category includes most fruits and vegetables. The selection criteria for these objects were based on geometries that provided diverse test cases to rigorously assess the grasp planning strategy. Figure 4.14 displays the chosen fruits and vegetables, the experimental setup, and various tested grips. During the manipulation trials, the fruits were suspended using transparent nylon threads. The robot followed an L-shaped motion path, gripping the object initially and then lifting it to validate the effectiveness of the grip.

Tab. 4.3.: Fruits tested with the reconfigurable soft gripper

Fruit	Fruit dimensions HxLxD (mm)	Fruit weight (g)	Grasp Pressure (kPa)	Grasping mode
Carrot	170x29x29	95.65	132	2 Finger and Palm
Mushroom	50x50x50	36.65	132	2 Finger and Palm
Cherry Tomato	24x24x24	12.70	160	1 Finger and Palm
Strawberry	60x43x34	40.55	160	1 Finger and Palm
Bell Pepper	90x82x82	220.75	120	Complete
Blackberry	30x25x25	7.70	162	1 Finger and Palm
Mango	130x80x70	372.60	120	Complete
Italian Pepper	200x29x29	65.60	120	Complete
Tomato	55x74x74	174.65	120	Complete
Artichoke	140x76x76	178.20	120	Complete
Tangerine	44x59x59	94.85	120	2 Finger and Palm
Banana	150x33x33	142.15	160	Complete
Avocado	100x60x60	184.60	120	Complete
Apple	71x76x70	172,90	120	Complete
Kiwi	70x50x44	92,90	120	2 Finger and Palm

During the experiments, all objects were successfully manipulated, demonstrating secure gripping and achieving both grasping and lifting actions. The success rate was 85% for quasi-cylindrical objects and 70% for spherical ones. Quasi-cylindrical objects offered an advantage in terms of manipulation compared to spherical ones,

Fig. 4.14.: Soft gripper validation. **(a)** Fruits and vegetables grasped; their properties are listed in Table 4.3. **(b)** Experimental setup. **(c)** Fruits and vegetables grasped using one finger and the palm. **(d)** Fruits and vegetables grasped using two finger and the palm. **(e)** Fruits and vegetables grasped with a full grip.

as the palm provided greater stability by limiting their movement. In contrast, spherical objects were less stable and more prone to slipping. Moreover, precise pressure calculation played a key role, as the natural inflation pattern of the soft actuators occasionally caused slippage on spherical surfaces.

Certain fruits, such as bell peppers or mangoes, could not be lifted due to the cobot's payload limitations. However, they were still tested to assess the gripper's grasping capability. These trials also emphasized the importance of identifying "non-reachable points" for the robotic arm, as shown in Figure 4.11. Some grasping positions increased motor torque, making it impossible for the arm to lift the object. This issue, specific to the robotic arm's design, requires further study beyond the scope of this work.

Additionally, it should be noted that during object handling, the object could sometimes shift unexpectedly during the grasping process due to the nature of the experimental setup. Since manipulation points were not dynamically recalculated, objects were sometimes grasped in unintended ways that were not initially planned. Addressing this limitation is a promising area for future research and could improve the overall success rate.

In summary, a hybrid reconfigurable soft gripper has been developed, capable not only of performing the types of manipulations proposed by [85, 179, 239] but also offering a high level of dexterity and adaptability by adjusting the positioning angles of its fingers. The gripper can lift objects weighing up to 400 g, positioning it in the mid-range among similar designs in the literature. Reconfigurable grippers in previous studies can lift between 100 g [239] and 700 g [129], with the latter being powered by servomotors instead of the pneumatic actuation used in this design. Furthermore, a novel grasp planning method has been proposed. This method integrates object detection and virtual object representation, setting it apart from other reconfigurable soft gripper solutions. A virtual fruit library in STL format has also been developed for detailed analysis of grips, and a SINDy-based model has been implemented to accurately simulate the behaviour of the patented reconfigurable soft gripper in virtual environments. This ensure precise manipulation while protecting objects from damage.

4.7 Discussion

In this chapter, the proposed uniaxial and biaxial soft pneumatic actuators configurations have been analysed, each with its own modelling and control approach. Firstly, a controller for diaphragm-type uniaxial pneumatic soft grippers was developed, integrating soft and rigid robotics technologies. This integration constraints the degrees of freedom of the soft actuators through a rigid structure, simplifying the control of the gripper and enhancing precision in specific applications. The main contribution of this controller to soft robotics research lies in its ability to manage these uniaxial pneumatic actuators without the need for embedded sensors. It uses a PID control system that receives feedback from pressure sensors to monitor object contact through variations in the internal pressure of the actuator. Additionally, a URDF model was implemented for integration into larger robotic systems, enabling efficient communication with robotic planning modules. The controller supports both manual and automatic operation, adapting to a wide range of applications. The use of vacuum-assisted exhaust in the actuators allows for faster response times, albeit at the cost of higher compressed air consumption. Overall, this approach marks a significant advancement in the control of uniaxial pneumatic actuators in soft robotics, providing a robust and adaptable solution for precise handling tasks while ensuring safe interaction with the environment.

Soft contact simulation also played a crucial role in advancing the understanding of the interactions between soft actuators and manipulated objects. FEM was employed to simulate large deformations, with the Mooney-Rivlin model characterizing the hyperelastic behaviour of the thermoplastic elastomer used in the actuators. This process required careful consideration of material properties and complex geometries, as well as adjustments to meshing using Gmsh software. The Python package Felupe was then utilized to execute soft contact simulations with different object geometries. These simulations provided valuable insights into the deformation behaviour of the actuators under load, contributing to the refinement of actuator design and performance during real-world interactions.

Finally, a data-driven model based on the SINDy algorithm was proposed to address the nonlinearities of biaxial pneumatic soft actuators with two chambers. Once the model was obtained, the strategy involved creating virtual entities representing the physical objects to be manipulated, allowing for the analysis and identification of grasping points on their contact surfaces. Combined with a grip solver, the SINDy model provided a systematic strategy for calculating achievable grasping points and actuator pressures for the proposed soft gripper. Experimental validation demonstrated a firm and secure grip on objects, achieving a success rate of 85% for quasi-cylindrical fruits and vegetables, and 70% for spherical ones. These results demonstrate the potential of data-driven methods in managing complex behaviours of biaxial soft actuators, where traditional physics-based models often encounter limitations.

In summary, soft contact simulations, data-driven models and proposed controllers represent significant advancements in the field of soft robotics. These approaches provide robust and adaptable solutions for precise manipulation tasks while addressing the challenges associated with modelling and controlling of soft actuators, ensuring safe and efficient interaction with the environment.

Part V

CONCLUSIONS AND FUTURE WORK

5 Conclusions

This thesis presents an in-depth investigation into soft robotics, with a particular emphasis on soft grippers, addressing fundamental challenges in design, sensing, and control. By advancing this core areas, this work contributes to the development of adaptable and efficient robotic systems capable of meeting the unique demands of agricultural applications. Soft robotics in agriculture, unlike its industrial counterparts, requires grippers that can delicately handle non-standardized objects while operating under variable environmental conditions. This research bridges the gap between theoretical advancements in soft actuator technology and their practical implementation in agricultural automation, a field where the adoption of robotics solutions is still emerging compared to more established applications in industrial sectors.

To understand the demands and challenges of the agricultural sector, a comprehensive state-of-the-art review was conducted. This review highlighted how soft grippers can aid automating various agricultural tasks and identified the key challenges in implementing this technology, such as handling delicate crops and maintaining efficiency in non-controlled environments.

Building on these findings, three novel soft gripper designs were developed, each exploring different types of materials, sensors, modelling strategies, and control techniques. All these prototypes were rigorously tested in real-world environments using dual-arm robotic systems intended for harvesting applications. The successful validation of these designs demonstrates their potential for practical use and scalability in the agricultural domain throughout the research, broader needs for the advancement of soft robotics were identified. These include the establishment of standardized quality control protocols to ensure the reliability and performance of soft actuator designs. Additionally, a critical gap in the characterization of soft grippers was noted, underscoring the need for standardized benchmarks to enable fair comparisons and consistent evaluations across different designs and applications.

The outcomes of this research provide valuable insights into the development and application of soft robotics, particularly in addressing sector-specific challenges. These advancements are further elaborated through the key contributions presented in the following section.

Fig. 5.1.: Proposed soft grippers designs and their implementation in dual-arm robotic systems.

5.1 Contributions

The main contributions of this thesis to the field of soft gripper technology, supported by relevant publications, conference presentations, research collaborations, or patents, are as follows.

- **State-of-the-art**
  - An extensive review of the state-of-the-art soft grippers has been conducted, focusing on their applications in automating tasks within the agricultural sector [145].
  - A detailed analysis of various crops has been performed to identify those with the greatest potential for the implementation of soft grippers in harvesting tasks. This was further explored during the international stay at ATB, Germany, with a specific focus on blueberries [139, 178].
  - Current and future challenges in adopting and integrating soft robotics into the agricultural industry have been highlighted [178].
- **Design**
  - Three innovative soft gripper designs have been developed, focusing on characteristics such as modularity, reconfiguration, cost-effectiveness, and ease of maintenance. These designs are detailed in [143, 147] and presented in [145].

- A novel design methodology has been introduced based on data collected through finger-tracing gloves, enabling the exploration of biomimetic movement patterns for soft gripper designs. This is part of ongoing research described in [147].

- Materials suitable for soft robotics, particularly thermoplastic elastomers, have been investigated and implemented due to their affordability, manufacturability, and capacity for producing complex geometries. Results are included in [18, 147] and demonstrated through the prototype patents [141, 142].

• **Soft Actuator and Contact Simulation**

  - The Finite Element Method (FEM) has been utilized with advanced hyperelastic material models, such as Mooney-Rivlin and Ogden, to simulate the behaviour of thermoplastic elastomers under large deformations and complex loading conditions [143, 147].

  - Open-source software has been leveraged for meshing and conducting soft contact simulations with diverse object geometries, enabling a detailed analysis of actuator deformation and refinement of design and performance.

• **Modelling**

  - The Sparse Identification of Nonlinear Dynamics (SINDy) algorithm has been applied to accurately model the trajectory of soft actuators, requiring fewer experimental data compared to other modelling methods. These findings were discussed in.

  - A virtual object library containing various fruits has been developed to support the implementation of gripping patterns and the identification of reachable points for grasping strategies.

• **Quality Control and Characterization**

  - The critical role of quality control in the commercialization and market integration of soft robotics technology has been identified and emphasized. Several methodologies have been proposed, including computer vision techniques [139, 145].

– A specialized device for measuring displacement and contact force has been designed, facilitating the detailed characterization of diaphragm-type soft actuators. This is reported in [143, 147] and discussed in conference presentations [145].

Together, these contributions advance the understanding, design, and implementation of soft gripper technologies, addressing key challenges in their application to dynamic and demanding environments such as agriculture.

5.2 Achievements

This doctoral thesis was primarily conducted at the Centre for Automation and Robotics (CAR) of the Spanish National Research Council (CSIC-UPM), located in Arganda del Rey, Madrid. Specifically, it was developed within the Field and Service Robotics Group, which has extensive expertise in robotics-related domains, such as navigation, manipulation, and artificial vision. One of the key research lines of the group, led by Dr. Roemi Fernández, focuses on intelligent perception and dual-arm manipulation in unstructured environments. Several projects within this line target precision agriculture applications, such as the selective harvesting of high-value crops. This alignment created a strong synergy between the ongoing research initiatives and this thesis, enabling the designed soft robotic grippers to be developed, fabricated and tested under real-world conditions and environments.

On the other hand, the international stay at the Leibniz Institute of Agricultural Engineering and Bioeconomy e.V. (ATB), located in Potsdam, Germany, has contributed significantly to the practical application of this thesis in the field of agriculture and its mechanization. In the Agromechatronics department, headed by Dr. Cornelia Weltzien, various projects are carried out for both public and private entities, focusing on the development of mechanization in the agricultural sector and especially on the introduction of robotics in this sector. During my stay there, I had access to several crops found in the Brandenburg region, such as blueberries, for the study of their mechanization using soft robotic grippers. Moreover, thanks to their experience in agricultural machinery, a synergy and fruitful professional relationship was established and continues to be maintained to this day.

Based on the research carried out during this thesis, the following articles have been published, addressing topics directly related to its subject matter:

1. Blanco, K., Navas, E., Emmi, L., & Fernandez, R. (2024). Manufacturing of 3D Printed Soft Grippers: A Review. IEEE Access.

2. Navas, E., Shamshiri, R. R., Dworak, V., Weltzien, C., & Fernández, R. (2024). Soft gripper for small fruits harvesting and pick and place operations. Frontiers in Robotics and AI, 10, 1330496.

3. Rodríguez-Nieto, D., Velázquez, M. O., Navas, E., & Fernández, R. (2023). Arquitectura software para el sistema robótico de manipulación dual HortiRobot. Revista Iberoamericana de Automática e Informática industrial.

4. Navas, E., Fernández, R., Armada, M., & Gonzalez-de-Santos, P. (2021). Diaphragm-type pneumatic-driven soft grippers for precision harvesting. Agronomy, 11(9), 1727.

5. Navas, E., Fernández, R., Sepúlveda, D., Armada, M., & Gonzalez-de-Santos, P. (2021). Soft grippers for automatic crop harvesting: A review. Sensors, 21(8), 2689. Award: Editor´s Choice Article.

Furthermore, in line with the thesis objectives, the following articles have been presented at international conferences:

1. Blanco, K., Navas, E., Emmi, L., Rodriguez-Gonzalez, A. A., & Fernandez, R. (2023, November). Design of a Modular Soft Tool for Automatic Seed Sowing. In Iberian Robotics conference (pp. 363-374). Cham: Springer Nature Switzerland.

2. Navas, E., Blanco, K., Rodríguez-Nieto, D., & Fernández, R. (2023, November). An Approach to Computer Vision Control of a Parallel Soft Gripper. In Iberian Robotics conference (pp. 327-337). Cham: Springer Nature Switzerland.

3. Navas, E., Dworak, V., Weltzien, C., Fernández, R., Shokrian Zeini, M., Käthner, J., et al. (2023). An approach to the automation of blueberry harvesting using soft robotics. GIL-Jahrestagung, Resiliente Agri-Food-Systeme 43.

4. Navas, E., Fernández, R., Navas-Merlo, C., Armada, M., & Gonzalez-de-Santos, P. (2022, April). Towards Quality Control in Soft Actuators by Computer Vision. In 2022 IEEE International Conference on Autonomous Robot Systems and Competitions (ICARSC) (pp. 1-6). IEEE.

5. Navas, E., Fernández, R., Sepúlveda, D., Armada, M., & Gonzalez-de-Santos, P. (2021, April). Soft gripper for robotic harvesting in precision agriculture applications. In 2021 IEEE International Conference on Autonomous Robot

Systems and Competitions (ICARSC) (pp. 167-172). IEEE. Award: Highly Commended Paper.

In addition, as a result of collaborative research efforts, the following articles and book chapters have been published in international journals and presented at conferences:

1. Shamshiri, R. R., Navas, E., Käthner, J., Höfner, N., Koch, K., Dworak, V., Hameed, I., Paraforos, D. S., Fernández, R., & Weltzien, C. (2025). Agricultural robotics to revolutionize farming: Requirements and challenges. In Mobile Robots for Digital Farming (pp. 107-155). CRC Press.

2. Shamshiri, R. R., Navas, E., Dworak, V., Cheein, F. A. A., & Weltzien, C. (2024). A modular sensing system with CANBUS communication for assisted navigation of an agricultural mobile robot. Computers and Electronics in Agriculture, 223, 109112.

3. Shokrian Zeini, M., Shamshiri, R. R., Dworak, V., Käthner, J., Höfner, N., Navas, E., & Weltzien, C. (2023). Overview of control systems for robotic harvesting of sweet peppers and apples. GIL-Jahrestagung, Resiliente Agri-Food-Systeme 43.

4. Shamshiri, R. R., Dworak, V., Shokrian Zeini, M., Navas, E., Käthner, J., Höfner, N., & Weltzien, C. (2023). An overview of visual servoing for robotic manipulators in digital agriculture. GIL-Jahrestagung, Resiliente Agri-Food-Systeme 43.

5. Gonzalez-de-Santos, P., Fernández, R., Sepúlveda, D., Navas, E., Emmi, L., & Armada, M. (2020). Field robots for intelligent farms—Inhering features from industry. Agronomy, 10(11), 1638.

6. Sepúlveda, D., Fernández, R., Navas, E., Armada, M., & González-De-Santos, P. (2020). Robotic aubergine harvesting using dual-arm manipulation. IEEE Access, 8, 121889-121904.

7. Navas, E., Fernández, R., Sepúlveda, D., Armada, M., & Gonzalez-de-Santos, P. (2020). A design criterion based on shear energy consumption for robotic harvesting tools. Agronomy, 10(5), 734.

8. Gonzalez-De-Santos, P., Fernández, R., Sepúlveda, D., Navas, E., & Armada, M. (2020). Unmanned ground vehicles for smart farms. Agron.-Clim. Chang. Food Secur, 6, 73.

Also noteworthy are the patent applications that have presented during the course of this thesis or through collaboration as a co-author:

1. Navas, E., Fernández, R. (2024) Garra robótica para agarre y manipulación. Fecha de prioridad: 23/01/2023. Número P202330042. Solicitud internacional PCT: Robotic gripper for grasping and manipulation PCT/ES2024/070035 (22/01/2024). Publicada: WO2024156930 (02/08/2024).

2. Navas, E., Fernández, R. (2024) Válvula neumática para el control de un caudal de aire. Fecha de prioridad: 09/01/2024. Número P202430011, ES1641.1942-PRIO.

3. Fernández, R., Navas, E., Rodríguez Nieto, D., Ojeda Velázquez, M. Sistema robótico móvil de doble brazo para realización de injertos en plantas y procedimiento de realización. Fecha de prioridad: 12/04/2024. Número P202430280, ES1641.1966-PRIO.

Finally, the list of research projects that have provided the funding resources for the work described above:

1. DPI2017-84253-C2-1-R, funded by FEDER/Ministerio de Ciencia, Innovación y Universidades - Agencia Estatal de Investigación (01/01/2018 – 30/06/2021).

2. RoboCity2030-DIH-CM, Madrid Robotics Digital Innovation Hub, S2018/NMT-4331, funded by “Programas de Actividades I+D en la Comunidad de Madrid” and cofunded by Structural Funds of the EU (01/01/2019 – 30/04/2023).

3. Proyecto Intramural IAMC-ROBI (Inteligencia Artificial y Mecatrónica Cognitiva para la Manipulación Robótica Bimanual), CSIC under Grant 202050E099 (13/04/2020 – 12/04/2023).

4. PDC2021-121578-I00 funded by MCIN/AEI/10.13039/501100011033 and by the “European Union NextGenerationEU/PRTR” (01/09/2021 – 28/02/2025).

5. PID2020-116270RB-I00 funded by MCIN/AEI/10.13039/501100011033 (01/01 /2018–31/12/2020).

6. TED2021-132710B-I00 funded by MCIN/AEI/10.13039/501100011033 and by the “European Union NextGenerationEU/PRTR” (01/12/2022 – 30/06/2025).

7. Proyecto Intramural IAMC-ROBI-II (Inteligencia Artificial y Mecatrónica Cognitiva para la Manipulación Robótica Bimanual — 2º Fase), CSIC under Grant 202350E072 (20/03/2023 – 19/03/2026).

In addition, a four-month research stay was completed at Leibniz Institute of Agricultural Engineering and Bio-economy e.V. (ATB) in the Agromechatronics department under the supervision of Dr. Cornelia Weltzien. This stay was funded by the University of Valladolid through the "MOVILIDAD DOCTORANDOS Y DOCTORANDAS UVa 2022" scholarship.

5.3 Future research lines

The field of soft robotics is rapidly evolving, branching into diverse areas in recent years. Significant efforts are focused on developing advanced materials with enhanced mechanical properties, flexible filaments suitable for additive manufacturing, and even self-healing materials. These innovations represent only the beginning of what is possible in this domain. Additionally, considerable attention is being directed toward soft sensors that preserve the intrinsic flexibility and adaptability of soft robotics enabling new functionalities.

One key future directions of this work involves studying novel sensors that can be seamlessly integrated into the designed gripper prototypes. These sensors would enable real-time measurement of various parameters of interest without compromising the gripper's dexterity or grip shape. Such data could facilitate the implementation of high-level controllers leveraging artificial intelligence and machine learning. Furthermore, dynamic feedback from these sensors could support advanced grip planning algorithms, allowing the gripper to adapt to object movements during manipulation. Another promising direction lies in the study of trajectory planning for robotic systems equipped with these grippers. The inherent advantages of soft robotics in unstructured environments provide greater flexibility in movement planning without risking damage toe surroundings. Achieving this would require full integration with ROS to ensure the gripper's behaviour aligns with real-world matches its real-world performance.

Finally, energy efficiency and durability of sot grippers present valuable avenues for future research. These aspects have received limited attention in the existing literature. Energy optimization efforts should focus on analysing the consumption of soft actuation devices to enhance the robot's autonomy. Similarly, conducting a life cycle analysis of soft actuators would help develop methodologies for evaluating and improving gripper durability.

All these future research lines, among others, remain open challenges that hold great potential to advance the field of soft robotics, particularly the development and refinement of soft robotic grippers.

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APPENDIX A

A.1 Peer-reviewed articles published in indexed journals

sensors

MDPI

Review

Soft Grippers for Automatic Crop Harvesting: A Review

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Abstract: Agriculture 4.0 is transforming farming livelihoods thanks to the development and adoption of technologies such as artificial intelligence, the Internet of Things and robotics, traditionally used in other productive sectors. Soft robotics and soft grippers in particular are promising approaches to lead to new solutions in this field due to the need to meet hygiene and manipulation requirements in unstructured environments and in operation with delicate products. This review aims to provide an in-depth look at soft end-effectors for agricultural applications, with a special emphasis on robotic harvesting. To that end, the current state of automatic picking tasks for several crops is analysed, identifying which of them lack automatic solutions, and which methods are commonly used based on the botanical characteristics of the fruits. The latest advances in the design and implementation of soft grippers are also presented and discussed, studying the properties of their materials, their manufacturing processes, the gripping technologies and the proposed control methods. Finally, the challenges that have to be overcome to boost its definitive implementation in the real world are highlighted. Therefore, this review intends to serve as a guide for those researchers working in the field of soft robotics for Agriculture 4.0, and more specifically, in the design of soft grippers for fruit harvesting robots.

Keywords: soft robotics; agriculture 4.0; soft grippers; end-effectors; review; harvesting process

Citation: Navas, E.; Fernández, R.; Sepúlveda, D.; Armada, M.; Gonzalez-de-Santos, P. Soft Grippers for Automatic Crop Harvesting: A Review. *Sensors* **2021**, *21*, 2689. https://doi.org/10.3390/s21082689

Academic Editor: Dionysis Bochtis

Received: 10 March 2021
Accepted: 9 April 2021
Published: 11 April 2021

1. Introduction

In the last decade, the agricultural sector has undergone a deep transformation to cope with the growing demand for food [1–3]. Among the main tasks in agricultural processes, those that involve the manipulation of fruits and vegetables continue to be one of the most time consuming and labour intensive, resulting in low efficiency and limited competitiveness. This situation is exacerbated by the labour shortages of seasonal workers unable to travel between regions, leading to the accumulation of fresh products and impressive food losses. For these reasons, a great research effort is underway to automate these manual operations, as in the case of selective harvesting, combining multidisciplinary fields such as biological science, control engineering, robotics and artificial intelligence. Special emphasis is being placed on topics such as the modification of plant peduncles [4], which could simplify the harvesting process [5]; machine vision and detection systems [6–10]; decision-making architectures [11–13]; autonomous navigation [14–16]; and dexterous manipulation [17,18]. Another critical topic, often underestimated, is that related to the design of the systems attached to the tip of robotic manipulators and that are in direct contact with the fruit, known as grippers or end-effectors.

In manual harvesting, humans use their hands to move different elements of plants, grasp the fruits and detach them, either directly or with the help of a tool. The kinematics of human hands, the deformability of the skin and muscle, and their sense of touch give us efficient grasping abilities. Attempts to emulate human skills during harvesting have resulted in numerous mechanical end-effectors that can be classified according to their numbers of fingers into two major groups: multi-fingered and parallel grippers [19].

Multi-fingered grippers, such as those proposed in [20–23], include multiple degrees of freedom (DoFs), giving them grasping characteristics similar to the human hand, although they are expensive and difficult to control due to the large number of actuators. On the other hand, parallel grippers exhibit a simpler mechanical structure, making them easier to control, as they have fewer actuators. However, this simplification translates into less adaptability during grasping.

With the emergence of soft robotics, grippers based on soft and deformable materials have recently begun to be proposed for industrial and medical applications [24–31]. These soft grippers, which are able to continuously vary their shape without requiring complex multi-joint mechanisms, have the potential to provide greater adaptability while presenting lower costs and simpler structures and control algorithms than hard end-effectors [32,33].

With all this in mind, this review aims to present and discuss the latest developments in the design and implementation of novel soft grippers and end-effectors. To that end, the suitability of each of the proposed grippers to the movements required during the harvesting processes is studied, as well as their manufacturing processes and low-level control methods.In addition, the picking patterns (i.e., movements required to harvest the fruit) reported in the literature are analysed, and classification is presented in which the correct picking patterns for a considerable number of fruits are identified. Moreover, a list of the remaining challenges for the implementation of soft grippers in robotic crop harvesting is presented.

Therefore, the beneficiaries of this review can be all companies, designers or researchers who want to see a complete picture of the current progress of soft robotics and its suitability for implementation in the agricultural sector. The rest of the review is organized as follows. In Section 2, an overview of the current state of robotic harvesting automation is introduced, delving into the most critical aspects for gripper design, such as the characteristics of the picking patterns and the nature of the different fruits. Section 3 describes the soft technologies applied to existing grippers that could be used for Agriculture 4.0 applications, as well as the main control solutions implemented for soft grippers. Section 4 lists the main challenges of soft grippers for robotic crop harvesting. Finally, Section 5 summarizes the major conclusions.

2. Harvesting Process

2.1. Harvesting Process Classification

Since gripper designs for robotic harvesting are highly dependent on the picking process, the main techniques currently in use are summarized below with the aim of finding the gaps where soft robotics can make the greatest contributions. The general classification presented in [34] divides the detachment of fruits into two methods: (i) mechanical detachment, which involves the removal of pieces of fruit from the tree branch by means of a machine or a mechanical mechanism, and (ii) manual detachment, which consists of the extraction of pieces of fruit from the tree branch by the human hand. In [35], mechanical fruit harvesting processes are classified as follows: (i) those that remove the fruits by shaking the entire plant through air blasting, canopy shaking, limb shaking or trunk shaking; sometimes these methods are assisted with a chemical agent, which makes ripe fruits easier to harvest; and (ii) those that use automatic robotic picking machines that require minimal or no human intervention in their operation.

With the introduction of a wide variety of robotic solutions for fruit harvesting and the design of new grippers and end-effectors in recent years, it is convenient to update the classification of automatic harvesting methods to include these latest technologies. The classification proposed in this review is an extension of that carried out in [36], which classified the removal of the fruits into two groups: (i) those in which the application of direct force to the harvested portion is necessary and (ii) those that deliver the removal energy indirectly as an inertial force response that causes detachment by accelerating the attachment support away from the harvest object. Consequently, harvesting methods are divided into three main groups, which are shown schematically in Figure 1:

1. Indirect harvesting: a technique that involves indirect mechanical movement towards the fruit through a force applied to the plant itself, such as that carried out when harvesting olives [37], almonds [38] or pistachio nuts [39]. To make the fruits fall without any contact points, methods such as air blasting, limb shaking, trunk shaking and canopy shaking are often used [34,35].
2. Direct harvesting: a method used in those crops that, due to the structural characteristics of the plant, cannot be shaken but require the direct application of a mechanical force on the fruit or its peduncle; these picking techniques, which are discussed in more detail in Section 2.2, are also known as picking patterns (e.g., twisting, pulling or bending) and cause fruits to detach from the stem [40]. Examples from this group are the methods used in the harvesting of strawberries [40,41], apples [42–45] and several varieties of tomatoes [46–49].
3. Direct harvesting with an actuation force on the peduncle: a technique that is applied to those fruits that require a direct mechanical movement, or another type of cutting method, applied directly to the stalk since due to their morphology they are connected to the plant by a hard peduncle that must be cut, as in the harvest of aubergines [50,51], melons [52], oranges [53], cucumbers [54] and peppers [55–57].

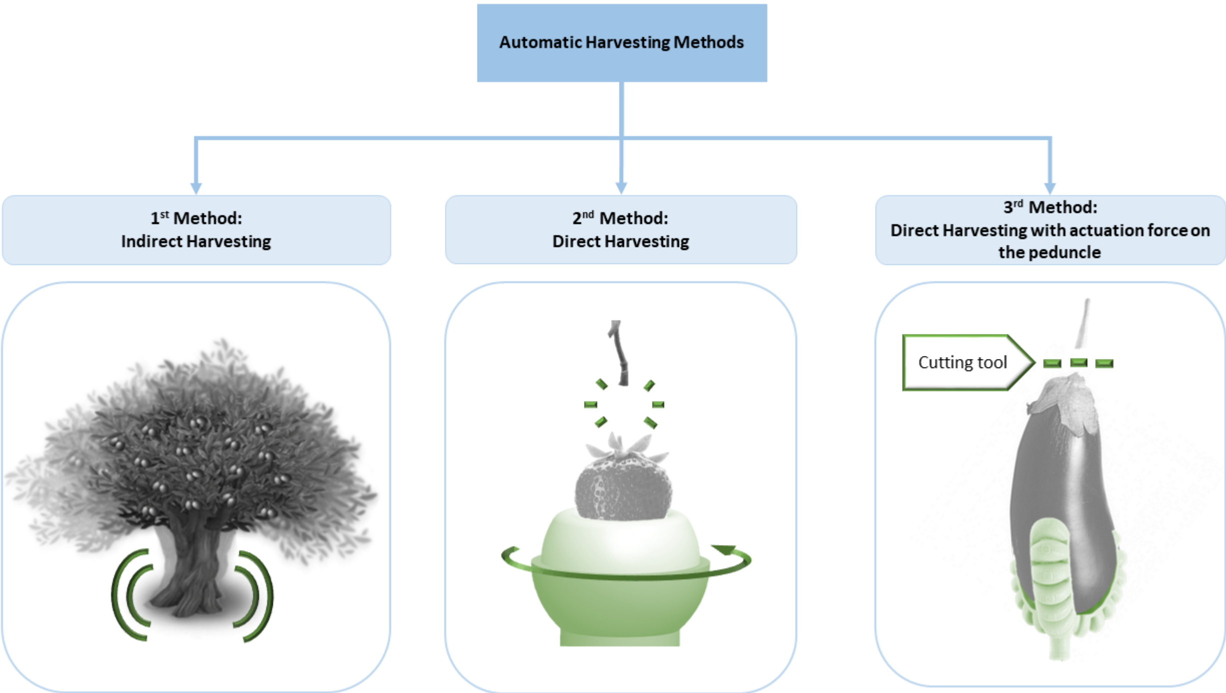

Figure 1. Classification of automatic harvesting methods.

In the classification of the harvesting processes presented above, it is important to highlight that the fruits included in the first group can also be harvested using the methods described in the second group due to the physical characteristics of the peduncle. The most suitable harvesting method to use must be studied on an individual basis depending on the crop. Several factors may influence the choice of the most suitable harvesting method, such as (i) the size and shape of the tree [36], (ii) the structural fragility of the plant [35,36], (iii) the maturity stage of the fruits [34,58], (iv) the lack of preharvesting chemical fruit looseners, which affect the ease of harvesting [34], (v) the requirements of avoiding damage to the fruit or the plant [36,58] and (vi) the financial profitability [34]. Some authors [34,59] discourage the use of products such as chemical fruit looseners before harvest due to their effect on the defoliation of the trees and the subsequent lack of bloom in the following year. This complicates harvesting through indirect contact of the various fruits within the first group, which in some cases are collected by air blasting, limb shaking, trunk shaking or canopy shaking [34].

There are also several differences between the requirements of the group 2 and group 3 techniques. For instance, the harvesting methods included in group 3 need a more sophisticated perception system than those in group 2, since in addition to the fruits, they have to detect peduncles; they also require a robotic system with greater precision to locate the peduncle between the blades of the tool and proceed to cut it without damaging the crop [47], while with the group 2 techniques, fruits can be harvested with part of the peduncle with just one picking action.

In the literature, authors of [60] resume the main capabilities of an ideal picking robot as the following: (i) the 3D location of the fruits in the plant, (ii) trajectory planning, (iii) the application of detachment method and adequate storage, and (iv) the application of reliable driving system. These operations must be carried out under the constraints of (i) increasing the harvest ratio between robotic picking and manual picking, (ii) increasing the quality of the harvested fruit, and (iii) being economically justified. Furthermore, ref. [61] highlights two main challenges in fruit harvesting: (i) an adequate manipulation of fruits to avoid the loss of quality and consequently, the loss of value in the market, which implies the development of grippers and end-effectors that meet this requirement, and (ii) the study of the detachment method for removing the fruit from the tree, which varies according to the type of fruit.

2.2. Picking Patterns

As stated above, the fruits harvested by means of the methods classified in group 2 pose a challenge in the field of robotic manipulation. One of the research paths in this field is based on the idea of studying and decomposing the human movements performed during the harvesting of fruits and replicating them using robotic grippers. These movements are grouped under the concept of picking patterns, which include, among others, the movements of bending, lifting, twisting, and pulling or a combination of them. In Figure 2, the basic picking patterns are shown conceptually.

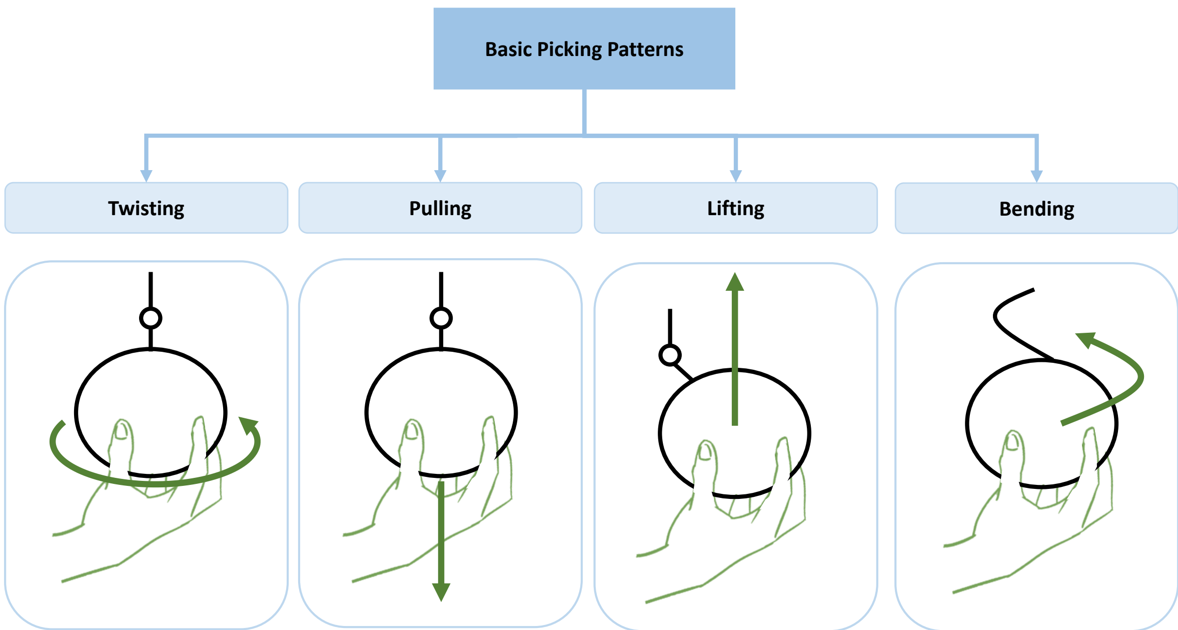

Figure 2. Simplified scheme of basic picking techniques.

An important factor that has been studied within the field of biological science for group 2 methods, and particularly for the application of the picking patterns, is the abscission layer, which is a barrier of thin-walled parenchyma cells that develops between the fruit and the fruit stalk or the fruit stalk and the branch. This development process occurs when the moment of the fall of a fruit from a plant approaches to facilitate detachment [62]. In most cases, fruit harvested before development of the abscission zone will not have well-developed sugar, volatile, or flavour attributes [63]. Some investigations are trying to modify or eliminate this layer by modifying the plant so that the next point of separation of the plant from the fruit is located right in the calyx and the fruit is easier to harvest [5,62]. Therefore, the identification of the abscission layer is important to determine where the fruit separates from the plant at the time of harvest, as well as the picking patterns to apply.

In the literature, there are studies available on picking patterns for (i) tomatoes [46,47,64], (ii) kiwis [65], (iii) apples [61] and (iv) strawberries [66,67]. It is also worth mentioning the study presented in [68], in which the movements of the hand and the human body in the harvesting process are analysed to provide a guide for the design of new grippers and end-effectors of anthropomorphic inspiration. The scheme shown in Figure 3 summarizes the proposed steps to follow for the design or selection of grippers and end-effectors required to harvest fruits by means of direct contact methods.

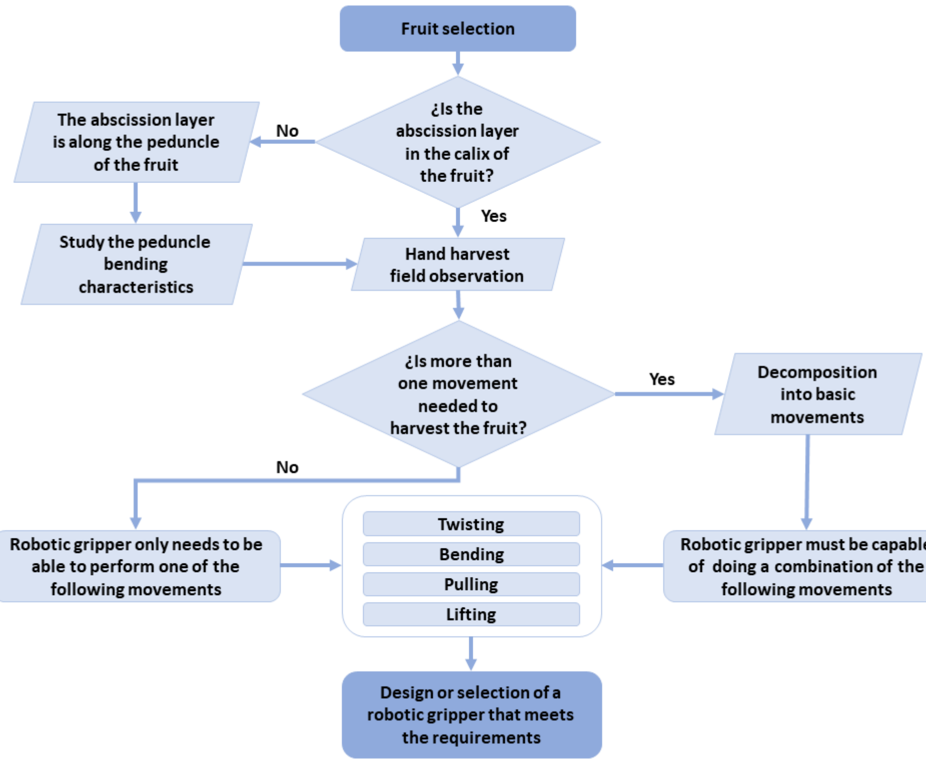

Figure 3. Steps to design or select a gripper or end-effector based on the study of a picking pattern.

Since the picking patterns described in this section involve direct contact with the fruit, the introduction of soft grippers may represent a significant advance in the automation of the harvesting methods classified in group 2, allowing a delicate manipulation that guarantees the integrity of fruits.

2.3. Direct Harvesting with an Actuation Force on the Peduncle

Regarding group 3, a comprehensive classification of the types of mechanisms used in grippers coupled to manipulators for the harvesting techniques of group 3 can be found in [2,24]. Research studies on this third group [69–75] have focused on the shear characteristics of the plants, such as the shear ultimate stress, the maximum force and the shear energy. These characteristics could be helpful in the study of the peduncles of fruits, with the aim of developing more energy-efficient cutting tools. For cutting peduncles, there are several techniques that can be classified into two groups: (i) techniques based on the bending characteristics of the stalk, such as the bending force, bending stress and Young's modulus, and (ii) techniques based on the shear characteristics, such as the shear force, shear strength and shear energy. Table 1 presents the classification of several cutting techniques. According to this table, the tools that do not use the bending force have in common the need to consider the cutting characteristics, in particular, the cutting force and the cutting energy required to separate the fruit from the plant. Since laser cutting is not based on the peduncle characteristics, it has not been included in this table [76].

Table 1. Classification of existing grippers.

Type	Bending Characteristics	Shearing Characteristics
Peduncle rotation [61]	X	-
Pushing some object into peduncle [53]	X	-
Knife, one sided blade [53,77]	-	X
Scissors [78]	-	X
Saw [49,53]	-	X
Hot wire [54,79]	-	X

Therefore, harvesting techniques of group 3 are also candidates for the introduction of soft gripper technology, provided they are complemented by a suitable cutting tool.

2.4. Literature Overview of Crop Harvesting Automation

Tables 2 and 3 present a collection of articles that propose technological solutions for automatic harvesting, botanically classified according to the target fruit [80]. This botanical-based classification divides fruits into simple fleshy, aggregate and multiple. Simple fleshy fruits (such as a berries, drupes, or pomes) are those derived from a single ovary of and individual flower [81]. Aggregate fruits (such as raspberries) consist of many individual small fruits derived from separate ovaries within a single flower, borne together on a common receptacle [82]. Lastly, multiple fruits (such as figs, mulberries, or pineapples) are those derived from the ovaries of several flowers that coalesce into a single structure [82].

In addition, in each table, the harvesting method used is identified, following the classification of harvesting techniques proposed above and taking as a reference both the information presented in [36,83] and the visualization of the harvesting processes. Although the proposed solutions may be valid for several crops, they have been assigned only to those crops where an experimental study has been reported. Additionally, it is taken into account that the crops classified in groups 2 and 3 are the most suitable for the adoption of soft gripper technology.

Table 2. Simple fleshy fruit classification.

Type of Fruit	Name	Actual Harvesting Method	Automatic Harvesting Method
Drupes	Apricot	2	1 [84,85]
	Blackberry	2	1 [86]
	Cafe	2	1 [87,88]
	Cherry	2	1 [89–95], 2 [96], * [97]
	Coconut	3	3 [98,99]
	Loquats	2	-
	Lychee	3	* [100–103]
	Mango	2,3	1 [104], 2 [105], 3 [106–108], * [109]
	Nectarine	2	* [110]
	Olive	1	1 [111–115]
	Peach	2	1 [116], * [117,118]
	Plum	2	2 [119]
	Raspberry	2	1 [120,121]

Table 2. *Cont.*

Type of Fruit	Name	Actual Harvesting Method	Automatic Harvesting Method
Berries	Avocado	3	* [122]
	Blueberry	2	1 [123]
	Eggplant	3	3 [50,51], * [124]
	Grape	1,3	1 [125–128], 2 [129], * [130]
	Guava	3	* [131]
	Kiwi	2	2 [132–134]
	Papaya	2	3 [105], * [135]
	Passion fruit	2	* [136]
	Pepper	3	3 [55–57,137–139], * [140,141]
	Persimmon	2	2 [142], * [143]
	Pitaya	3	* [144]
	Pomegranate	3	* [145]
	Tomatoes	2,3	2 [46–49], 3 [146,147], * [148–150]
	Wolfberry	2	1 [151], 2 [152], * [153]
Pomes	Apple	1,2	1 [154], 2 [42–45,155,156], 3 [157], * [158,159]
	Pear	2	3 [157], * [160]
	Quince	2	-
Hesperidium and Pepo	Banana	3	* [161]
	Cucumber	3,2	3 [54], * [162,163]
	Grapefruit	3	1 [164]
	Lemon	3	* [165]
	Lime	3	-
	Melon	3	3 [52]
	Orange	3	1 [34,164,166,167], 3[53], * [168,169]
	Pumpkin	3	2 [170], * [171]
	Watermelon	3	3 [172]

(*) Artificial vision research.

Table 3. Aggregate and multiple fruit classification.

Type of Fruit	Name	Actual Harvesting Method	Automatic Harvesting Method
Aggregate fruit	Custard Apple	2	-
	Strawberry	2	2 [40,41,66,67,173,174], * [175,176]
Multiple fruit	Fig	2	-
	Pineapple	2	2 [177], 3 [178], * [179–181]

(*) Artificial vision research.

3. Soft Grippers

Soft grippers are those end-effectors that use materials and actuation methods that are soft, flexible and compliant and that enable the holding of an object to be manipulated. The softness characteristic provides the adaptability and robustness seen in natural organisms, allowing grasping and manipulation to be achieved with ease. These systems have the potential to interact more safely within an unstructured human environment and deal with dynamic and uncertain tasks [182].

Since fruits must be handled properly to avoid the loss of quality and reach their maximum value in the market, soft grippers are presented as one of the best solutions for harvesting crops, given their adaptability and the delicacy with which they can grasp and manipulate the target products.

In this context, soft technologies can be defined as the set of theories, techniques and procedures that enable key functions of soft robotic grippers, such as actuation, gripping and shape control methods. Although different authors have proposed a great variety of soft technologies [183–187], the main objective of all of them is to guarantee the safe interaction of the device with humans and the environment by using materials with a module similar, in terms of rigidity, to that of soft biological materials [187]. Several reviews of soft grippers can be found in the literature [19,33,182–184,187–189], presenting various approaches to classify existing technologies. One of the most widely used approaches is the one that classifies the soft gripping technologies according to three different categories [190,191]: (i) actuation, (ii) control stiffness and (iii) controlled adhesion. However, it is currently possible to find devices whose designs simultaneously combine characteristics from several of these categories. Figure 4 shows the complete classification of the current soft gripping technologies based on the mentioned categories.

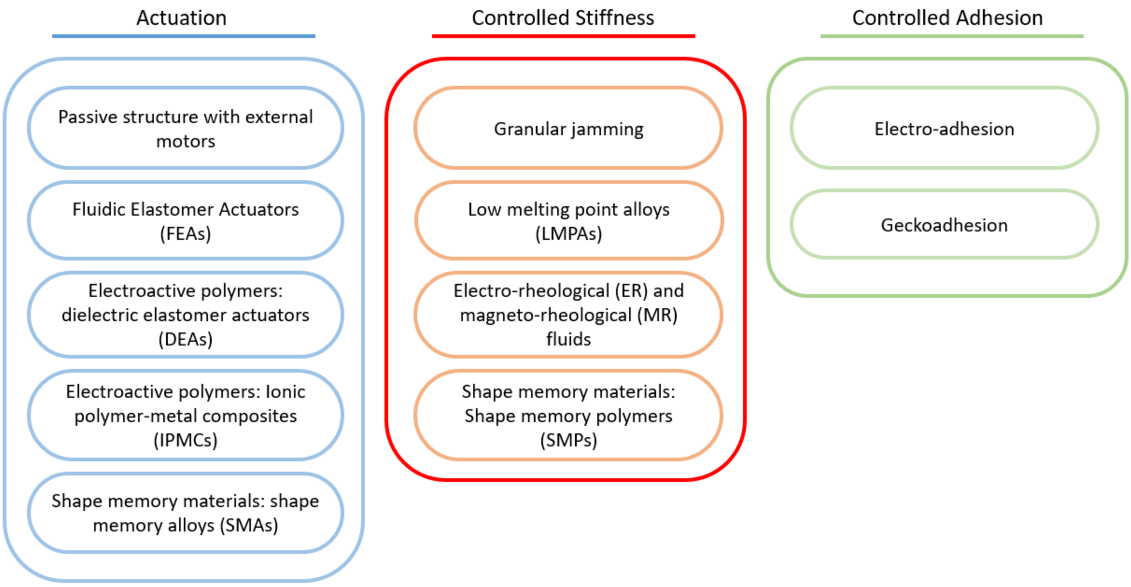

Figure 4. Classification of soft gripping technologies proposed by [190].

From an agricultural point of view, some of these technologies may be more relevant than others. Based on the reviews carried out in [189,190], evaluation criteria adapted to Agriculture 4.0 can be established to perform a quantitative and qualitative analysis of the existing soft grippers. These criteria are listed below.

- Object size: This is one of the most critical aspects to evaluate soft technology since its use in certain crops depends on it. Passive structures with external motors, fluidic elastomer actuators (FEAs) and controlled adhesion are the technologies with the best capacity to grasp large objects.
- Gripper size: Another criterion is the size of the device, which can be critical to access certain crops.
- Lifting ratio or operation range: This variable can be interpreted as the ratio between the mass of the object and the mass of the gripper or as the force that the soft actuator can exert. If interpreted as a ratio, it should always be related to the maximum size of the object that can be grasped. For example, shape memory alloy (SMA) actuators have a higher lift ratio than FEAs but a less manipulable object size, which reduces their suitability for fruit picking.
- Power consumption: Each soft technology requires a different type of support device. The technologies that require electric motors or pumps to operate demand the highest energy consumption.
- Scalability: This feature takes into account not only the ease of manufacture but also the modularity of the technology used. This is especially important for the adaptation of soft grippers to various types of crops, and it is desirable that they be as universal as possible to increase their viability.
- Controllability: Depending on the soft technology used, several proposals for low-level control systems can be found. Normally, the most widely used control method is

open-loop. With respect to fluidic actuators, liquid-based devices can exhibit more linearity than pneumatic devices.

- Response time: This variable can affect the efficiency of the agricultural task. It may be difficult for soft actuators that rely on a fluid to achieve high actuation frequencies due to the fluidic impedance of the channel and the flow actuation level.
- Surface conditions: Soft gripper technologies that require a clean surface, such as controlled adhesion, are less suitable than those that do not have any surface-related requirements.
- Degree of skill to working in unstructured environments: Although soft technology is one of the most suitable for working in unstructured environments, not all soft grippers that can be found in the literature are suitable for agriculture scenarios. This is the case for devices that require complex support devices that are sensitive to large holes or that can suffer tears from sharp objects [192].
- Mechanical compliance: Each soft technology has an advantage in terms of compliance. For instance, FEAs, shape memory polymer (SMP) actuators and dielectric electroactive polymer (DEAP) actuators are inherently compliant due to the materials used. With other technologies, such as SMA actuators, this parameter depends on the shape of their structures.
- Lifetime: The parameter is the number of cycles that a soft actuator can remain in operation before failing or exhibiting altered motion patterns. Lifetime is an important characteristic in FEA technology, which is subjected to constant fill and empty cycles that tend to wear away the material.
- Technology readiness level (TRL) [189]: Another criterion to compare the feasibility of each technology could be the TRL. Those that have experimentally demonstrated their efficiency in real operating environments, as well as those that are also easier to put into production due to the type of support devices they use and the materials and manufacturing process they require, have a higher TRL.

According to this classification, controlled adhesion technology may be difficult to adapt to agricultural tasks, as it requires a special surface to be able to grip an object, although the weight lifted/weight gripper ratio (39 [193]–286.7 [194]) and the size of the object could be suitable (0.16×10^{-2} m [195] to 100×10^{-2} m [196]). Regarding the grippers grouped around control stiffness, granular jamming ones stand out, since they have a good weight lifted/weight gripper ratio, as well as a good response time and the ability to lift small to medium-size fruits. The other components in this group are discarded for harvest purposes since their performance is not ideal for these tasks. Finally, in the actuation technology group, passive structures with external motors and FEA actuators could be ideal ones for fruit harvesting grippers because (i) they have a large lifted size/gripper weight ratio; (ii) the size of the object can be between 0.01 and 100×10^{-2} m, which includes the sizes of most fruits; (iii) they have a good response time; and (iv) they have the ability to grasp any object. A disadvantage may be their energy consumption since they are hampered by the need for an electric motor or pump. Nevertheless, these technologies present the highest TRL level, which would facilitate their production.

3.1. Materials and Manufacturing Methods

3.1.1. Materials

As mentioned above, a wide variety of soft grippers have been proposed. Soft components typically used in the actuators of these grippers include urethanes, hydrogels, braided fabrics, hydraulic fluidics and polymers, such as silicone elastomers [197]. However, actuators based on silicone elastomers have attracted strong interest due to their low cost and ease of manufacture; they do not require the use of complex machinery or skilled labour. In addition, these compliant materials are also advantageous when considering the safety of interaction with biological products, making them appropriate candidates for agricultural applications. Figure 5 presents a bar graph showing the commercially available materials (silicone elastomers and other polymers) that are most frequently reported in the soft robotics literature and that consequently can be used for soft grippers implementation.

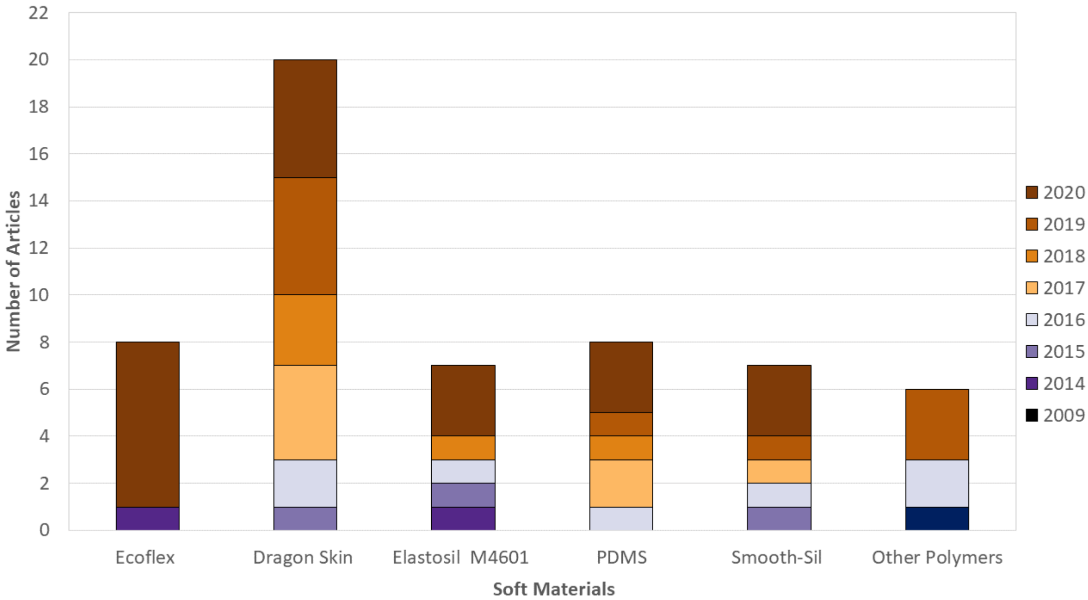

Figure 5. Silicone elastomers and other polymers used in soft robotics literature, as well as the corresponding number of citations. For this graph, 45 articles were examined: Ecoflex [198–205], Dragon Skin 10/20/30/FX-Pro [206–225], Elastosil M4601 [199,202,218,226–229], PDMS [198,208,230–232,232–234], Smooth-Sil [200,207,209,218,222,223,227] and Other Polymers [235–241].

Several of these soft materials, particularly silicone elastomers, can be modelled as rubber elastomeric membranes that are hyperelastic and nearly incompressible. Various approaches based on developing free energy density functions can be found to describe the phenomenological constitutive models of rubber-like materials, such as the Neo-Hookean, Mooney–Rivlin (Mooney, 1940; Rivlin, 1948), Ogden (Ogden et al., 2004) and Gent models (Gent, 1996).

As shown in Figure 5, the five most commonly used materials are Dragon Skin, Ecoflex, polydimethylsiloxane (PDMS), Elastosil M4601 and Smooth-Sil, which are all silicone elastomers. Other polymers are Agilus30/VeroClear, ultra-high molecular weight polyethylene, electrostatic discharge (ESD) plastic sheet, thermoplastic elastomers (TPEs) and thermoplastic polyurethane (TPU).

Although there are no specific studies that categorically confirm the suitability of the above materials for the agricultural sector, all materials are declared in their safety data sheet as non-hazardous substances. However, it would be convenient to carry out studies that analyse the life cycle of soft actuators made with these materials, to determine if their degradation may leave particles on the products manipulated.

Dragon Skin, Ecoflex and Smooth-Sil are commonly used for manufacturing objects outside the scientific field, so determining their exact chemical composition is difficult. However, they are versatile, easy to use and handle, and low cost compared to other silicones, and their hardness is between 10 and 50 Shore A. Elastosil M4601 is highly resistant to bending and elongation; it has low viscosity in its uncured form, which makes it easy to mould; and its hardness is approximately 28 Shore A. PDMS has high elasticity [242], it is a thermoset [230], and its behaviour can be mathematically modelled with great precision by means of finite element method (FEM) analysis due to its well-known chemical composition. Furthermore, the variation in its hardness through several mixing ratios has been extensively studied in the literature [243,244]. The main advantage of other soft materials, such as TPU and TPE, is that they can be 3D printed. Additionally, another advantage of TPU-95 is its durability (85A Shore hardness), making it suitable for agricultural environments, where harmful collisions with objects are frequent [236].

A common advantage of all of these silicones is their ability to cure at room temperature, without the need for an oven, although an oven can be used to shorten the cure time.

3.1.2. Manufacturing Methods

The main soft actuator manufacturing methods, comprehensively reviewed in [182], are (i) the moulding process, where fused deposition modelling (FDM) printers are commonly used for mould making; (ii) shape deposition manufacturing (SDM), which facilitates the construction of 3D soft actuators composed of multiple materials with different properties; (iii) soft lithography, which facilitates the development of multichannel soft actuators; (iv) lost-wax cast fabrication [245]; and (v) soft 3-D printing. The latter can be considered a promising technology due to the elimination of several moulding stages, which facilitates the manufacturing process and the design of more complex inner chambers or pneumatic networks.

3.2. Soft Grippers for Food

In the field of soft robotics, particularly in soft grippers, there is a lack of soft actuators designed for picking fruits and vegetables. This absence is most noticeable for harvesting tasks. Although this is discussed in more detail in the following sections, note that the handling of this type of product requires precise control of the gripper to successfully carry out the movements of the picking patterns that are listed above without damaging the fruit. Furthermore, the current state-of-the-art soft actuators tend to be researched in the field of manipulation, which in many cases is very generalist and is not particular to the diverse characteristics of individual objects.

However, in the field of industrial food handling, there are more research studies that could be considered the basis for soft grippers in Agriculture 4.0 applications. These studies are listed below, classified according to the type of soft actuator they use, indicating the advantages of each technology. Only studies that specifically refer to food handling have been taken into account.

- FEA [206,220,224,225,230,236,246–251]: This type of actuator technology is emerging as a potential winner for fruit handling. This is due to the use of affordable materials, the simplicity of their manufacture and control, and the grip strength obtained. Special mention should be made of the solution proposed in [223], which can be defined as a hybrid gripper, combining vacuum pressure and an origami-inspired compliant structure. This design has a high gripping force of approximately 50 N, and the authors provide a detailed study of its grasping.
- Tendon-driven [252,253]: This type of technology offers other advantages over the previously mentioned technology, such as greater precision in position control. Specifically, this type of technology can be associated with a structure made up of rigid or soft materials that are passively acted upon by tendons that offer soft-type manipulation.
- FEA-tendon-driven [254]: This approach combines both of the above technologies. Tendon drive technology is used for grasping motions, and actuation is achieved by linear soft vacuum actuators. This type of synergy improves the diversity of objects that can be manipulated, as well as the combination of the advantages of each technology. In one particular case [254], the gripper was able to lift a total of 2.7 kg, which represents a maximum payload-to-weight ratio of 7.06.
- Topology-optimized soft grippers [255]: This type of soft gripper, which operates via elastic deformation, can be adapted to the sizes and shapes of objects without mechanical joints or sensors. In one particular case, the gripper could lift maximum loads of 1.4 kg.

Table 4 gathers the main soft grippers that have been proposed for delicate food handling and robotic harvesting applications. All of them are results of ongoing researches in the field of soft robotics.

Table 4. Literature review of food soft grippers.

Soft Technology	Reference	Grasped Object	Object Size or Weight	Gripper Type	Gripper Size	Lifting Ratio	Scalability	Controllability	Response Time	Surface Condition	Mechanical Compliance	Lifetime
FEAs	[251] *	Lettuce	250 × 250 mm	Two pneumatic actuators and a blade	8000 g, 450 × 450 × 300 mm	-	✓	Close-loop with force sensor feedback	31.7 s	-	✓	-
	[236] *	Apple	-	Three soft finger design	Two fingers length: 95,25 mm One Finger length: 152,4 mm	-	-	Open-loop	7.3 s	-	✓	-
	[230]	Mushroom	-	Three soft chambers in circular shell	Chamber height: 20 mm Chamber arc angle: 60°	30	✓	-	-	Any surface	-	-
	[246]	Apple, Tomato, Carrot, Strawberry	69 mm, 5–150 g	Magnetorheological gripper	-	-	-	PID	0.46 s	Any surface	✓	-
	[248]	Cupcake liners filled with peanuts	34–64 g	Three soft finger design	Finger size: 82 × 16 × 15 mm	-	✓	FE analysis	-	-	✓	-
	[250]	Cupcake liners filled with red beans, higiki, ohitashi	75.2 g	Soft fingers	Finger length: 97 mm	1805 %	✓	Open-loop	10 s pick and place (total procedure)	-	-	1100
	[224]	Defrosted broccoli	33.54 × 23.94 mm, 3.8–7.0 g	Two soft fingers	Actuator size: 50 × 20 mm	-	-	-	3 s for inflation			
	[225]	Granular kernel corn, Chopped green onion, Boiled hijiki	0.77–26.6 g	Four soft fingers	Finger size: 43 × 61,5 mm	-	✓	Open-loop	-	Any surface	-	-
	[206]	Orange	1000 g	Soft fingers	Finger size: 95 × 20 × 18 mm	-	✓	Open-loop	-	Any surface	-	-
	[220]	Tomato, Kiwifruit, Strawberry	45 to 76 mm	Four soft chambers in circular shell	Internal diameter: 46 mm Height: 30 mm	-	✓	Open-loop	2–5 s	Any surface	✓	-
Tendon-driven	[253]	Tomato	500 g	Three soft finger design	-	-	✓	Preprogrammed rotation of motors	-	-	✓	1000
	[252]	Tomato, Cucumber (slices) Avocado (Strips) Cherry Tomato, Olives, Pineapples cubes, Broccoli	-	Quad-Spatula design	-	-	✓	-	-	Flat surfaces	-	-
FEA-Tendon-driven	[254]	Banana, Apple, Grapes	2700 g	Three soft finger design with a suction cup	389.69 g	7.06	✓	Teleoperation Control	0.094 s (Rise time)	Any surface (irregular shapes and sharp corners)	✓	26–20 cycles
Topology optimized soft actuators	[255]	Apple, Grapefruit, Guava, Orange, Kiwifruit	1400 g	Two compliant fingers	-	-	✓	Open-loop (Arduino)	-	-	✓	-

* Soft Gripper for harvesting purposes. - Data not provided.

As can be seen in Table 4, the cited studies do not list the characteristics of the proposed soft grippers in a homogeneous way, which makes their comparative evaluation difficult. Thus, for example, with regard to the size of the object to be manipulated, each study proposes a different target, which in many cases is carefully selected to ensure an adequate grip. Hence the importance of having standard methods to quantitatively determine and compare the characteristics of soft actuators. It should also be noted that most of the proposed solutions are focused exclusively on the mechanical design, leaving the implementation of the control system for future work. Other crucial aspects such as the adaptation of the grippers to conventional robotic systems, the energy consumption and the power sources required for their operation are not addressed either. More detailed research on the life cycle of actuators is also lacking, which can affect their optimal performance due to the loss of properties that soft materials experience over time.

Figure 6 displays several soft grippers from the literature that could be adapted for precision harvesting of crops.

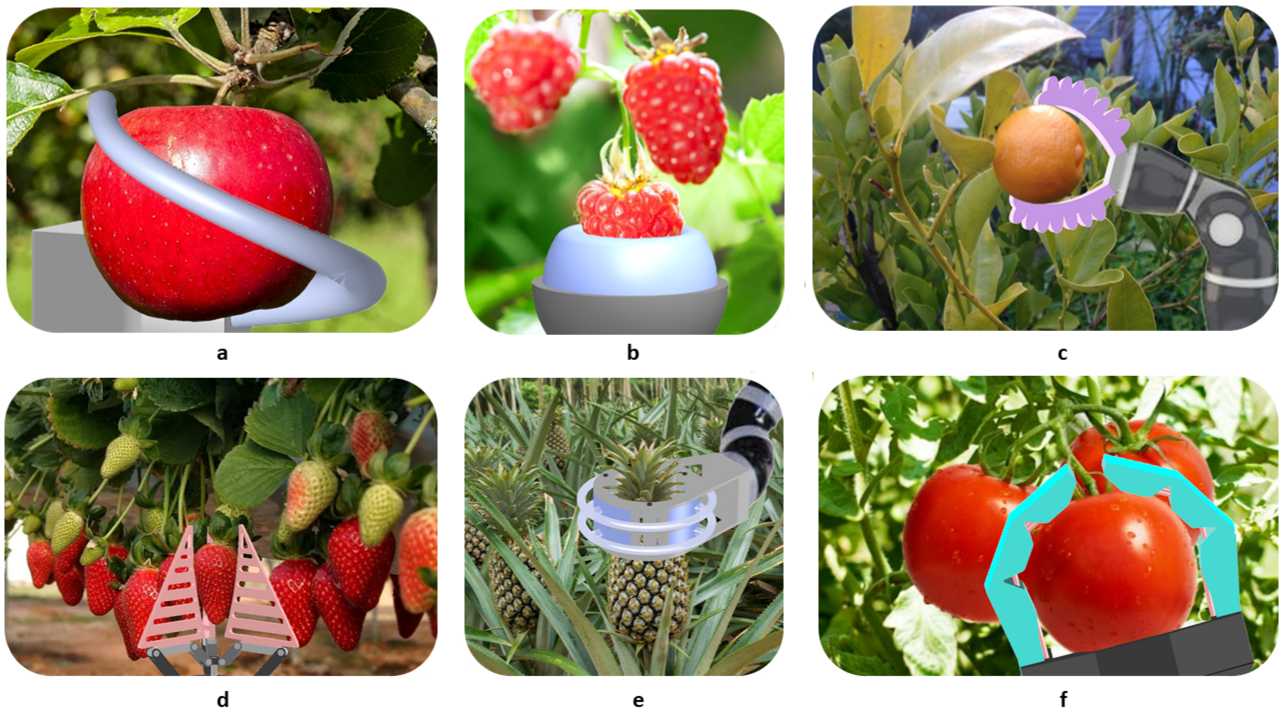

Figure 6. Hypothetical harvest scenarios with several soft grippers. (**a**) Soft continuum gripper based on [256], (**b**) end-effector based on [257], (**c**) bellow-type soft gripper based on [224], (**d**) multi-choice gripper based on [258], (**e**) circular soft gripper based on [220,230], and (**f**) tendon-driven soft gripper based on [254].

3.3. Control

Deformability and compliance are some of the main characteristics of soft actuators [259], which translate into a large intrinsic number of DoFs. This obviously affects the control system in terms of complexity. Low-level control for soft actuators, which is highly dependent on the soft materials used, can be decentralized to simplify the complexity [260]. For this reason, it is essential, as a design step, to study the passive mechanical dynamics of soft actuators to achieve the desired deformation behaviour [261].

As seen above, there are several soft technologies that have their own implications due to the type of actuator they use. Thus, for example, controlling a servo, actuating a cable in tendon-driven technology, controlling compressors and pressure regulators in FEAs, and controlling the amount of electric charge, electro-adhesion, or a thermal stimulus in SMA actuators are different challenges. The geometry of the actuator also has implications for the control system, as it affects the number of axes and movements that soft actuators can execute. The widest variety of control philosophies can be found for FEA soft actuators, as summarized in Figure 7.

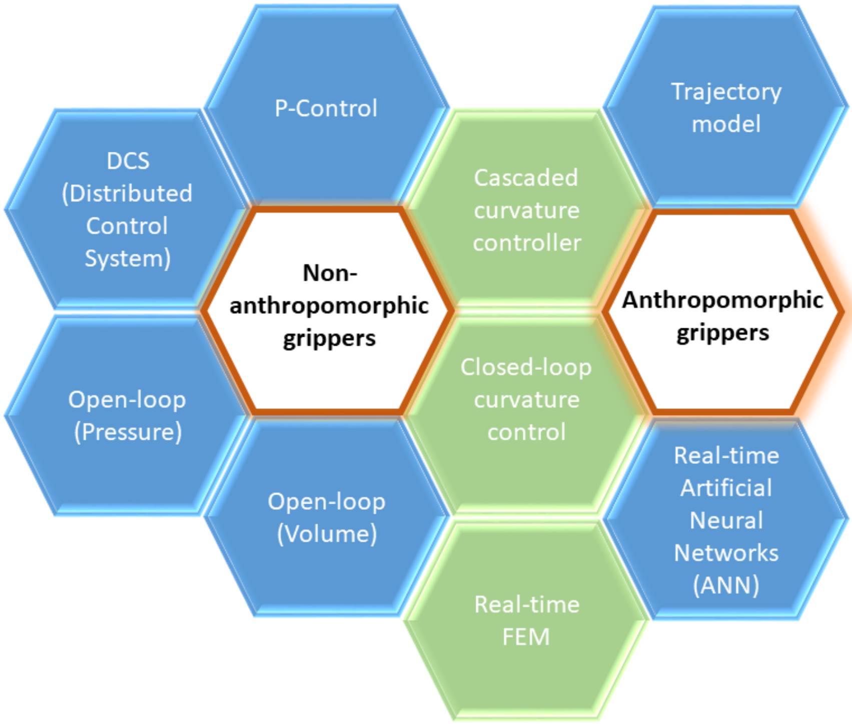

Figure 7. Several control philosophies proposed for FEA-type soft actuators. The control philosophies that have been proposed for a particular type of soft gripper (anthropomorphic or non-anthropomorphic) are presented in blue, while those proposed for both types are shown in green.

Although diverse control strategies have been proposed for FEA-type actuator technology, open-loop control is one of the most frequently used. Several authors [32] report difficulties in controlling certain types of FEA soft actuators due to their deflection around the object. This is especially intricate in anthropomorphic grippers in terms of achieving speed, flexibility and dexterity [191]; not only in FEA actuators but also in passive structures actuated by external motors or tendon motors. This disadvantage can be partially solved by sensing the actuator or by real-time control using FEM [187,262]. On the other hand, tendon-driven soft technology has more mature actuators than pneumatic actuators, and therefore, the control is more straightforward than that of FEAs [237].

4. Challenges of Soft Grippers for Robotic Crop Harvesting

Although a number of different soft actuator technologies have been proposed for various applications, soft grippers for robotic crop harvesting are not yet being sufficiently addressed. This is mainly due to the complexity of the unstructured agricultural environment, the intrinsic challenge posed by soft materials and the need to demonstrate the economic viability of robotic harvesting in the sector. Some of the main barriers that soft robotics, and more particularly soft grippers, face against their possible application in agricultural scenarios are listed below.

- Design process: One of the main challenges of soft technology is the design process. A wide diversity of generalist soft grippers can be found in the current state of the art. However, these designs are more focused on achieving new improvements in the field of soft robotics than on developing a specific gripper that solves the issues of the particular field of applications. In terms of robotic crop harvesting, characteristics such as modularity, ease of repair, and the ability to handle food and multiple crops are desired. Apart from this, another gap that needs to be studied is the mathematical model that represents the behaviour of the material in FEM software.

This is directly related to the nature of the various materials used, described in the Materials Subsection.

- Repeatability: Another of the main challenges of soft robotics, particular soft grippers, is the need to standardize manufacturing processes. This is the first point to be addressed because it would ensure that the designed soft actuators are suitable for production, facilitating their incorporation into the robotic market. Repeatability studies should research how to mitigate the common effects that appear in soft actuators, such as delamination or interstitial bubbles, that can be the result of faulty manufacturing. To solve these problems, several solutions have been proposed, such as the use of vacuum chambers [227,263–265]. Although positive results from this process have been reported, it is impossible to find a method where, for example, variables such as pressure or time are controlled as a function of volume to ensure the repeatability of the process. Obviously, the method would depend on the material used. On the other hand, in most cases, the manufacturing processes are very handmade, and therefore, repeatability can be compromised. However, processes based on 3D printing of soft materials, as well as lost wax manufacturing, may become interesting options in the future, given their greater options for achieving repeatability during the manufacturing process.
- Standard method for determination of soft actuator characteristics: One of the main gaps that has not yet been addressed in soft actuators is the definition of a method to determine their characteristics. However, it is clear that there is a need for a reliable method that can quantify the soft actuator features to facilitate its evaluation and comparison. Properties such as the contact pressure, contact force, contact area and slip force are crucial for benchmarking and determining room for improvement in this field. Thus, this would not only be useful for selecting the optimal option for each process but also for providing a true picture of the progress of this technology.
  In the current state of the art, several approaches can be found for the characterization of soft actuators, in which the experimental measurement is always performed with non-standardized objects. However, the proposed methodologies of the studies differ, presenting various approaches, among which the following stand out.
  - The measurement process proposed in [210] consists of grabbing a spherical object connected by an inextensible cable to a force sensor mounted on a motorized platform to measure the slip properties. A similar approach can be seen in [211] but with a six-axis force transducer.
  - Others, such as [218], use a pressure-mapping sensor to obtain the contact force and the pressure. This method offers a reliable measurement for grasping a static object. Grip strength is measured in a similar way to that in the studies mentioned above.
  - In [230], a payload test is presented to obtain the grip strength. Furthermore, the contact pressure is determined by means of FEM software. This last method can give inaccurate solutions due to its dependence on the mathematical model of the material used.
  - Finally, in [266], a deep and detailed analysis is proposed for the measurement of parameters such as grabbing height, pressure and motion acceleration for a soft actuator. In this case, the tests are carried out not only in static but also in dynamic conditions, differentiating between vertical and horizontal positions. Variables such as size, weight and constituent material are also taken into account, as well as the actuation pressure and the grabbing height. Finally, one of the main contributions of this study is the introduction of the handling ratio, which offers a measurable performance comparison.
- Design of control systems: Most of the soft grippers that have been proposed use open loop control. All of these grippers also have a low-cost goal associated with them. However, this results in impractical soft grippers that are difficult to implement in the agricultural environment. Their lack of real control of the deformation and

compliance can affect the handling of fruits in different stages of maturity without damaging them. Thus, the study of new control algorithms that take into account the stiffness of the object to be manipulated is essential for the implementation of soft technology in robotic crop harvesting.

- Improvement of energy source systems: Depending on the type of soft actuator used, the energy support required for the gripper can be an electrical source, a pump or air compressor, or a chemical source. In any of these cases, more efficient equipment must be developed to support these technologies. In the literature, descriptions of energy solutions that drive soft-design systems are scarce. Typically, the proposed solutions are suitable for a laboratory or industrial environment, which is far from the unstructured environments of the agricultural sector. Therefore, the development of new energy solutions must be a compromise between functionality and energy consumption. In addition, the optimisation of the system is necessary not only to increase the autonomy of the overall robotic harvester, but also to simplify it, with the aim of enabling its implementation in current agricultural robotics.
- Economic analysis: Economic studies are often the necessary driving force to incentivize research and development in a given area. In the field of Agriculture 4.0, these economic studies can provide information on the most viable way to harvest different crops. However, at present, there is a need for economic research in this field. A study published in 2019 [267] highlights that only 18 investigations in the literature are dedicated to estimating the profitability of crop automation. This affects not only soft robotics but also other automation technologies, hindering its growth in this sector. However, although the lack of research in this direction is noteworthy, it is clear that in certain crops, such as tomatoes and peppers, the labour cost at harvest time represents 30% of the total cost [268,269]. Thus, mechanical harvesting by using soft grippers may be an economically beneficial alternative to manual harvesting [270].

Another challenge, such as the relatively slower actuation speed, is currently addressed in part with the use of pneumatic channels, also known as pneumatic networks [199] or low-pressure actuators [271]. Furthermore, hybrid gripper technology [272], which combines some advantages of soft and hard robotics, may be another potential solution, providing a soft grip and a structural strength capable of withstanding external agents or objects existing in unstructured environments.

5. Conclusions

Agriculture mechanization is still in a growth phase. Tasks such as sowing, weeding and harvesting are the spearhead of the development of Agriculture 4.0. Soft robotics is presented as a suitable technology for the manipulation of fruits and vegetables, which are often delicate and easy to mark or bruise and sometimes slippery. This field of robotics can pave the way for the automation of maintenance, harvesting and post-processing tasks in the agro-food industry.

In this article, a detailed review of the latest advancements in the design of novel soft grippers and end-effectors that could be used for robotic harvesting applications is presented. To that end, the current state of automatic picking tasks for several crops is analysed, identifying the main techniques that are commonly used based on the botanical characteristics of the fruits. Since direct harvesting methods based on twisting, bending, pulling, lifting or a combination of them involve the direct contact with the fruits, the introduction of soft grippers for automation of these techniques may represent a significant advantage, allowing a delicate manipulation that guarantees the integrity of fruits. Direct harvesting techniques with an actuation force on the peduncle are also candidates for the introduction of soft gripper technology, provided they are complemented by a suitable cutting tool.

Regarding the material used for the manufacturing of soft grippers, silicone elastomers are attracting strong interest due to their low cost and because they do not require the use of complex machinery or skilled labour. In addition, these compliant materials are also advantageous when considering the safety of interaction with biological products, making them appropriate candidates for agricultural applications.

It should also be noted that most of the proposed solutions are focused exclusively on the mechanical design, leaving the implementation of the control system for future work. Although diverse control strategies have been proposed for soft actuators, open-loop control is one of the most frequently used. The results of this study also underline that FEA grippers are one of the most promising technologies for robotic harvesting due to their ease of manufacture, compliance and output force. Nevertheless, it is important to note that the implementation of the different soft grippers in agriculture must be associated with the development and improvement in other components of the robotic system, such as artificial vision and navigation.

Furthermore, some of the main challenges that soft grippers still have to overcome to boost is definitive implementation are the design of control systems that consider the stiffness of the fruit to be harvested, the implementation of standardised manufacturing process that guarantee repeatability, the implementation of standard methodologies for the determination of the soft actuators characteristics, and the improvement of the energy sources.

On the other hand, it is important to take into account that the final quality required for fresh market fruits and fruits for the processing industry differs significantly. Soft grippers are presented as the most suitable solution for the harvesting of high value crops, so that mechanical damage is minimised and the products can reach their maximum value in the market. For fruits and vegetables intended for other industrial processing, such as the production of juices, jams and sauces, the economic feasibility of solutions based on soft grippers should be further evaluated. Therefore, future research should be directed to conducting economic studies that provide information on the most viable way to harvest different crops [267], and on the measures that should be taken to minimize losses [273]. Moreover, the study of methods to accurately assess the extent of surface and internal fruit damage caused by excessive external forces should also be addressed [274]. Finally, it would be convenient to carry out studies that analyse the life cycle of soft actuators made with silicone elastomers, to determine if their degradation may leave particles on the products manipulated.

Author Contributions: Conceptualization, E.N. and R.F.; methodology, E.N. and P.G.-d.-S.; validation, D.S. and M.A.; formal analysis E.N.; investigation, E.N.; writing—original draft preparation, E.N.; writing—review and editing R.F.; visualization, E.N. and D.S.; supervision R.F.; funding acquisition R.F. and P.G.-d.-S. All authors have read and agreed to the published version of the manuscript.

Funding: The research leading to these results has received funding from (i) FEDER/ Ministerio de Ciencia, Innovación y Universidades—Agencia Estatal de Investigación/Proyecto ROBOCROP (DPI2017-84253-C2-1-R), (ii) RoboCity2030-DIH-CM, Madrid Robotics Digital Innovation Hub, S2018/NMT-4331, funded by "Programas de Actividades I+D en la Comunidad de Madrid" and cofunded by Structural Funds of the EU, and (iii) CSIC under Grant 202050E099, Proyecto Intramural IAMC-ROBI (Inteligencia Artificial y Mecatrónica Cognitiva para la Manipulación Robótica Bimanual).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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Diaphragm-Type Pneumatic-Driven Soft Grippers for Precision Harvesting

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Abstract: Soft actuator technology and its role in robotic manipulation have been rapidly gaining ground. However, less attention has been given to the potential advantages of its application to the agricultural sector, where soft robotics may be a game changer due to its greater adaptability, lower cost and simplicity of manufacture. This article presents a new design approach for soft grippers based on modules that incorporate the concept of bellows and combine it with the versatility and replicability of a 3D printed structure. In this way, the modules can be freely configured to obtain grippers adaptable to crops of different diameters. Furthermore, the definition of a method to determine the soft grippers features is also presented, with the aim of serving as the basis for a future benchmarking study on soft actuators. The experimental tests carried out demonstrated the feasibility and capability of the end-effectors to manipulate various fruits, ensuring a sufficient contact area for the safe handling of the targets and avoiding damaging the products.

Keywords: harvesting; soft grippers; modular; benchmarking; robotic manipulation; precision agriculture

Citation: Navas, E.; Fernández, R.; Armada, M.; Gonzalez-de-Santos, P. Diaphragm-Type Pneumatic-Driven Soft Grippers for Precision Harvesting. *Agronomy* **2021**, *11*, 1727. https://doi.org/10.3390/agronomy11091727

Academic Editor: Baohua Zhang

Received: 5 July 2021
Accepted: 27 August 2021
Published: 29 August 2021

1. Introduction

Although robotics has traditionally been dominated by rigid link designs, during the last two decades this field has undergone a major paradigm shift thanks to the incorporation of soft technologies. The growing interest in the use of new materials has made soft robotics a well-defined research area that aims to improve the interaction between robots and unstructured environments and humans by providing variable adaptability and compliance [1].

In the literature, soft robotics can be found in diverse fields of application, such as medicine and rehabilitation [2,3], assistance [4–6], search and rescue [7,8] and agroforestry [9]. Applications that require manipulation in low-information environments have also been attracting much attention, with prototypes ranging from those attempting to replicate a human hand [10–13] to those that see nature as a source of inspiration for other types of grips [14–17]. Soft grippers can provide significant advantages when there is a need for actuation without precise positioning or without knowledge of the shape or material of the object to be grasped [18]. On the other hand, the ease of manufacture of this type of soft device is remarkable, without the need for heavy machines or machining skills. All these advantages have led many researchers to develop new soft designs, which have been on the rise in recent years and will continue to increase in the coming future.

Another emerging application area where soft robotics can have a significant impact is precision agriculture [19–21] and more specifically, automatic and selective crop harvesting [22,23]. In recent years, the agricultural sector has undergone a deep transformation to cope with the growing demand for food [24–26], introducing advances on machine vision and detection systems [27–30], decision-making architectures [31,32] and autonomous navigation [33]. However, less attention has been paid to improve the dexterous manipulation and the grasping capabilities for selective harvesting. The variability of agri-food products and the delicacy with which it is necessary to handle them to avoid bruising make soft robotics especially suitable for this purpose. However, it is important that the proposal for new soft grippers is linked to the fulfillment of certain performance requirements, and therefore, methodologies that enable a comparative evaluation of them should also be envisaged. From an agricultural point of view, these methodologies can include different evaluation criteria, such as the capacity to grasp different types of fruits, grippers size, lifting ratio, power consumption, scalability, response time, surface conditions or technology readiness level (TRL) [34–37]. Otherwise, the literature will tend to be filled with novel but impractical designs.

For this reason, this article aimed to present a new design approach for soft grippers based on modules that combine the use of a pneumatic-driven soft diaphragm actuator and a 3D printed structure. The main advantage of the pneumatic-driven diaphragm actuators over other soft actuators is the ease of manufacture. On the other hand, the 3D printed structure establishes a series of constraints on the degrees of freedom (DoFs) of the soft actuator, which facilitates the control of the gripper. The proposed modules can then be freely configured to obtain grippers adaptable to products of different diameters. Another contribution of this article is to propose a series of easy-to-implement measurement tests to characterize all types of soft diaphragm actuators so that they can serve as the basis for a benchmarking analysis.

The remainder of the article is organized as follows. Section 2 details the steps followed for the design and manufacturing of the modular soft grippers, while Section 3 presents the control system implemented for the pneumatic-driven diaphragm actuators. A proposal for the measurement of the characteristics of soft actuators is described in Section 4. Section 5 discusses the main results obtained from the experimental evaluation of the proposed soft grippers. Finally, Section 6 summarizes major conclusions.

2. Design and Manufacturing Approach

To identify the essential requirements that a soft gripper should meet to be fully operational, agricultural processes and, particularly, harvesting tasks have been reviewed [19,36,38]. One of the requirements identified for increasing the profitability of harvesting machinery is the capability to handle different types of crops. For this reason, the goal was to achieve a fully adaptable and modular design concept. The engineered module can be assembled in a variety of ways to obtain a large number of diameters and lengths. This feature allows a gripper designed under this concept to be recombined to adapt it to the harvesting of different types of fruits. Another requirement in this field is simplicity, which translates into interchangeable and easy-to-fix systems. That is why the design approach is based on single modules, which can work independently and are easy to manufacture. Other requirements are more related to the preservation of the quality standards of the fruit than the harvesting process itself, such as avoiding damage to the fruit and the use of non-hazardous materials and designs that prevent the spread of diseases and pests. This important aspect has been ignored in the design of new grippers, whose main disadvantages were the use of materials that could damage the fruits and the complex designs that made cleaning difficult. Hence, the need to use a combination of soft robotics technology with hygienic designs and variable compliance prevents damage to the fruit and the crop. Environmental friendliness, durability and robustness are also important requirements for agricultural and industrial applications. For this reason, the selection of the materials for the manufacturing process has been carefully made to meet these requirements. Finally, the modular soft gripper is designed to be used as the end effector of a robotic manipulator [39,40], being able to perform almost all the harvesting movements required, also known in the literature as picking patterns [20–23]. These picking patterns are in some cases a combination of simple movements, which can be grouped into twisting, pulling, lifting and bending.

In the following, the type of soft material selected and how the material is modeled to achieve the proposed pneumatic-driven soft diaphragm actuators are described. In addition, the strengths of the design, which are based on its geometry and modularity, are also explained. Lastly, the manufacture and assembly of the soft grippers modules are presented.

2.1. Materials

Several materials, such as Ecoflex [41,42], Dragon Skin [12,43–45] or Elastosil M4601 [42,46–48] are commonly used for soft robotics. Although all of them have been demonstrated to be a valuable option in the manufacturing process due to their ultra-smooth features, it is difficult to know their exact chemical composition since their main applications refer to the manufacture of objects outside the scientific field. Nevertheless, polydimethylsiloxane (PDMS), commercially known as Sylgard 184, has been used in many research applications [41,44,49–52] and allows not only the determination of its mechanical properties, such as high elasticity [53] and thermosetting [49], but also the mathematical modeling of its behavior with great precision by means of a finite element method (FEM) analysis. Another advantage that this material shares with some of the commonly used materials in soft robotics is the ability to cure at room temperature, which is key to simplifying the soft gripper modules' manufacturing process and reducing its cost. However, if required, this process could be accelerated in their industrial manufacture through the use of ovens, which could reduce the curing times from 24 h to 10 min at 150 ºC [53]. In addition, PDMS is declared in their safety data sheet as a non-hazardous substance, which guarantees safe interaction with biological products and makes it suitable for agricultural applications. Lastly, PDMS is relatively resistant to fatigue and does not age readily. This means that the PDMS actuator is very suitable for agricultural and industrial applications. Furthermore, PDMS composites that dissipate little energy during normal the operation of cyclic loads (low hysteresis), but dissipate much energy to resist rupture (high toughness), and survive prolonged cyclic loads (fatigue resistant) have recently been proposed [54].

2.2. Soft Design

Regarding the geometric design, the grippers proposed in this article consist of single-channel diaphragm-type actuators. One of the advantages of this kind of geometric design is the simplicity of the process required for its manufacture, which can be divided into two main steps. The first step is the filling of the molds, the diaphragm and the cover, which facilitates molding in comparison to other multiple-channel actuators. The second step is the fixing of these two parts, in which the same material from other parts is used. Another advantage of this kind of soft actuator is the ease of its control. This benefit is because soft diaphragm actuators are designed to only move on one axis, while motion on other axes is considered negligible. Thus, it directly affects the control of the DoFs of the gripper.

The proposed soft diaphragm is also characterized by using the bellows concept, which differs from other geometries in its inflation behavior. In other geometries, such as those based on cylinders, cubes or spheres, the inflation behavior tends not only to produce a forward elongation but also to waste forces on the side walls. This effect tends to reduce the forward advance in both cylindrical and cubic geometries due to radial expansion. A special case is the spherical geometry, which exhibits better inflation behavior than the others, although it has the great disadvantage of requiring intricate molding for its manufacturing process. However, the bellows-based geometry, particularly the proposed bellows-cylinder geometry, can be studied as a combination of cylindrical and spherical shapes. This approach partially solves the problem described because the forces applied by radial inflation are also used for forward elongation, extending almost the entire body of the gripper in that direction. The difference between these geometries can be observed in Figure 1.

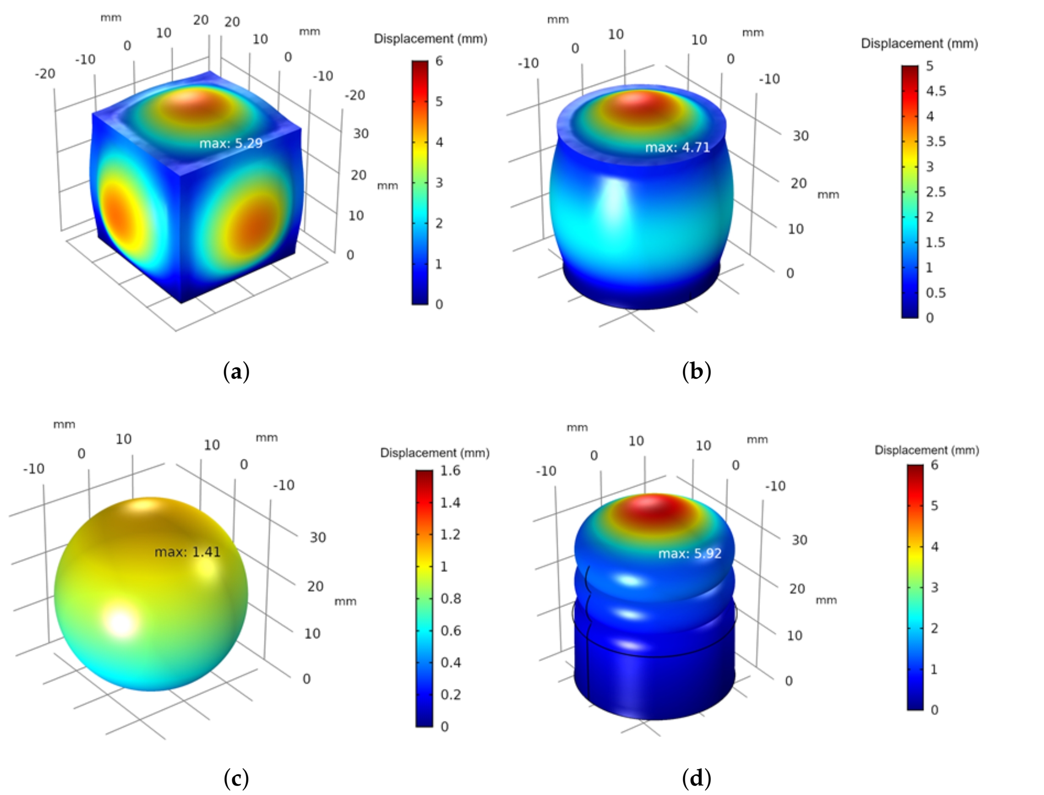


Figure 1. An example of the inflation behavior of 30 mm geometries with 3 mm walls under an internal pressure of 50 kPa. (**a**) Cubic geometry. (**b**) Cylindrical geometry. (**c**) Spherical geometry. (**d**) Bellows-based geometry. As can be observed in (**a**) and (**b**), part of the air flow is wasted on the expansion of the walls to different degrees depending on the geometries, which does not contribute to the forward displacement. This method does not seriously affect sphere-based geometry, but due to manufacturing criteria, bellows-based geometry is an important option to consider.

With the purpose of designing suitable soft grippers for medium- to large-sized fruits, two types of soft diaphragms are considered: one with smaller bellows than the other but both with the same diameter. To determine their inflation behavior, the two designs were modeled in COMSOL Multiphysics® using an FEM (see Figure 2). For this, PDMS was modeled as a hyperelastic material. In the literature, several mathematical models can be found to describe the behavior of this type of soft material. However, the second-order Ogden model, compared with Mooney–Rivlin's or Neo–Hookean's models, more accurately represents its response [55]. Furthermore, due to the inflation pressure, the soft diaphragm will be under equibiaxial tension. This type of tension in hyperelastic materials, which is the case for the PDMS material, was theorized by Ogden [56]. This method involves elastic solids with a strain–energy function and isotropic behavior relative to the stress-free ground state. It also assumes that the solid is incompressible. Thus, it can be formulated as follows:

$$\sigma_i = \mu_r a_i^{\alpha_r} - p, \tag{1}$$

where σ_i, $i \in \{1,2,3\}$, represents the principal Cauchy stresses (σ_1,σ_2,σ_3), the parameters μ_r and α_r are experimentally obtained constants, a_i represents the stretches (a_1,a_2,a_3) and p is an arbitrary hydrostatic pressure introduced because of the incompressibility constraint. Due to the equibiaxial tension, two out of three principal stresses are equal, and the third one is zero:

$$\sigma_2 = \sigma_3 = \sigma, \sigma_1 = 0 \quad (2)$$

Moreover, the stretches can be written as follows:

$$a_2 = a_3 = a, \quad (3)$$

and due to the incompressibility assumption, it can be considered that $a_1 = a^{-2}$. The substitution of the aforementioned into (1) is as follows:

$$\sigma_i = \mu_r a^{\alpha_r} - p, 0 = \mu_r a^{\alpha_r - 2} - p. \quad (4)$$

The elimination of p yields:

$$\sigma_i = \mu_r (a^{\alpha_r} - a^{\alpha_r - 2}). \quad (5)$$

Finally, Equation (5) is inserted into the FEM software together with the values of μ, α and bulk modulus, which were obtained from [55]. The PDMS mix ratio used was a 15-part base elastomer and a one-part curing agent. The data obtained from the FEM software were shown in Figure 2 for the soft actuators, and in Figure 3 for a gripper with a hexagonal configuration. All cases were analyzed under an air pressure of 50 kPa.

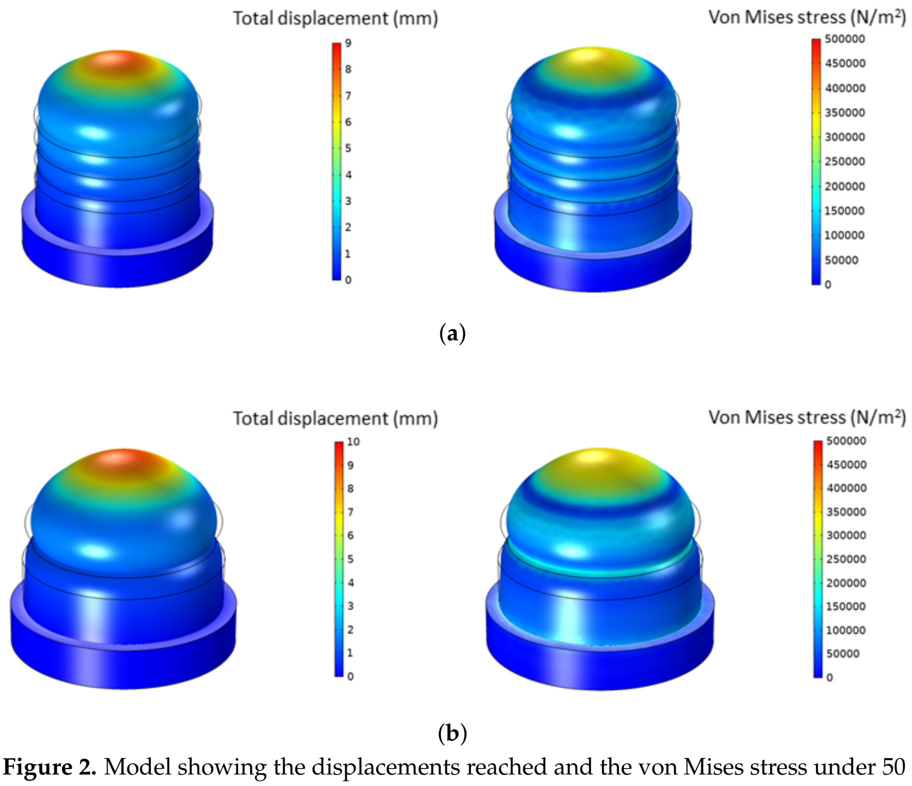
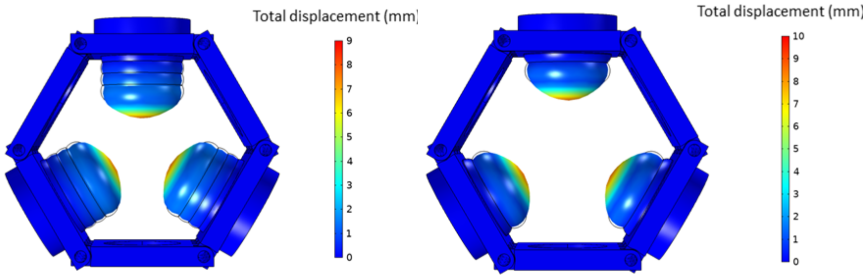


Figure 2. Model showing the displacements reached and the von Mises stress under 50 kPa pressure: (**a**) 4-bellows soft actuator; and (**b**) 2-bellows soft actuator.



(**a**) (**b**)

Figure 3. Model showing the displacements reached on the actuators of the soft gripper with hexagonal configuration under constant pressure: (**a**) 4-bellows soft actuator; (**b**) 2-bellows soft actuator.

As can be seen in the figures above, the FEM analysis yields a larger displacement for the 2-bellows actuator than for the 4-bellows actuator—10 and 9 mm, respectively. Regarding the stresses, both actuators have a tensile strength of approximately 6.7 MPa, which is the value indicated by the manufacturer.

2.3. Design of the Rigid Structure

One of the largest challenges in agricultural automation is to design a gripper that can be multipurpose, i.e., it can harvest different types of fruits with minimal modifications. Referring to soft robots, and more particularly to soft grippers, the aforementioned task becomes even more intricate because this type of robotics requires a prior design of the gripper, which obviously limits its scope. In the literature, a few research studies that explore the concepts of modularity and scalability can be found. For example, the soft gripper described in [49] presents a modular design, but it is only conceived for small fruits and edible fungi, with simplified computational modeling and relatively minor displacement, at the same inlet pressure, than the proposed soft actuator.

This article aimed to go one step further and advance in modularity and scalability to achieve a quasi-universal gripper concept adaptable to each fruit. To this end, a 3D-printed module is designed and made of polylactic acid (PLA), which is one of the best-known synthetic biodegradable polymers, with good mechanical strength and low toxicity. Its faster degradation makes it an environmentally friendly option compared to traditional plastics [57]. As higher toughness is desired for durable applications, research progress on toughening PLA based on plasticization, copolymerization, and melt blending with different tough polymers, rubbers and thermoplastic elastomers can be found in several recent review articles [58–64]. In addition, many PLA formulations with improved toughness are available in the market for durable applications, as summarized in [65]. The proposed PLA structure has the following advantages. First, the module is independent of the gripper; i.e., it can work on its own and make the gripper adaptable to a wide variety of tasks. Second, the gripper is interchangeable, which makes it deeply reliable. This novel feature is an advantage over other soft grippers, which are usually formed in a single body configuration. Therefore, if any failure occurs in these devices, it is necessary to change the entire gripper. Third, this module is completely replicable: as both the rigid components and the mold of the soft components can be easily 3D printed, the materials used for their manufacture are fully available and inexpensive, and there is no need for the postprocessing of the parts. The main parts of the soft gripper module can be seen in Figure 4.

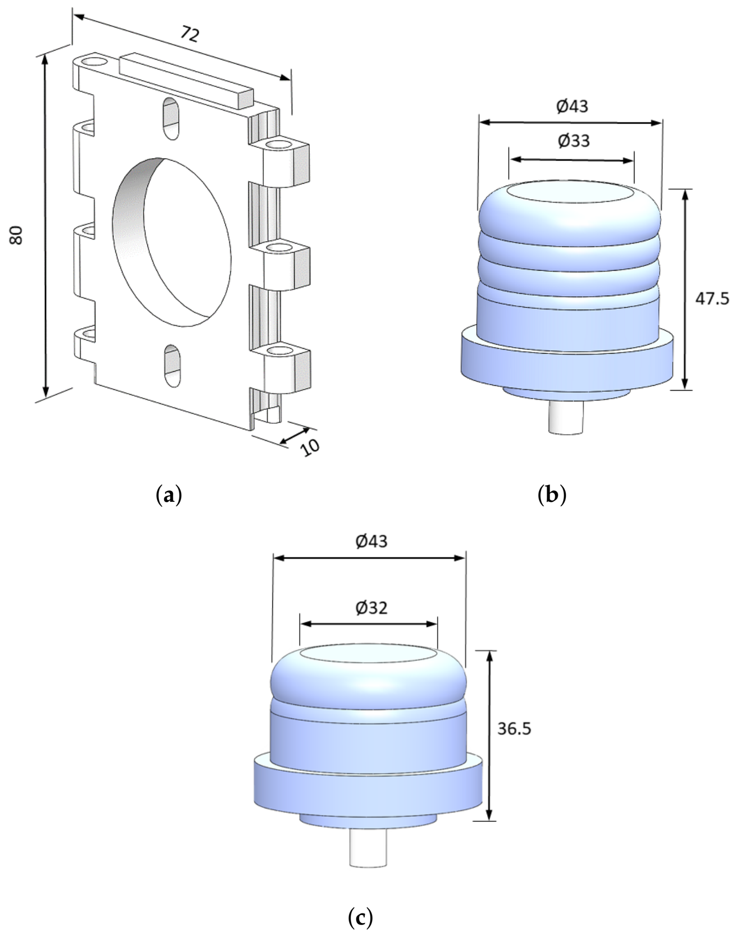
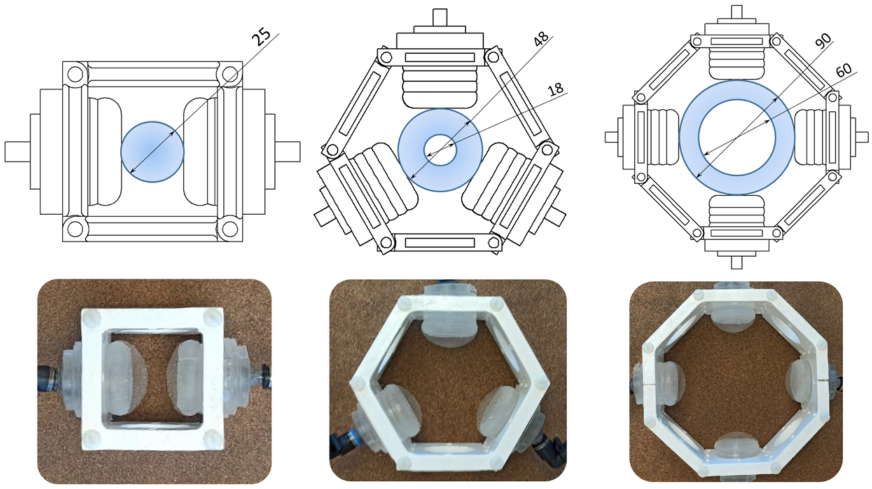


Figure 4. Main parts of a single soft gripper module with the two types of actuators: (**a**) rigid structure; (**b**) 4-bellows actuator; and (**c**) 2-bellows actuators. All dimensions are in mm.

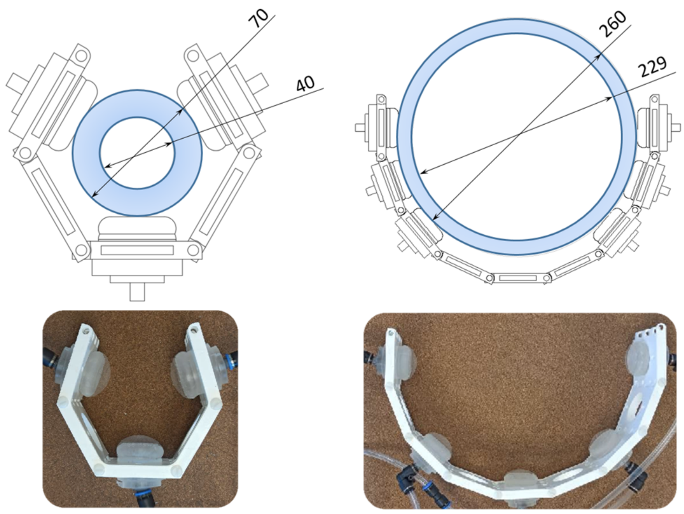
Finally, the proposed design concept allows the soft grippers to be configured with diverse geometries, which makes them fully adaptable not only to different types of fruits and vegetables but also to different manipulation methods. Figure 5 shows several examples of soft grippers obtained from different configurations of the proposed modules.

In Figure 5a, several closed gripper configurations are presented. These close configurations are suitable when multiple points of contact are needed. Thus, these grippers offer better control of the object and are capable of performing almost all the required harvesting movements or picking patterns. On the other hand, the proposed modules can also be configured in open configuration, as shown in Figure 5b. Unlike close chain configurations, which are intended to harvest fruits that are always hanging vertically, open chain configurations are indicated for medium-to-large sized fruits that usually lay on the ground, such as watermelons, melons or pumpkins.

It is also worth mentioning that the interaction between the soft components and the rigid structure was studied by FEM, confirming that no relevant load values are presented in the structure.



(**a**)



(**b**)

Figure 5. Examples of soft grippers obtained from the proposed design approach: (**a**) closed gripper configurations; and (**b**) open gripper configurations.

2.4. Manufacturing and Assembly

For the manufacture of the gripper actuators, a molding process widely used and discussed in the soft robotics literature was followed [66–68]. A graphical summary of the molding process is shown in Figure 6.

The process is described as follows: (i) The mold is printed by a 3D printer; in this case, the plastic used was PLA; (ii) once the mold is mounted (Figure 6a), PDMS is poured over it (Figure 6b); (iii) then, the two molds with PDMS are placed in a vacuum chamber (Figure 6c) to eliminate internal bubbles. After this vacuum process, the entire assembly is left to cure at room temperature for one to two days, depending on the environmental conditions; (iv) next, the demolding process is carried out (Figure 6d), gluing the two resulting parts with PDMS (Figure 6e); and (v) finally, after waiting one day, the soft actuator is fully operational (Figure 6f). In some cases, a silicone sealant, Loctite 5699, is applied to prevent air leakage between the polyurethane (PUR) pipe and the PDMS of the soft actuator.

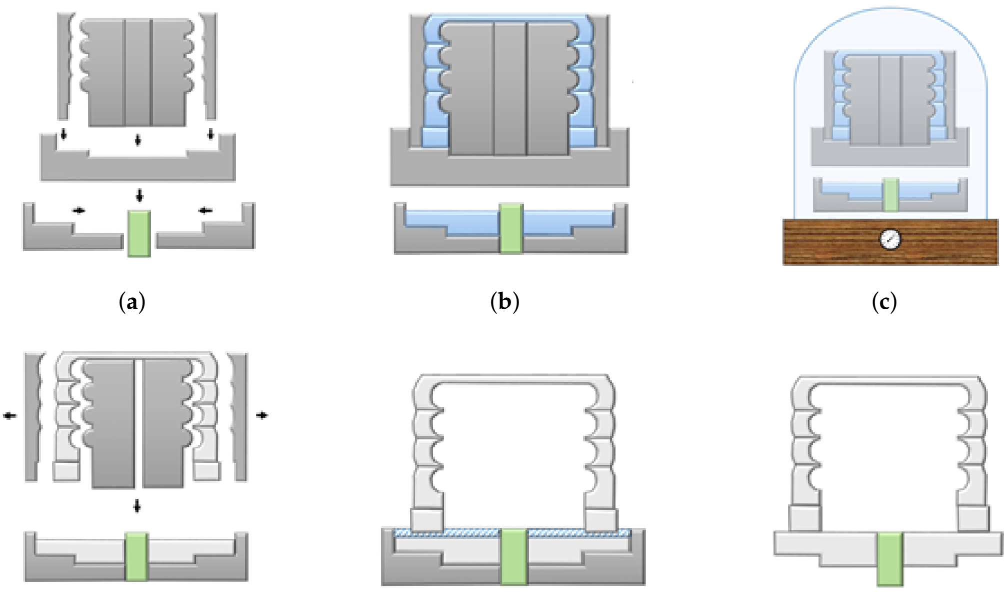
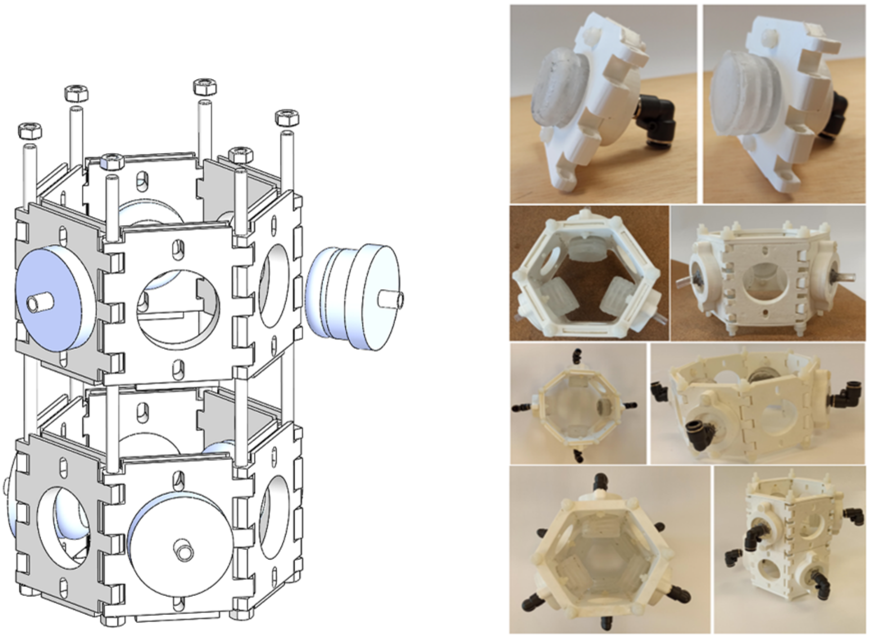

(a) (b) (c) (d) (e) (f)

Figure 6. Molding process. The PLA mold is shown in dark gray, the fresh PDMS soft gripper is represented in blue, the precured PDMS is in striped blue, the cured PDMS soft actuator is displayed in light gray and the PUR pipe is in green. (**a**) Mold assembly. (**b**) Pouring of the PDMS on the mold. (**c**) Vacuum process. (**d**) Demolding. (**e**) Gluing with PDMS of the two resulting parts. (**f**) Fully assembled soft actuator.

Although the ease of manufacture of the proposed approach is remarkable, it is worth mentioning the need for repeatability and accuracy studies that research how to mitigate the common effects that appear in soft actuators, such as delamination or interstitial bubbles that can be the result of faulty manufacturing. To solve these problems, several solutions have been proposed, such as the use of vacuum chambers [47,69–71], for which positive results have been reported. However, it is impossible to find in the literature a method where, for example, variables such as pressure or time are controlled as a function of volume to ensure the repeatability of the process. Procedures based on the 3D printing of soft materials, as well as lost wax manufacturing, may become interesting options in the future, given their greater possibilities for achieving repeatability and accuracy during the manufacturing process.

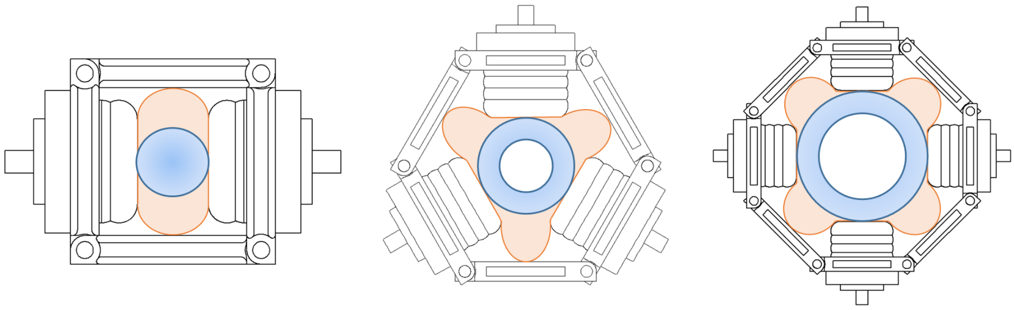
Once the soft actuator is manufactured and the rigid components are printed with a 10% infill, the soft part is inserted into the hole of the rigid structure and attached to it via a screwed clip. With all this, the standalone module is fully assembled. To mount the modules for different gripper configurations, nylon threaded rods, washers and nuts can be used (see Figure 7a). The preference for the use of nylon fasteners is due to their low-density property, which is useful for lightweight robotic manipulators. However, it can be replaced by steel if the application requires it. A fully assembled module and some examples of soft grippers' configurations are shown in Figure 7b.

One of the main advantages of the proposed design approach is that it allows the rigid structures of the modules to be assembled following various geometries that facilitate the positioning of the soft actuators to ensure sufficient contact areas that provide stable grips for different types of fruits. Figure 8 shows that due to the proposed design, even other grips, different from the ideal one (i.e., one in which the fruit is centered at the midpoint of the gripper) are equally feasible. If the object (represented by the blue areas in Figure 8) and the closed configuration gripper are concentric, all the actuators will be involved in the grasping. On the contrary, if the target is located in other areas, such as in the orange areas, the grasping could be carried out by means of only two actuators.

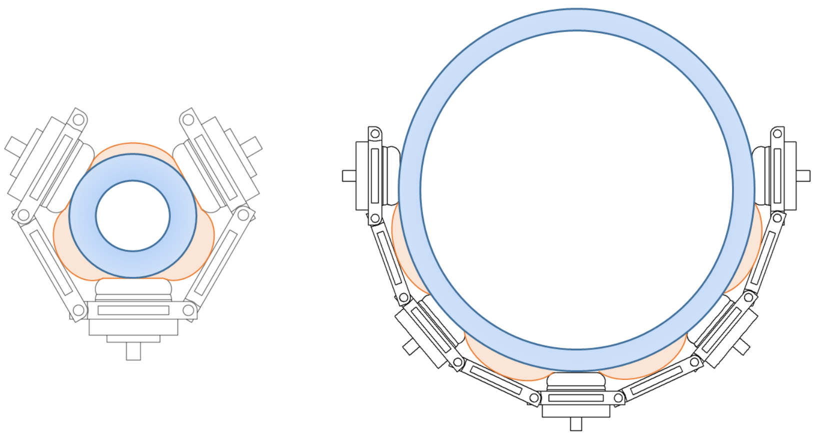


(**a**) (**b**)

Figure 7. Modules, assembly process and various configurations. (**a**) Assembly of the modules. (**b**) Fully assembled modules and several soft grippers configurations.



(**a**)



(**b**)

Figure 8. Feasible grip areas. (**a**) Closed gripper configurations. (**b**) Open gripper configurations.

As can be seen in Figure 8a, the closed configurations offer a larger grasping area than open configurations, as shown in Figure 8b, since the object can even be placed between the rigid part, which acts as a fulcrum, and the soft actuators. Furthermore, it could be derived that the grasping points of an object in closed configurations will be from 2 to n, where n is the number of soft actuators placed on the gripper, which depends on the fruit. On the other hand, in open configuration, it is necessary to adapt the pressure of each actuator independently, since generally the actuators at the ends support the load of the target, while those on the inside help to prevent its rotation during the grasping. Another important advantage of the proposed design approach is that the 3D printed structure establishes a series of constraints on the DOFs of the soft actuator, which facilitates the control of the grippers.

3. Control System

Deformability and compliance are some of the main characteristics of soft robotics, which translate into a large intrinsic number of DoFs. This obviously affects the control system in terms of complexity. However, such DoFs, given the elastic behavior of the material, offer the possibility of performing movements such as bending, twisting, stretching, compression, and buckling wrinkles [72]. Typically, the soft control barrier is compensated by a high level of sensorization of the systems. Other authors [73] have used real-time FEMs to control soft elastomer robots. This approach can be a good option, as long as a good mathematical model of the material is used, which is complicated for certain soft materials.

On the other hand, authors such as [74] used rigid components embedded in soft actuators. This hybrid concept was developed in recent decades as a combination of soft robotics and rigid robotics [74,75]. The gripper concept proposed in this article can be studied as a particular case of a hybrid grippers, not only because there is a physical combination between these two technologies but also because the rigid structure establishes a series of constraints on the DoFs of the soft actuator, which facilitates the control of the gripper. The modular soft grippers are then controlled by a LabView interface, from which the pneumatic electrovalves can be activated and their pressure can be manually adjusted.

Furthermore, as can be seen in Figure 9, the soft actuators can operate automatically via proportional–integral–derivative (PID) control, where the feedback is the internal pressure measurement provided by the pressure sensor located at the inlet of the soft actuator. This controller reads the pressure change with a frequency of 50 Hz, and if its rate of change is greater than that caused by the electropneumatic regulator, it means that the soft actuator is in contact with the object due to the decrease in the volume of the gripper and the increase in the actuator internal pressure (see the red point in Figure 9). This makes it possible to monitor the contact of the soft actuator without sensors embedded in it.

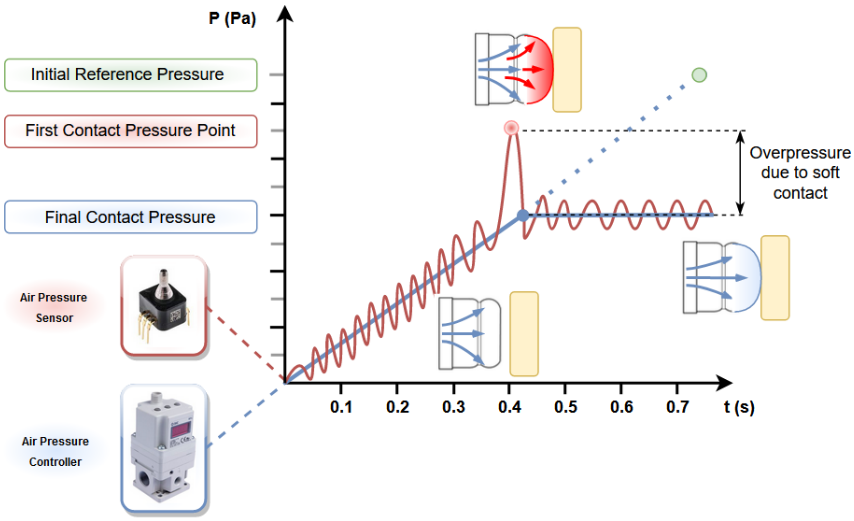
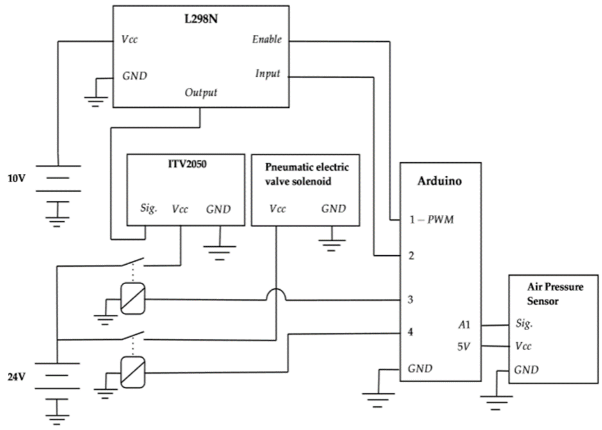


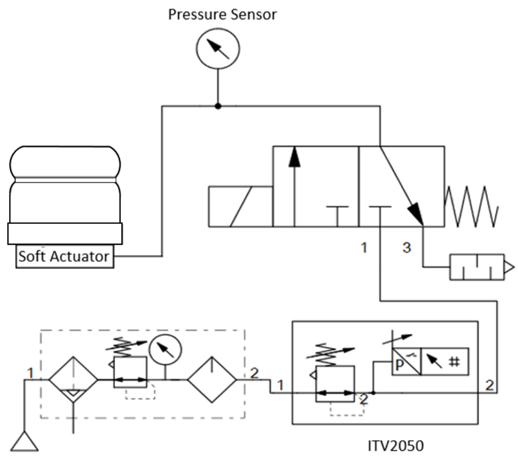
Figure 9. Diagram of the control method for the soft actuator without embedded sensors.

Electronic and Pneumatic System

To drive the modular soft grippers, sensor and control elements are required to ensure the accuracy of the air pressure measurement and a constant airflow. In Figure 10, the electronic and pneumatic systems are schematically described.



(**a**)



(**b**)

Figure 10. Electric and pneumatic systems. (**a**) Electric scheme of the modular soft grippers. (**b**) Pneumatic scheme.

Figure 10a shows that the core of the electronic system is an Arduino, particularly a Mega 2560, which controls the different elements by means of a LabVIEW interface. Table 1 shows the features of the air pressure regulator used. Furthermore, Figure 10b displays the pneumatic system, which consists of (i) an Abart Start O15 air compressor with a power of six liters and 1.1 KW; (ii) pneumatic air treatment equipment; (iii) a pneumatic solenoid valve; (iv) an SMC ITV2050 electropneumatic regulator; and (v) a Honeywell 40PC air pressure sensor (measurement range: 0–100 kPa, output voltage: 0.5–4.5 V, measurement precision: ±0.4%).

Table 1. Electropneumatic Regulator ITV2050 specifications.

Characteristic	Value
Pressure range	0.005–0.9 Mpa
Max. supply pressure	1.0 MPa
Power consumption	4 W
Max. flow rate	1500 L/min
Input signal	0–10 Vdc
Mass	0.350 kg
Linearity	±1%
Hysteresis	0.5%
Repeatability	±0.5%
Response time	0.1 s

4. Determination of Soft Actuators Features

One of the main gaps that has not yet been addressed in soft actuators is the definition of a method to determine their characteristics. However, it is clear that there is a need for a reliable method that can quantify the soft actuator features to facilitate a comparative study between the different models and establish not only different categories according to their capabilities but also an index of improvement in the soft technology.

One of the most important characteristics of a soft gripper is the contact force that it can exert on an object and its control, since its ability to grasp more or less sensitive objects depends on this. The research studies presented in [12,48,49] use different types of contact force measurements. In [49], the contact pressure (P_c) is found by means of FEM software, and the contact area (A_c) is measured by the "fingerprint" of the soft gripper on a Styrofoam surface. The contact force (F_c) is found by the well-known Equation:

$$F_c = P_c \cdot A_c \tag{6}$$

Although it is a nice approximation, the method used to find the contact pressure is not very reliable because it depends on the mathematical model implemented in the FEM software, the Mooney–Rivling model, which describes the behavior of PDMS with low accuracy [55].

In [12], the measurement process is divided into three tests. In two of them, the procedure is a trial and error, whereas in the last one, the Takei Physical Fitness Test is performed. However, this test is only suitable for humanoid hands, so it is not applicable for diaphragm-type grippers. Finally, another interesting measurement process can be found in [48], where a pressure map is used. In the latter case, the pressure map is wrapped in a tube with a radius adjusted to an appropriate curve for the soft gripper.

Thus, there is no standardized tests for measuring soft gripper properties. For this reason, this article aims to propose a measurement process using two measuring devices by which soft grippers can be objectively analyzed, particularly those of the soft diaphragm type.

Figure 11 shows the two devices used in the proposed processes to measure the various features of soft actuators, which are the relation between the forward displacement, contact force, contact area, contact pressure in the middle of the soft actuator and the inlet air pressure.

The first parameter, the forward displacement, is measured in a press by means of a dial gauge with an accuracy of 0.01 mm, the scheme of which can be seen in Figure 11a. The other parameters, which are the contact force, the contact area and the contact pressure, are measured using a press, such as the one outlined in Figure 11b, with an Entran ELW-D1-500N compression load cell, whose technical specifications are listed in Table 2. This load cell is selected because its load reading range is within the expected values for this type of pneumatic actuator.

Table 2. Main technical specifications of the compression load cells.

Characteristic	Value
Nonlinearity	±1%
Hysteresis	±1%
Thermal Zero Shift	±2.5 mV/50 °C
Thermal Sensitivity	±2.5%/50 °C
Deflection at "FS"	<0.013 mm nom.
Operating Temperature	(−40 to 120) °C
Thickness	3.81 mm
Diameter	25.4 mm

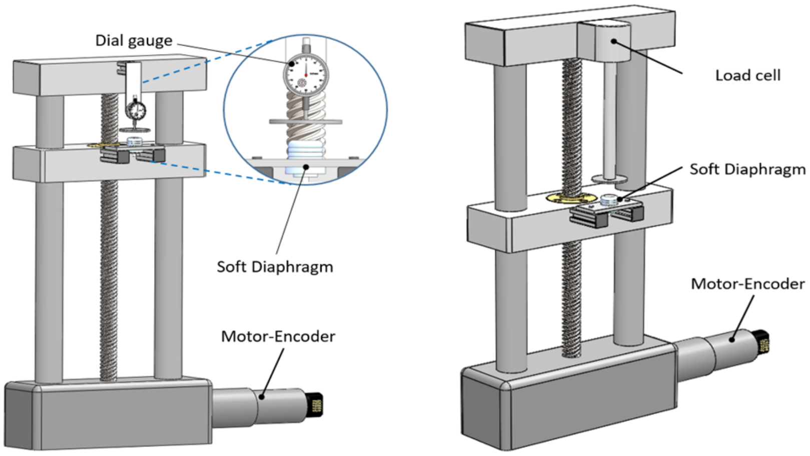


Figure 11. Devices for measuring the soft actuators features. (**a**) Assembly of the dial gauge to measure the displacements in the soft diaphragm. (**b**) Assembly of the load cell to measure the contact force in the soft diaphragm.

To proceed with the measurement process, it is necessary to take into account some basic knowledge of geometry, which is better explained with the graphic description shown in Figure 12.

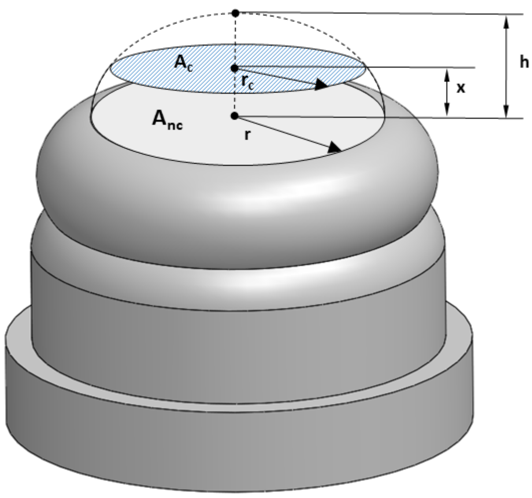


Figure 12. Graphic description of the contact area and the non-contact area, where r is the actual radius of the soft actuator, r_c is the radius of the contact area, x is the distance between the actuator and the object and h is the relative longitudinal distance between the soft actuator at rest and its maximum displacement at a given pressure.

Therefore, taking into account the diverse cases, the contact area can be stated as follows:

$$A_c(x) = \begin{cases} \pi r^2, & x = 0 \\ 0, & x > 0; h < x \\ \pi r_c^2, & x > 0; h > x \end{cases} \quad (7)$$

where r_c can be expressed through various geometric relationships as: $r^2 - (x + r - h)^2$.

Therefore, the contact area will be accurate for each pressure and displacement. The only assumption made was that the contact area was circular, which has been experimentally determined to be valid for this actuator geometry.

Once the contact area was obtained and the contact force was measured, the contact pressure in the middle of the soft actuator can be obtained by the contact pressure distribution formulated by [76], here presented in Equation (8):

$$p(r_v) = C_k \frac{N}{\pi r_c^2} \left[1 - \left(\frac{r_v}{r_c} \right)^k \right]^{\frac{1}{k}} \quad (8)$$

where N is the normal force, r_c is the radius of the contact explained above, r_v is the variable radius, $0 \leq r_v \leq r_c$, k determines the shape of the pressure profile, and C_k is a coefficient that adjusts for the profile of the pressure distribution over the contact area to satisfy the equilibrium condition.

In [77], the author shows that for soft contact, the value of k is approximately 1.8. With that, the value of C_k can be calculated as follows:

$$C_k = \frac{3}{2} \frac{k\Gamma\left(\frac{3}{k}\right)}{\Gamma\left(\frac{1}{k}\right)\Gamma\left(\frac{2}{k}\right)} \quad (9)$$

Since p_0, which is the pressure in the middle of the actuator, can be a target value for evaluating a soft actuator, r_v is substituted by 0 to obtain the contact pressure in the middle of the soft actuator, leaving Equation (8) as

$$p_0 = p(0) = C_k \frac{N}{\pi r_c^2} \quad (10)$$

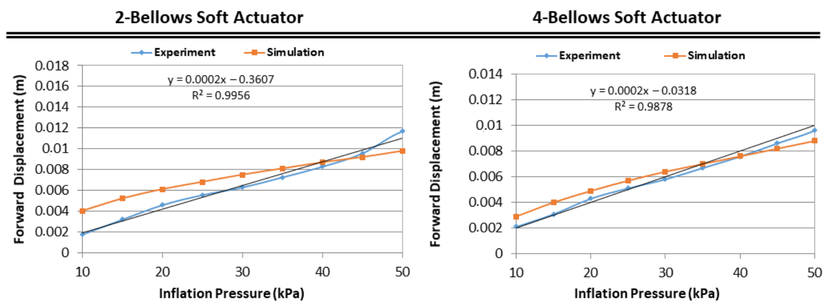
With all of the above, the proposed measurement process has been described in order to characterize the soft actuators in terms of forward displacement, contact force, contact area and contact pressure.

5. Evaluation

In order to validate the feasibility of the proposed approach and evaluate its performance, several experimental tests were carried out.

First, two types of soft actuators were characterized following the method described in Section 4, one with four small bellows and the other with two larger bellows, with the aim of comparing their behavior. The graphs in Figure 13 show the experimental results obtained during these tests.

As can be observed in Figure 13a, the two soft actuators exhibit an almost linear behavior and a similar performance to that obtained in the FEM simulations. In addition, it has been experimentally proven that the 2-bellow actuators can reach more force than the 4-bellow actuators, as shown in Figure 13b. Thus, it can be concluded that the thicker the actuator walls are, the more force they can exert due to the input pressure that this actuator can handle. However, if the walls are thinner, then the reliability of the actuator is reduced, even though the displacements may increase. Therefore, the wall thickness should be a variable in the actuator design. This thickness might be different depending on the parts of the actuator in order to take advantage of the chosen geometry. Figure 13c shows how the area increases almost linearly when the object is separated from the actuator by a certain distance. This behavior is because the contact surface is flat, with an area larger than the actuator head. In Figure 13d, the results of the two previous graphs are displayed, where it can be observed that the contact pressure will remain constant due to the conditions of the experiment. During the tests, several behaviors are also observed among actuators of the same type. This finding is due to the manufacturing process, which causes the existence of some bubbles in the actuators. Finally, it can also be deduced from the different experiments carried out that for the same actuator bellows diameter, short bellows tend to behave as cylindrical geometries, which shortens their displacement, while high bellows improve their displacement due to their spherical-like behavior.



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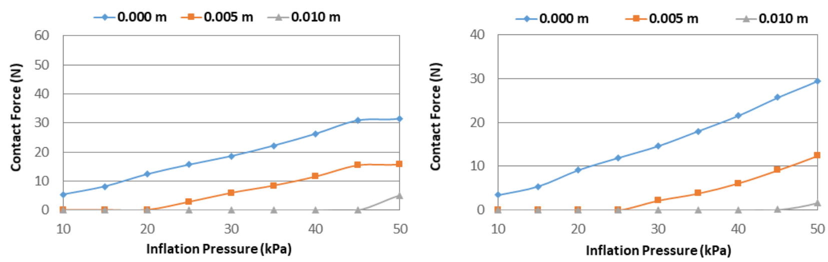

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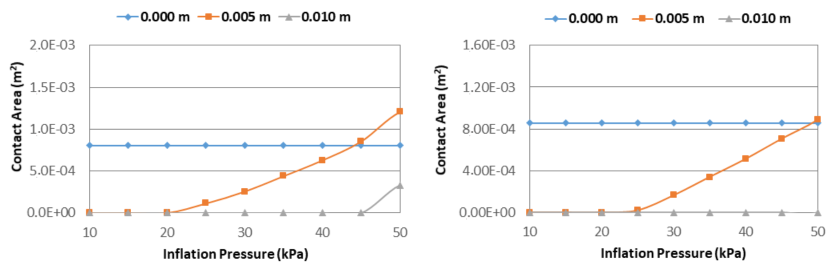
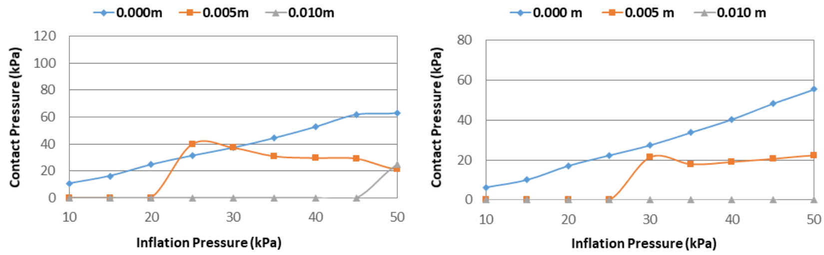


(**c**)

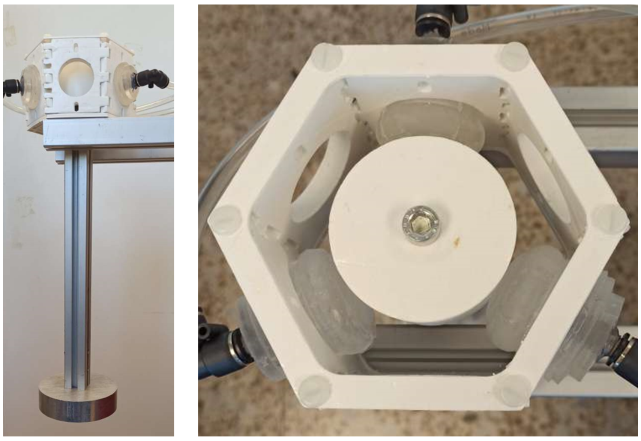
Figure 13. *Cont*.



(**d**)

Figure 13. Experimental characterization of soft actuators. (**a**) Experimental measurement of the forward displacement as a function of the inflation pressure. (**b**) Measurement of the contact force as a function of the inflation pressure. (**c**) Relationship between the contact area and the inflation pressure. (**d**) Relationship between the contact pressure in the middle of the soft actuator and the inflation pressure. Graphic legends show the distance between the soft actuator and the object.

Then, to evaluate the gripping force of the modular soft gripper, a grasping force test [68] was conducted. This test, also known in the literature as a slip payload test [49] or pull-off force test [67], was performed by using a system designed to both generate a downward force and measure the slip payload. The system setup can be seen in Figure 14.



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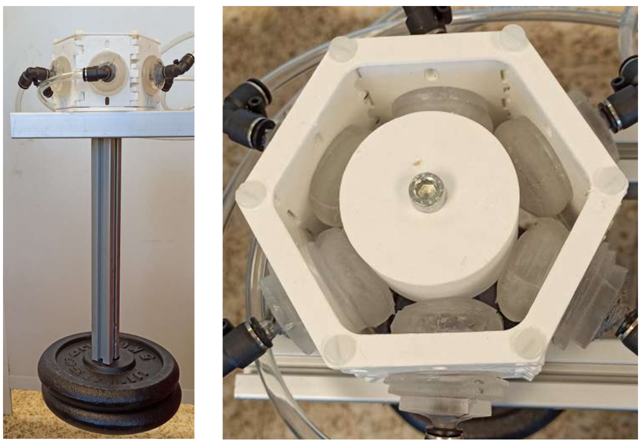


(**b**)

Figure 14. Slip test setup in a hexagonal configuration: (**a**) Soft gripper with three soft actuators; (**b**) Soft gripper with six soft actuators.

In this slip payload test, a constant pressure of 50 kPa is used, and load is added until either slippage occurs due to the vertical force exceeding the frictional forces of the gripper, or until the failure or cracking of the soft actuator occurs. The test result is a limit load of 4.75 kg and 10 kg for a hexagonal configuration of three and six soft actuators, respectively. This limit load is sufficient to grasp most of the fruits on the market and does not limit the load that a normal robotic manipulator can lift. This test also shows the modularity and scalability of the proposed approach, considerably increasing the load capacity of the gripper, without significantly influencing its structural design.

Several tests were also carried out to evaluate the grasping performance, as well as the possible damages produced in real harvested fruits. To that end, a hexagonal configuration gripper endowed with three soft actuators was mounted on one of the Kinova Mico manipulators [78] that make up the ROBOCROP dual-arm robot [79,80] (see Figure 15a). The gripper was tested with 20 artificial aubergines and 25 pieces of real fruits (5 pieces of sweet peppers, pears, lemons, tomatoes and kiwis, respectively) that had reached a stage of sufficient maturity to be edible and be satisfactorily accepted by consumers. Figure 15b displays an example sequence of the harvesting process. The experimental results show that the proposed design is capable of ensuring sufficient contact areas that provide stable grips for different types of fruits, even when the target is not centered on the midpoint of the gripper during the grasping (see Figure 15c). In this last particular case, the grasping is carried out by means of only two actuators. The actual harvested fruits (see Figure 15d) were also carefully observed both after the grasping tests and 24 h later, and no surface damage was detected.

Table 3 summarizes the main characteristics obtained experimentally from both a single soft gripper module and a hexagonal gripper endowed with six soft actuators.

Finally, Figure 16 lists the preferred soft gripper configurations for the different types of fruits. This classification was made taking into account: (i) the particular characteristics of the fruits to be harvested, such as their dimensions, mass, orientation and shape; and (ii) the intrinsic properties of the proposed gripper configurations, including the gripping range (maximum diameter between two contact points), the maximum lifting mass and the number of contact points.

Table 3. Characterization of a soft gripper module and a hexagonal configuration gripper endowed with six soft actuators.

Characteristic	Value
Mass of a single module fully mounted	69×10^{-3} kg
Max. displacement of the soft actuator (75 kPa)	0.017 m
Max. contact force (75 kPa)	54 N
Operating pressure range	0–75 kPa
Mass of a fully assembled single floor hexagon configuration	0.3 kg
Slip payload test (50 kPa)	10 kg
Mean response time	≈1 s

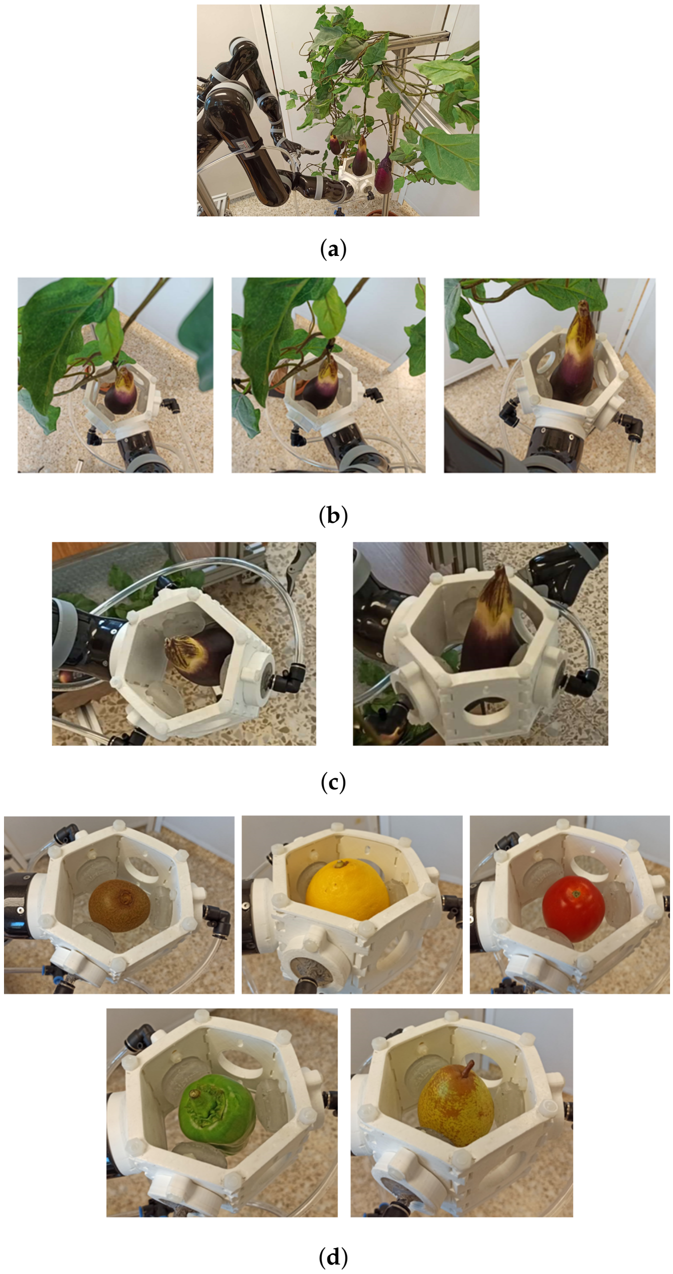


Figure 15. Experimental tests to evaluate the grasping performance. (**a**) Soft gripper with hexagonal configuration mounted on one of the Kinova Mico manipulators that make up the ROBOCROP dual-arm robot. (**b**) Example sequence of the harvesting process with the proposed soft gripper. (**c**) Grasping a target that is not centered on the midpoint of the gripper. (**d**) Evaluation of the soft gripper with several real fruits.

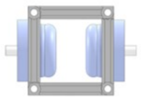
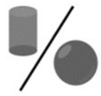
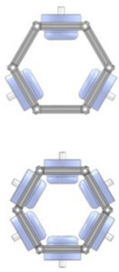
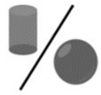
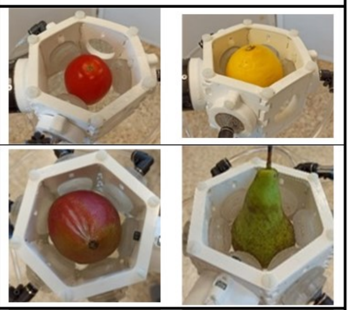
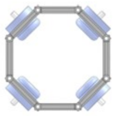
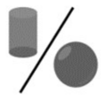
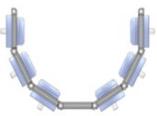
Soft Gripper Properties				Fruit Specifications		Experimental Tests
Suggested Configuration	Nº of Actuators	Gripping Range (m)	Max. Lifting Mass (kg)	Fruit Shape	Dimension and Orientation	
(a) 	2	0 – 0.025	3.4		Small-sized fruits that hang vertically, e.g., strawberry, small pepper or fig.	
(b) 	3	0.018 – 0.048	4.7		Medium-sized fruits that hang vertically, e.g., apple, orange, aubergine, tomato, lemon, mango, pear or kiwi.	
	6		10	All types of geometries due to its several contact areas.		
(c) 	4	0.085 – 0.115	6.7		Medium-sized fruits that hang vertically, e.g., pepper or pomegranate.	
(d) 	6	0.165 – 0.195	5		Large-sized fruits that lay on the ground, e.g., pumpkin, watermelon or melon.	

Figure 16. Preferred gripper configuration based on fruit type: (**a**) square configuration (two soft actuators); (**b**) hexagonal configuration (three and six soft actuators); (**c**) octagonal configuration (four soft actuators); and (**d**) open configuration (six soft actuators).

As can be seen in Figure 16, the square configuration is suitable for small fruits. In this case, the gripper was tested with a small pepper of 11.6×10^{-3} and a fig of 7.1×10^{-3} kg. On the other hand, the hexagonal configuration equipped with three soft actuators is capable of gripping a wide variety of fruits, given its grasping range and load capacity. However, the hexagonal configuration with six soft actuators is the most recommended to ensure the grip on heavy non-symmetrical fruits, since this gripper is capable of lifting more weight than that of three actuators, due to its multitude of contact areas. In the examples presented in Figure 16, the hexagonal configuration gripper equipped with three soft actuators was used to grasp a tomato of 0.11 kg and a lemon of 96.6×10^{-3} kg, while the hexagonal configuration gripper equipped with six soft actuators was used to grasp a mango of 0.38 kg and a pear of 0.20 kg. The octagonal configuration, such as the previous one, is also versatile, since it can provide two, three or four contact areas, being suitable for most medium-sized fruits. The gripper was tested with a pomegranate and a red bell pepper of 0.49 and 0.33 kg, respectively. Lastly, the open configuration is indicated for medium-to-large fruits that usually lay on the grown. It is important to note that for this configuration it is necessary to adapt the pressure of each actuator independently, since generally the actuators at the ends support the load of the target, while those on the inside help to prevent its rotation during the grasping. This configuration was experimentally tested with a pumpkin and a watermelon of 2.26 and 2.15 kg, respectively.

6. Conclusions

The soft robotics field has been rapidly increasing, especially in sectors such as manipulation and rehabilitation. However, less attention has been given to the agricultural sector, where soft technology can have a significant impact, enabling the development of robotic harvesters with responsive, safe and adaptable grasping capabilities.

This article proposes a modular soft gripper design whose main features are its versatility, ease of manufacture and assembly, affordability and adaptability for medium- to large-sized fruits and the capability to handle agricultural products with all the advantages offered by soft robotics technology. To this end, the concept of diaphragm-type soft actuators, particularly bellows-type design, is studied in depth by analyzing and experimentally checking their behavior.

Furthermore, several steps were proposed to quantitatively determine the characteristics of the soft actuators, an often controversial issue, covered quite briefly in the literature, especially with regard to the tools used to perform such measurements. The relevance of soft characterization is crucial for its implementation in the industry and in other sectors, such as agriculture and health, to make a fair benchmark. For this reason, the proposed soft grippers are characterized in a broad sense, and the measuring instruments used are also presented.

As a future line, it is intended to characterize sensorization, as well as to integrate higher-level controllers based on artificial intelligence and machine learning, using the virtues of diaphragm-type soft actuators. The trajectory planning of the ROBOCROP dual-arm robot endowed with the proposed soft gripper for harvesting applications will also be investigated. Furthermore, the energy consumption in this type of soft actuator [81,82] could also be examined to increase its autonomy in real agricultural applications [38,83–85]. The study of methods to accurately assess the extent of surface and internal fruit damage caused by excessive external forces from this type of gripper will also be addressed. Finally, we will also carry out durability tests that analyze the life cycle of the proposed soft actuators during the continuous operation of the grippers.

Author Contributions: Conceptualization, E.N. and R.F.; methodology, E.N. and P.G.-d.-S.; validation, M.A.; formal analysis E.N.; investigation, E.N.; writing—original draft preparation, E.N.; writing—review and editing R.F.; visualization, E.N.; supervision R.F.; funding acquisition R.F. and P.G.-d.-S. All authors have read and agreed to the published version of the manuscript.

Funding: The research leading to these results has received funding from (i) FEDER/Ministerio de Ciencia, Innovación y Universidades – Agencia Estatal de Investigación/Proyecto ROBOCROP (DPI2017-84253-C2-1-R), (ii) RoboCity2030-DIH-CM, Madrid Robotics Digital Innovation Hub, S2018/NMT-4331, funded by "Programas de Actividades I+D en la Comunidad de Madrid" and cofunded by Structural Funds of the EU, and (iii) CSIC under Grant 202050E099, Proyecto Intramural IAMC-ROBI (Inteligencia Artificial y Mecatrónica Cognitiva para la Manipulación Robótica Bimanual).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: MDPI Research Data Policies.

Conflicts of Interest: The authors declare no conflict of interest.

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TYPE Original Research
PUBLISHED 18 January 2024
DOI 10.3389/frobt.2023.1330496

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RECEIVED 30 October 2023
ACCEPTED 31 December 2023
PUBLISHED 18 January 2024

CITATION
Navas E, Shamshiri RR, Dworak V, Weltzien C and Fernández R (2024), Soft gripper for small fruits harvesting and pick and place operations.
Front. Robot. AI 10:1330496.
doi: 10.3389/frobt.2023.1330496

Soft gripper for small fruits harvesting and pick and place operations

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Agriculture 4.0 presents several challenges for the automation of various operations, including the fundamental task of harvesting. One of the crucial aspects in the automatic harvesting of high value crops is the grip and detachment of delicate fruits without spoiling them or interfering with the environment. Soft robotic systems, particularly soft grippers, offer a promising solution for this problem, as they can operate in unstructured environments, manipulate objects delicately, and interact safely with humans. In this context, this article presents a soft gripper design for harvesting as well as for pick-and-place operations of small and medium-sized fruits. The gripper is fabricated using the 3D printing technology with a flexible thermoplastic elastomer filament. This approach enables the production of an economical, compact, easily replicable, and interchangeable gripper by utilizing soft robotics principles, such as flexible structures and pneumatic actuation.

KEYWORDS

3D printing, agriculture 4.0, fruit harvesting, grasping, gripper, robotic device, robotic manipulation, soft robot

1 Introduction

Agriculture 4.0 is a rapidly developing field that utilizes advanced technologies such as robotics, artificial intelligence, and the Internet of Things to improve agricultural productivity, sustainability, and efficiency (Liu et al., 2020). Some of the main challenges of Agriculture 4.0, in terms of robotics, are (i) the capacity to operate in unpredictable and unstructured environments, including irregular terrains and variable weather conditions, (ii) performing a wide range of tasks such as planting, harvesting, and pest control. Each of these tasks requires specific knowledge and expertise, and developing a robotic system that can perform them all effectively is a major engineering challenge. (iii) Reliability and durability are crucial considerations when designing agricultural robots. They must be able to operate continuously for long periods with minimal maintenance. Finally, (iv) cost is another major challenge associated with the development and deployment of agricultural robots (Cheng et al., 2023). The high cost of research and development, production, and deployment of these systems can limit their adoption, especially by small farmers.

In this context, soft robotics, and particularly soft grippers, have been proposed as a promising solution to the problem of automated agriculture tasks that require manipulation capabilities (Navas et al., 2021). The main advantages that this technology can bring to

TABLE 1 Medium and small-sized fruits classification.

Type of fruit	Name	Actual harvesting method	Automatic harvesting method
Drupes	Blackberry	2	1 Crandall (1995)
	Cherry	2	1 Halderson (1966); Norton et al. (1962); Peterson and Wolford (2001); Zhou et al. (2012), Chen et al. (2012a), Zhou et al. (2013); He et al. (2013), 2 Tanigaki et al. (2008), * Amatya et al. (2017)
	Cafe	2	1 Santinato et al. (2016); Aristizábal et al. (2000)
	Raspberry	2	1 Patzlaff (1971), Patzlaff (1972)
Berries	Blueberry	2	1 Richard (1982), 2 Navas et al. (2023)
	Grape	1,3	1 Shaulis et al. (1966); Shepardson et al. (1969); Studer and Olmo (1969); Pezzi and Caprara (2009), 2 Monta et al. (1995), * Luo et al. (2016)
	Kiwi	2	2 Chen et al. (2012b); Mu et al. (2017); Williams et al. (2019)
	Passion fruit	2	* Tu et al. (2018)
	Wolfberry	2	1 Qiang et al. (2009), 2 Bing and Jing, (2011), * Lvcheng et al. (2013)
Hesperidium and Pepo	Lime	3	2 Nemlekar et al. (2021)
Aggregate fruit	Strawberry	2	2 Rajendra et al. (2009); Hayashi et al. (2010); Dimeas et al. (2015); De Preter et al. (2018); Klaoudatos et al. (2019); Huang et al. (2020)
Multiple fruit	Fig	2	-

[1]Mechanical motion towards the fruit indirectly via force exerted on the plant itself.
2Application of a mechanical force directly onto the fruit or its peduncle.
3Direct mechanical motion or an alternative cutting approach implemented directly on the stem.
*Artificial Intelligence researches for fruit detection.

agriculture are: (i) Flexibility: Soft robots are made of flexible materials that allow them to move and adapt to unstructured agricultural environments more easily than traditional rigid robots. (ii) Human interaction: Soft robots are safer to operate near humans and delicate objects since they are less likely to cause damage or injuries. (iii) Versatility: Soft robots can be designed to perform a wide range of tasks, from harvesting to maintenance or pick and place operations. (iv) Durability: Soft robots can withstand impacts and deformations, making them ideal for use in difficult or unpredictable environments. This is common in agricultural applications, where machinery is exposed to significant wear and tear. (v) Cost-effectiveness: Soft robots can be made with low-cost materials and fabrication techniques, which makes them more affordable and accessible for a wider range of applications, as well as easy to repair or replace.

Therefore, these soft grippers can be a game changer for all those fruits that, either due to their difficulty, economic feasibility, or other factors, have not yet been automated. This is the case for blueberries, for which the software part has been widely investigated (Li et al., 2010; Kuzy et al., 2018), but the hardware part has not been researched as much, and attempts to automate their harvesting have had little success (Hall et al., 1983). Table 1 shows a list of all those small and medium-sized fruits for which automation still poses a challenge.

For this reason, this article aims to present a soft gripper design approach based on the integration of a pneumatically actuated soft diaphragm actuator and a 3D-printed flexible structure into a single compact module. Data collected by finger-tracking gloves have been used to design the gripper, which has helped to adapt the design to human movement patterns. This results in a soft gripper suitable for agricultural tasks and pick and place operations. The main novelties and contributions are:

- The study of the movement patterns involved in blueberry harvesting from data collected with finger-tracking gloves to better adapt the soft gripper.

- The design of a compact hybrid soft gripper that combines flexible structure technologies with different levels of stiffness, indirect motion through pneumatic actuation, and a rotating rigid structure that allows for various types of grip or picking patterns. The pneumatic structure is isolated from potential failure risks through puncture prevention measures.
- The development of a design that, through the use of a uniaxial motion diaphragm actuator, simplifies the complexity of controlling soft grippers.
- The development of an easily replicable, cost-effective, and replaceable actuator suitable for agricultural tasks and pick and place operations.
- The design of a gripper capable of harvesting fruits or objects found in clusters without damaging surrounding ones.

The remainder of the article is organized as follows. Section 2 details the steps followed for the design and manufacturing of the soft gripper for berries harvesting while section 3 presents the control system. Section 4 describes a testbed for measuring the characteristics of soft actuators, followed by a discussion of the main results obtained from the experimental evaluation of the proposed soft gripper. Finally, the main conclusions are summarized in Section 6.

2 Design and manufacturing approach

To identify the essential requirements that a soft gripper should meet to be fully operational, the agricultural processes that involve manipulation and, more particularly, the harvesting tasks (Duckett et al., 2018; Navas et al., 2020; Navas et al., 2021), as well as the pick and place operations (Blanes et al., 2011) have been reviewed. One of the recognized prerequisites for enhancing the profitability of harvesting machinery is the ability to customize the design for various crop varieties. With this objective in mind, the aim was to attain a completely parameterizable and scalable design concept. The soft actuator can be produced in diverse dimensions to yield a wide range of diameters and lengths. This characteristic enables a gripper conceived within this framework to be reconfigured for accommodating the harvesting of distinct kinds of fruits. Another demand in this domain is simplicity, leading to systems that are interchangeable and effortless to repair. This is why the design approach is founded upon a compact soft actuator featuring a flexible gripping structure, which can be swiftly manufactured using 3D printing technology. The additional requirements are more related to maintaining the quality standards of the fruit than to the harvest process itself. These requirements include preventing fruit damage, utilizing non-hazardous materials, and employing designs that prevent the spread of diseases and pests. Unfortunately, these crucial aspects were overlooked in the design of previous grippers, which used materials that could harm the fruits and featured complex designs that hindered cleaning. To address this, a combination of soft robotics technology, hygienic designs, and adjustable flexibility is used to ensure fruit and crop protection. Furthermore, the modular soft gripper is specifically designed to serve as the end effector of a robotic manipulator (Sepúlveda et al., 2019; Navas et al., 2021). It is capable of executing nearly all the necessary harvesting movements, commonly referred to as picking patterns in the literature (Yaguchi et al., 2016; Li et al., 2019; Huang et al., 2020; Mu et al., 2020). These picking patterns encompass a range of simple actions, such as twisting, pulling, lifting, and bending, which can be combined as required.

The following section delineates the field study that was conducted to develop a design that adequately meets the needs of the harvest process. Then, the type of soft material that has been selected for the implementation of the gripper is described highlighting its main advantages. Subsequently, the design specifications for both the rigid and soft components of the gripper is presented, with the latter having been modelled using finite element analysis. Finally, a detailed description of the manufacturing and assembly process of the gripper is provided.

2.1 Picking pattern study

During the design process, finger-tracking gloves have been used to gain a better understanding of the movement patterns involved in the harvesting process and consequently use this knowledge to better adapt the soft gripper design to these human movements. The utilization of finger-tracking gloves constitutes a novel approach in investigating fruit harvesting practices.

Conventionally, visual methodology has been the most widely employed approach in scientific literature for identifying harvesting movements (Dimeas et al., 2015; Zheng et al., 2022). However, this method is often imprecise in capturing the intricate movement patterns exhibited by human agents in fruit collection tasks. By employing finger-tracking gloves, it becomes possible to meticulously monitor the movement patterns involved in the fruit harvesting process, through numerical quantification. Consequently, this enables the detailed analysis of different harvesting patterns within a manipulation study. The experimental trials for fruit harvesting were conducted under naturalistic conditions at the Leibniz Institute of Agricultural Engineering and Bioeconomy e.V. (ATB). The chosen specimens for the experimental tests were blueberries (Vaccinium corymbosum), which were harvested from the fields of ATB Marquardt located in Potsdam, Germany. The finger-tracking gloves utilized for the data acquisition, illustrated in Figure 1, were the Manus Prime 2 (Meta, 2023), which are capable of tracking the angles between different joints, as well as the stretching angle between fingers.

To evaluate the characteristics of blueberries, a sample of 20 berries was chosen at random. The average diameter of the berries was 13 mm, with a range of 10–15 mm. The average weight was 1 g, with the weight of individual berries ranging from 0.6 to 1.4 g. Throughout the harvesting of these 20 samples, the monitoring of finger joint angles was carried out, as illustrated in Figure 2. The thumb and index finger were predominantly utilized for manipulations employing a pulling picking pattern. Quick analysis was performed using the maximum values of the joints to determine the involved fingers. The spread angles for the thumb, index, middle, ring, and pinky were 39°, 0°, 0°, 0°, and 0°, correspondingly. It is worth emphasizing that these angles remained constant, with the thumb and index finger maintaining a completely stationary position, indicating heightened rigidity in the grasping motion. Based on these observations, it can be deduced that a two-point grip is well-suited for the harvesting of blueberries.

2.2 Soft materials

3D printing has emerged as a promising method for the fabrication of soft actuators. This technology provides a more efficient and accurate approach, reducing the incidence of manufacturing defects and enabling a higher degree of experimental reproducibility. Moreover, software-based design modifications allow for greater control over the actuator's performance and behavior.

In the soft robotic field, Polymer-based materials such as Ecoflex (Mosadegh et al., 2014; Hsiao et al., 2020), Dragon Skin (Connolly et al., 2017; Shih et al., 2017; De Barrie et al., 2020; Wang et al., 2020), Elastosil M4601 (Mosadegh et al., 2014; Galloway et al., 2016; Seibel et al., 2020; Teeple et al., 2020), and polydimethylsiloxane (PDMS), commercially known as Sylgard 184 (Wang et al., 2016; Rodrigue et al., 2017; Shih et al., 2017; Modabberifar and Spenko, 2018; Galley et al., 2019; Hsiao et al., 2020), are commonly used due to their unique mechanical properties and ease of processing. However, the manufacturing process for soft robots using these materials is often a time-consuming and challenging endeavor, involving several stages such as mold design and intricate fitting to prevent material leakage. Moreover, the manufacturing process may suffer from interstitial bubbles and delamination, which may lead to actuator performance degradation or even failure.

On the other hand, thermoplastic elastomers (TPEs) (Liu et al., 2020; Dilibal et al., 2021) have gained significant interest in soft robotics due to their unique properties, which enable the fabrication of complex geometries that are otherwise unattainable through traditional manufacturing processes like molding. TPEs, which are a type of polymeric material, possess elastomeric behavior and thermoplastic processability, making them ideal for use in additive manufacturing techniques such as 3D printing. The ability to produce intricate shapes using TPEs has made them a promising material for the development of soft robots, which rely on compliant structures to achieve versatile and adaptive motion.

Therefore, the material selected for the implementation of the soft gripper is a 1.75 mm TPE filament manufactured by Multicomp Pro. TPEs possess unique properties, allowing the fabrication of complex geometries through 3D printing. Their elastomeric behavior and thermoplastic processability make them ideal for creating compliant soft actuators, enabling versatile and adaptive motion. TPEs also offer flexibility, durability, and biocompatibility, further enhancing their usability in the agricultural field.

2.3 Soft design

Once data on fruit characteristics and picking patterns have been collected, design requirements are determined. Pattern analysis, along with other criteria such as simplicity, avoidance of fruit bruising, and the ability to harvest clustered fruit, define the design constraints. Ultimately, the soft gripper design is conceived not only as an end effector, but also as a tool for a robotic arm, capable of performing almost all picking patterns required for harvesting (Navas et al., 2021).

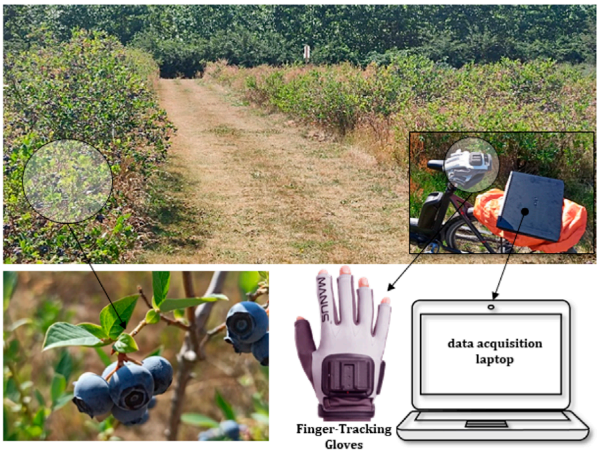

FIGURE 1
View of the Blueberry experimental field and data acquisition setup.

Regarding the geometric design, shown in Figure 3, the grippers proposed in this article consist of a single-channel diaphragm-type actuator with a flexible structure. One advantage of this design is its simplicity of manufacture, as it can be 3D printed in one piece. Another advantage is the ease of control. Soft diaphragm actuators are designed to move primarily on one axis, with negligible motion on other axes, simplifying the control of the Degrees of Freedom (DoFs) of the gripper.

The suggested flexible diaphragm also utilizes the bellows concept, which distinguishes it from other shapes in terms of how it expands. Unlike geometries based on cylinders, cubes, or spheres, where inflation typically leads to both forward elongation and wasted forces on the side walls, the bellows-based design addresses this issue. Cylindrical and cubic shapes experience reduced forward advancement due to radial expansion. Although the spherical shape performs better in terms of inflation behavior, it requires complex molding for manufacturing. However, the proposed combination of cylindrical and spherical shapes in the bellows-cylinder design partially solves this problem. It leverages the forces generated by radial inflation to achieve forward elongation, extending the gripper's body in that direction.

Regarding the actuator structure, the finger-tracking glove data indicates that a two-point grip is well-suited for the harvesting of blueberries. However, it is important to emphasize that the design objective goes beyond optimizing the gripper for a specific fruit. The intention is to create a gripping mechanism with a more generalized design capable of not only adapting to other small and medium-sized fruit, but also performing a wide range of picking motions, including pulling, twisting, and bending the fruit peduncle, while maintaining a strong grip. Consequently, the proposed gripper comprises three contact elements that contribute to secure gripping and manipulation. While the two-points grip may be optimal for blueberries, the inclusion of a third grip point provides additional versatility for handling fruits of different shapes

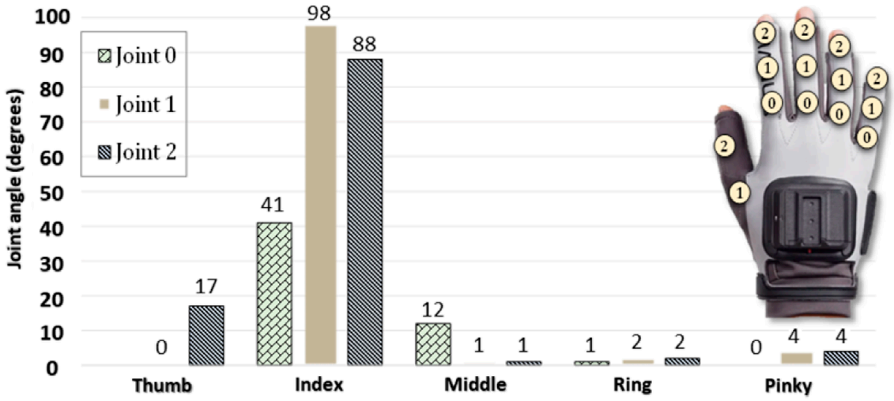

FIGURE 2
Maximum angle reached by the finger joints during blueberry harvesting (Navas et al., 2023).

and sizes. Moreover, the three contact elements are reinforced by a thicker TPE wall compared to the diaphragm, ensuring a stable support point for the opening and closing actions of the gripper.

Finally, the choice of a more generic gripper aligns with the practical challenges faced in agricultural settings where a robot may encounter a high variability during harvesting or pick-and-place operations. A gripper designed for versatility can adapt to different scenarios without the need for frequent reconfigurations or specialized attachments.

With the aim of devising suitable soft grippers for small-sized fruits, the COMSOL Multiphysics® platform is employed to model its inflation behavior through Finite Element Method (FEM), as shown in Figure 4. To accomplish this, TPE is simulated as a hyperelastic material. In existing literature, numerous mathematical frameworks exist to describe the behaviour of such 3D printed thermoplastic elastomers. Among these, the five-order Ogden model, in contrast to Yeoh's, Van der Waals's, or Arruda-Boyce's models, provides a more precise depiction of its response (Adams et al., 2019).

Furthermore, as a result of the inflation pressure, the soft diaphragm will experience equibiaxial tension. This form of tension in hyperelastic materials, applicable to thermoplastic elastomers, was theorized by Ogden (Ogden, 1972). This approach pertains to elastic solids characterized by a strain–energy function and isotropic behavior in relation to the stress-free ground state. It also assumes the solid's incompressibility. Therefore, its formulation can be expressed as follows:

$$\sigma_i = \mu_r a_i^{\alpha_r} - p, \tag{1}$$

where σ_i, $i \in \{1,2,3\}$, represents the principal Cauchy stresses $(\sigma_1, \sigma_2, \sigma_3)$, the parameters μ_r and α_r are experimentally obtained constants, a_i represents the stretches (a_1, a_2, a_3) and p is an arbitrary hydrostatic pressure introduced because of the incompressibility constraint. Due to the equibiaxial tension, two out of three principal stresses are equal, and the third one is zero:

$$\sigma_2 = \sigma_3 = \sigma, \sigma_1 = 0 \tag{2}$$

Moreover, the stretches can be written as follows:

$$a_2 = a_3 = a, \tag{3}$$

and due to the incompressibility assumption, it can be considered that $a_1 = a^{-2}$. The substitution of the aforementioned into (Eq. 1) is as follows:

$$\sigma_i = \mu_r a^{\alpha_r} - p, 0 = \mu_r a^{\alpha_r - 2} - p. \tag{4}$$

The elimination of p yields:

$$\sigma_i = \mu_r \left(a^{\alpha_r} - a^{\alpha_r - 2}\right). \tag{5}$$

Finally, Eq. 5 is incorporated into the FEM software, alongside the values of μ, α, and bulk modulus, acquired from (Kim et al., 2011). The results obtained from the FEM software are illustrated in Figure 4 for the soft gripper. The working principle of the soft gripper is as follows. When positive pneumatic pressure is applied to the inlet of the actuator, an expansion occurs in the bellows, as seen in Figures 4B, D, resulting in an opening movement. On the other hand, when negative pneumatic pressure is applied to the actuator, the bellows collapses and a closing movement is generated, as shown in Figures 4C, E. Both movements are possible due to the flexible structure of the actuator. When establishing the working pressure range for analysis, a prioritization is made for a range that ensures an adequate working volume for small fruits while maintaining low energy consumption and sufficient gripping force for various manipulation movements. Therefore, through an iterative process, a study pressure range of 50−−50 kPa is reached.

As for the structure of the soft gripper, it has been designed in such a way that different levels of rigidity have been achieved by varying the thickness of the walls, since some must be rigid for a stable grip and other requires flexibility. Regarding the latter, the walls of the bellows are printed at 0.8 mm, with a rounding radius of 1 mm and an angle between walls of 90°.

2.4 Design of the rigid structure

Following a comprehensive analysis of the collection patterns of various fruits, it was observed that a rotational motion is frequently

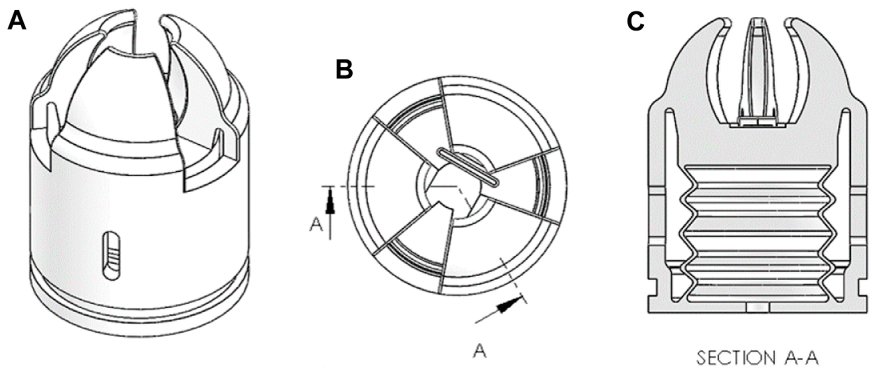

FIGURE 3
Soft Actuator. **(A)** Isometric View. **(B)** Top view. **(C)** Section view.

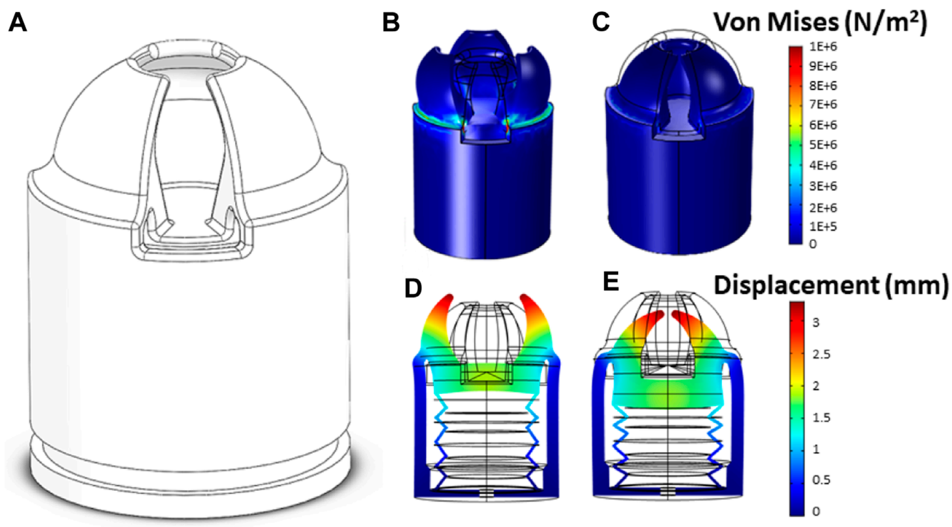

FIGURE 4
Model showing the displacement reached on the soft gripper in **(A)** normal position, **(B)** deformation in open position, **(C)** deformation in closed position, **(D)** deformation in open position and **(E)** deformation in close position.

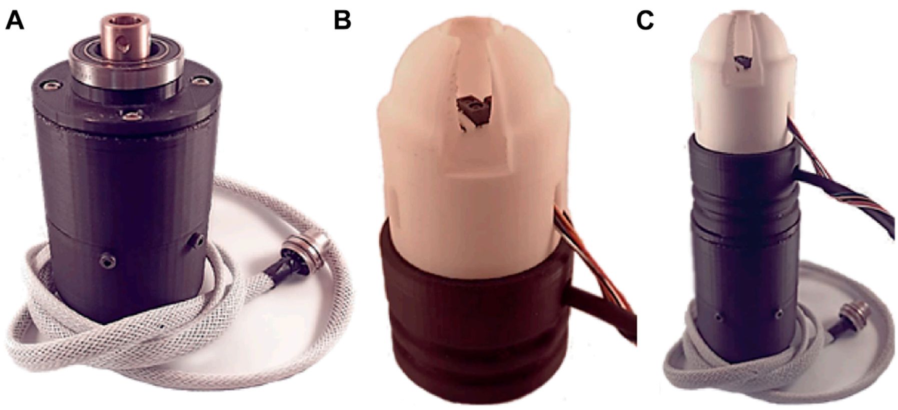

FIGURE 5
View of the **(A)** soft gripper rotating base, **(B)** soft Actuator, and **(C)** complete assembly of the soft gripper.

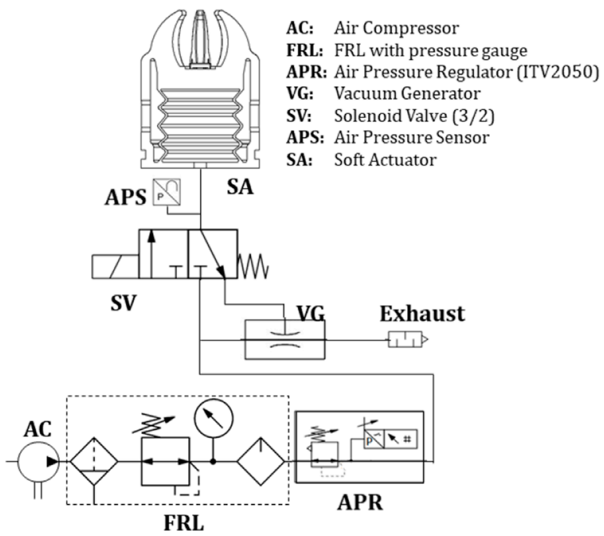

FIGURE 6
Schematic of the pneumatic control system for the soft gripper.

employed to facilitate their detachment from the plant. In order to incorporate this characteristic into the designed soft gripper, a degree of freedom pertaining to rotation around the gripper's axis was introduced. To this end, a PLA-based rotating base, as shown in Figure 5A, was integrated and actuated by a Nema 17 stepper motor.

2.5 Manufacturing and assembly

The fabrication of the soft gripper was carried out using Fused Filament Fabrication (FFF), in particular a Creality Ender 3 3D printer adapted to print flexible material. The printing parameters required for the proper printing of the flexible TPE filament are detailed in Appendix 1. This fabrication approach represents a promising methodology for the production of soft robotics components, as it enables the production of complex geometries and customization in a cost-effective and time-efficient manner.

The rigid components of the soft gripper were fabricated using Polylactic acid (PLA). The attachment of the soft actuator to the rigid base was accomplished using a press-fit mechanism, show in Figure 5B, avoiding the use of screws or other types of rigid fasteners. The motor was secured to the gripper claw with screws, and the coupling of the motor shaft with the movable part of the gripper was achieved through a motor coupling supported by a bearing. The lower portion of the claw is designed to be detachable, allowing it to be used as a primary soft gripper or as a soft tool for a robotic arm. Figure 5C provides a detailed illustration of the fully assembled soft gripper.

3 Control system

In general, soft robotics are characterized by their deformability and compliance, resulting in a large number of intrinsic DoFs. While this can increase the complexity of the control system, it also allows for a wide range of movements, including bending, twisting, stretching, compression, and buckling wrinkles (Rus and Tolley, 2015). High levels of sensorization are typically employed to tackle the soft control barrier. Alternatively, some researchers (Duriez, 2013) use real-time Finite Element Method (FEM) simulations to control soft elastomer robots. Nonetheless, for certain soft materials, establishing a reliable mathematical model can be challenging.

On the other hand, the gripper presented in this article could be seen as a specific instance of hybrid grippers (McKenzie et al., 2017; Park et al., 2020), not because it physically combines rigid components embedded in soft actuators, but because the rigid structure imposes constraints on the DoFs of the soft actuator, making it easier to control the gripper.

To operate the soft gripper effectively, it is essential to have sensor and control components that guarantee accurate air pressure measurement and a steady airflow. Figure 6 and Table 2 show the pneumatic elements schematically and their main characteristics, respectively.

The proposed soft gripper is then controlled by MATLAB/Simulink, enabling manual activation and adjustment of pneumatic electrovalves pressure. Moreover, the grippers can operate automatically using a proportional-integral-derivative (PID) control mechanism, in which the pressure sensor positioned at the soft actuator's inlet provides the feedback. This allows contact detection between the soft actuator and the objects without the need for embedded sensors within it. Whilst the soft gripper has been devised for integration with a bimanual robot that employs computer vision for object detection (Sepúlveda et al., 2020), it is also integrated with an infrared sensor GP2Y0E03 (measurement range: 4–50 cm, output voltage: 2.7–5 V) that provides position feedback to the vision system, thereby assisting the execution of successful grasping. Algorithm 1 summarizes the different steps described above.

A Unified Robotics Description Format (URDF) model of the soft gripper has also been implemented in Robot Operating System in order to facilitate its integration with the dual-arm robotic platform and to enable the communication of the robotic planning module with the low level controller of the soft gripper. Figure 7 shows the soft gripper in the 3D visualization program RVIZ.

4 Characterization and assessment of the soft actuators

In order to characterize the soft actuators and ascertain the viability of the proposed approach, a series of experimental tests were conducted. Firstly, various static experiments were carried out to measure the physical characteristics of the actuator. These included the weight of the actuator, the range of fruit diameters that could be manipulated, the maximum opening diameter, and the range of pressure. Figure 8 depicts the gripper in its open and closed positions.

Experiments were also conducted to determine the maximum grasping or detachment force of the gripper for a specific geometry at different pressures, which is essential to select the appropriate target fruits for use. This geometry is determined by the target fruit to be manipulated, which in this case was a smooth sphere with a

TABLE 2 Main features of the pneumatic elements of the system.

Pneumatic element	Main characteristic	Value
Air Compressor	Compressed air deposit	6 L
	Power comsumption	1.1 kW
FRL unit	Standard nominal flow rate	1600 L/min
Pneumatic solenoid valve	Type	3/2-Way Normally Close
Air pressure regulator	Pressure range	0.005–0.9 MPa
	Power comsumption	4 W
	Max. Flow rate	1500 L/min
	Repeatability	±0.5%
	Response time	0.1 s
Air pressure sensor	Pressure range	0–100 kPa
	Measurement precision	±0.4%
Vacuum generator	Max. Vacuum pressure	80 kPa

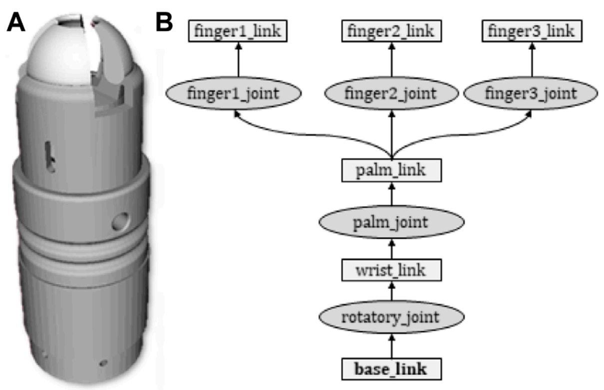

FIGURE 7
URDF model of the soft gripper implemented in ROS. **(A)** Soft gripper displayed in RViz; and **(B)** URDF specification. The links and joints are visualized by boxes and ellipses, respectively.

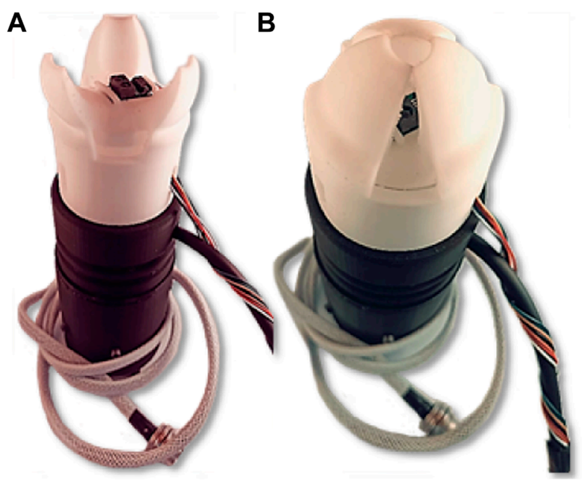

FIGURE 8
(A) Soft Gripper in open position. **(B)** Soft Gripper in closed position.

diameter of 20 mm that was printed in PLA using 3D technology. This experiment, commonly known as slip test (Galley et al., 2019) or pull-off force test (Hao et al., 2016), involved setting up a movable element consisting of: (i) the movable base of a mechanical press, (ii) the soft gripper, (iii) fixed elements that included a dynamometer, a pressure measuring device and vacuum generator, and the object to be manipulated. The schematic view and the experiment setup are shown in Figure 9.

The experimental procedure involved varying the position of the soft gripper, which held the object to be manipulated at a predetermined vacuum pressure, while recording the peak force exerted by the object as it slipped off the gripper. This process was repeated while varying the vacuum pressure.

The results of these experiments are presented in Figure 10, which depicts the relationship between the gripping force and the vacuum pressure exerted by the soft gripper.

As shown in Figure 10, the maximum grasping force of the soft gripper was found to be 13 N at a vacuum pressure of −52 kPa. The gripping force was observed to vary linearly with pressure, with an R^2 value of 0.93, indicating a strong linear

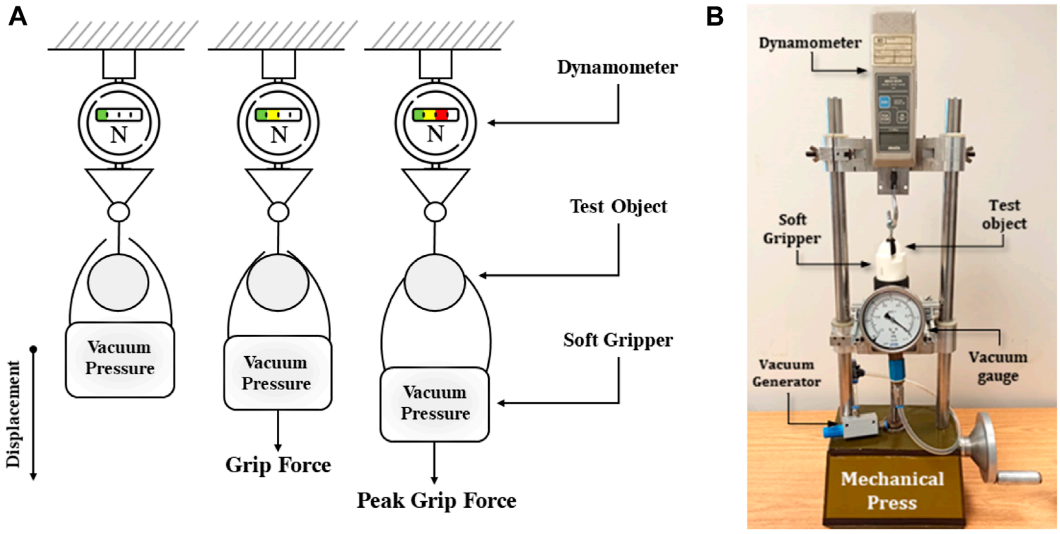

FIGURE 9
Slip test. **(A)** Experiment schematic view. **(B)** Experiment setup.

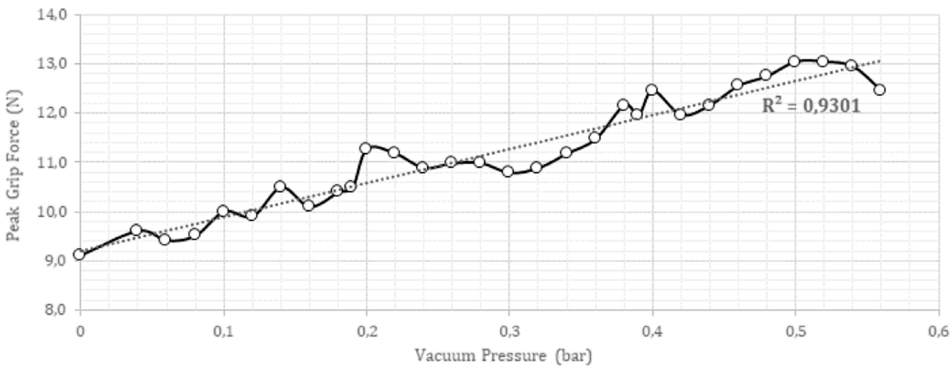

FIGURE 10
Plot of the slip test for soft gripper characterization showing peak grip force *versus* vacuum pressure.

TABLE 3 Soft gripper characterization.

Soft gripper weight	38.05 g
Weight of the fully assembled gripper	577.55 g
Max. soft actuator diameter (150 kPa)	0.045 m
Min. soft actuator diameter (-52 kPa)	0.007 m
Max. slip force (-52 kPa)	13 N
Operating pressure range	−52–150 kPa
Mean Response Time	≈1 s

correlation. To ensure the consistency of the results, three soft grippers were tested, and no significant variation was observed among them.

Finally, with all the experiments detailed above, Table 3 summarizes the characteristic values of the designed soft gripper.

Two other sets of experiments were conducted to evaluate the performance of the soft gripper in picking tasks. In the first set of experiments, the proposed soft gripper is used as a tool manipulated by a human operator. We call this mode of operation soft tool mode. Figure 11 shows several sequences with the proposed gripper in soft tool mode. These experimental tests demonstrate the feasibility of the gripper for pick and place applications, as well as for the harvesting of different fruits in bunches, minimizing the damage caused to the products.

In the second set of experiments, an ABB YuMi IRB 14000 dual-arm collaborative robot is used to test the capabilities of the gripper in harvesting tasks (see Figure 12). As the first step of the test, the surface condition of the fruits, which were cherry tomatoes, blueberries, raspberries and grapes, was recorded. The robot and the

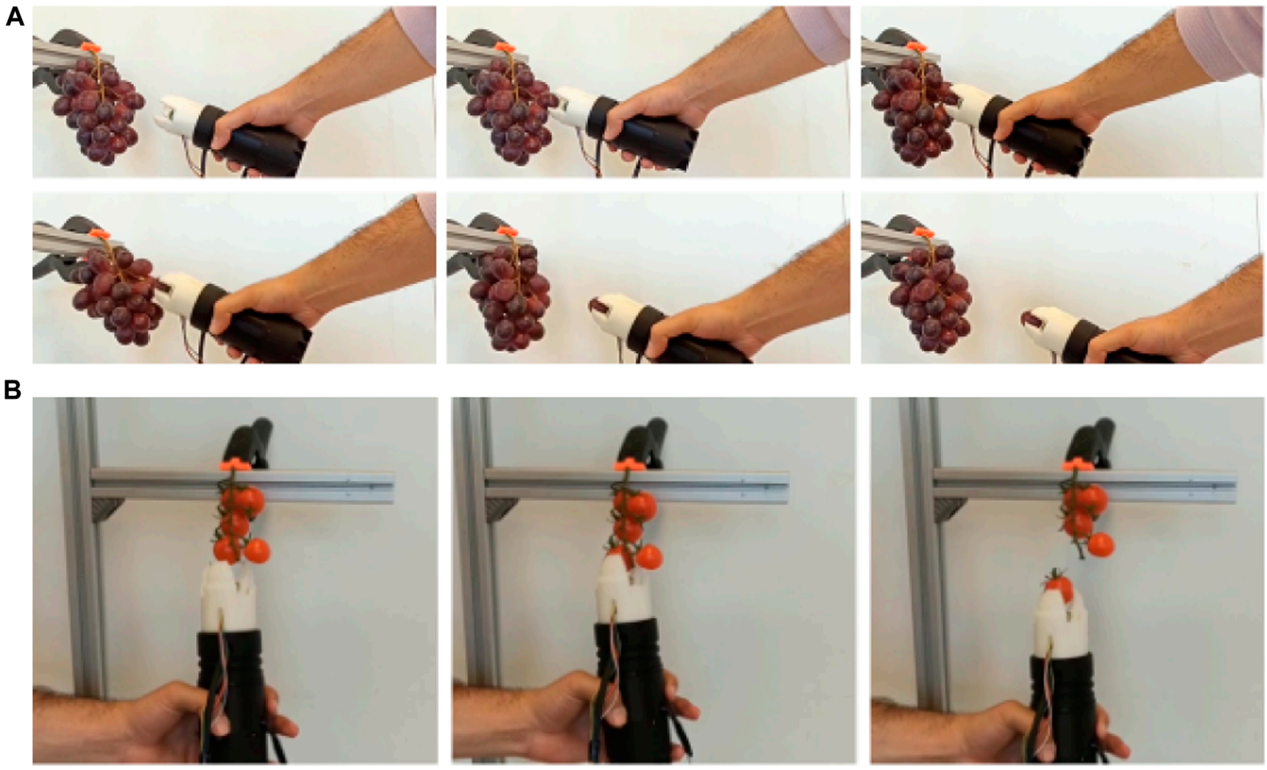

FIGURE 11
Evaluation of the designed gripper used as a soft tool for picking operations of clustered fruits such as **(A)** grapes and **(B)** cherry tomatoes.

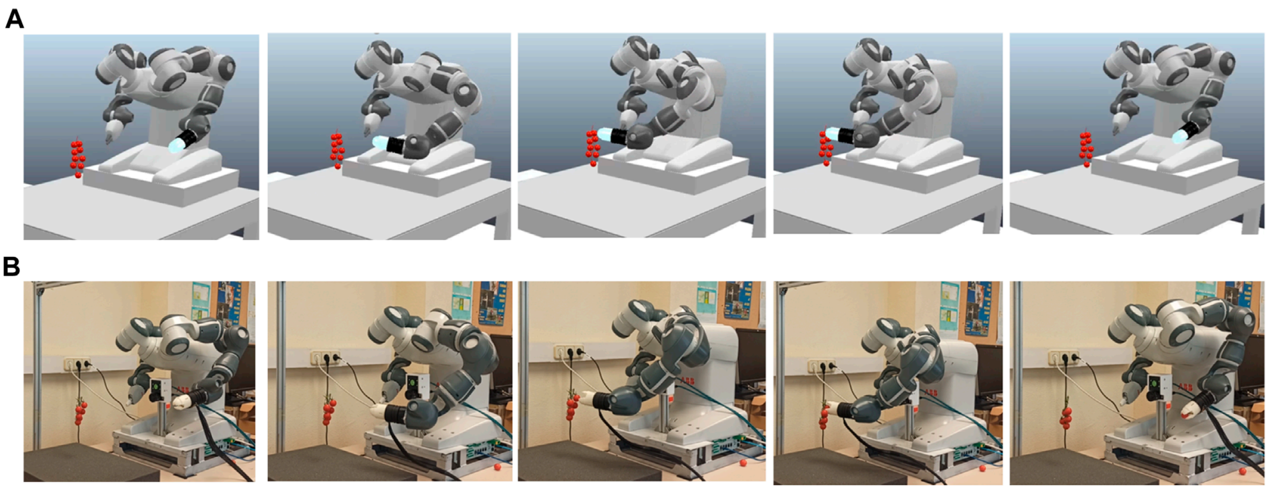

FIGURE 12
Evaluation of the soft gripper for tomato bunch harvesting operations. **(A)** Simulation of the process in CoppeliaSim. **(B)** Harvest test in laboratory conditions.

operation scenario were then simulated in a virtual environment using the CoppeliaSim software. Once the joint positions were obtained in simulation to carry out the movements required for harvesting, the joint coordinates were sent to the robot. As a result of this test, the fruits were successfully harvested without any changes or damage being observed on their surface 1 week after the picking test. It should be noted that although grapes and cherry tomatoes are not typically harvested in this manner,

Algorithm 1 Algorithm to address soft gripper grasping

Input : List of detected fruit(s) *det*
Output : List of picked fruit(s) *picked*
Parameters:

- Pressure threshold P_t
- Soft gripper current pressure P_c
- Current distance D_c
- Desired target fruit F_{goal}
- Position error tolerance Err_{tol}
- Air pressure sensor APS
- Current time T_c
- Filling start time T_{start}
- Max. filling time $T_{f.max}$
- Flag - Target fruit not reached R_{Flag}
- Flag - Soft actuator leakage L_{Flag}
- Flag - Robotic manipulator reached release position RM_{Flag}
- Solenoid valve status (True=Close/False=Open) SV

```
begin
    Set P_t for F_goal
    Set Err_tol
    for each fruit i to det do
        Read P_c from APS
        Read D_c from IR sensor
        Read T_c
        if D_c ∈ Err_tol: then
            SV ← True
            while P_c < P_t do
                Read T_start
                Increase P_c
                Read P_c from APS
                if (T_start − T_c) > T_f.max then
                    Set L_Flag
                    break
                end
            end
            Wait until RM_Flag is set
            SV ← False
            Add F_goal to picked list
        else
            Set R_Flag
        end
    end
end
```

Algorithm 1. Algorithm to address soft gripper grasping.

each piece of fruit is picked from a bunch, which represents a challenge in the development of robotic grippers for harvesting (Bachche, 2015). This type of grip is possible thanks to the shape and material used in this soft gripper, which ensures the picking of the selected fruit without damaging the rest of the fruits in the surrounding area.

5 Conclusion

The field of soft grippers has seen significant advancements, especially in industrial and medical rehabilitation applications. However, the agricultural sector poses unique challenges, creating opportunities for improvement. This article presents a novel compact hybrid soft gripper design that combines flexible structure with a pneumatic actuation motion suitable as a primary claw or soft tool in robotic manipulators. The proposed design results in a versatile soft gripper, easy to manufacture and assemble, affordable and suitable for unstructured agricultural scenarios, which can harvest small and medium-sized fruits in bunches without damaging the surrounding ones. Moreover, it can also be used in pick and place operations in the food industry.

The design takes advantage of the benefits offered by soft robotics technology. In order to accomplish this objective, the utilization of 3D additive manufacturing has been leveraged, specifically through the use of flexible filaments, with the aim of designing a gripper that integrates two components of soft robotics, flexible structures and pneumatic actuation, in a compact form.

As a future line, there is a need to achieve reliable integration of a variety of sensors into the designed gripper, allowing it to withstand the harsh conditions encountered during the execution of tasks in unstructured environments. Moreover, there is an urgent need to research into the definition of soft gripper joints in ROS to match their actual behavior, in order to facilitate their integration into a next-generation of robot harvesters. The trajectory planning of the ROBOCROP dual-arm robot endowed with the proposed soft gripper for harvesting applications will also be investigated.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/supplementary material.

Author contributions

EN: Conceptualization, Data curation, Investigation, Writing–original draft. RS: Visualization, Writing–review and editing. VD: Supervision, Writing–review and editing. CW: Supervision, Validation, Writing–review and editing. RF: Funding acquisition, Supervision, Writing–review and editing.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. The research leading to these results was supported in part by: (i) the Grant PID2020-116270RB-I00 funded by MCIN/AEI/10.13039/501100011033; (ii) the Grant PDC2021-121578-I00 funded by MCIN/AEI/10.13039/501100011033 and by the "European Union NextGenerationEU/PRTR"; (iii) the Grant TED2021-132710B-I00 funded by MCIN/AEI/10.13039/501100011033 and by the "European Union NextGenerationEU/PRTR"; and (iv) CSIC under Grant 202350E072, Proyecto Intramural IAMC-ROBI-II (Inteligencia Artificial y Mecatrónica Cognitiva para la Manipulación Robótica Bimanual — 2º Fase).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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Appendix

The 3D printing parameters were optimized using Ultimaker Cura for printing an airtight soft pneumatic bellow gripper. A nozzle temperature of 230°C was used for the bellow actuator with a printing bed temperature of 50°C. The printing speed was set to 20 mm/s for the actuators infill while the outline printing speed was lowered to 10 mm/s, to ensure high-quality exteriors and air tightness. A 20% infill was used for both structures with a perimeter overlap of 30%. Finally, a 0.2 mm layer height with 0.4 mm extrusion width were used for the whole structure.

A.2 Patents

TRATADO DE COOPERACIÓN EN MATERIA DE PATENTES NOTIFICACIÓN DE LA RECEPCIÓN DE LOS DOCUMENTOS QUE CONSTITUYEN SUPUESTAMENTE UNA SOLICITUD INTERNACIONAL PRESENTADA DE FORMA ELECTRÓNICA.

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Referencia del expediente del solicitante o mandatario	PCT1641.1817BIS	
Solicitante	Consejo Superior de Investigaciones Científicas (CSIC)	
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0-3	Nombre de la Oficina receptora y "Solicitud Internacional PCT"	

0-4	**Formulario PCT/RO/101 Petitorio PCT**	
0-4-1	Preparado usando	PCT Online Filing Version 3.51.000.276e MT/FOP 20141031/0.20.5.24
0-5	**Petición**	
	El abajo firmante pide que la presente solicitud internacional sea tramitada con arreglo al Tratado de Cooperación en materia de Patentes	
0-6	**Oficina receptora (indicada por el solicitante)**	Oficina Española de Patentes y Marcas (RO/ES)
0-7	**Referencia al expediente del solicitante o del mandatario**	PCT1641.1817BIS
I	**Título de la invención**	GARRA ROBÓTICA PARA AGARRE Y MANIPULACIÓN
II	**Solicitante**	
II-1	Esta persona es:	Solicitante únicamente
II-2	Solicitante para	Todos los Estados designados
II-4	Nombre	Consejo Superior de Investigaciones Científicas (CSIC)
II-5	Dirección	C/ Serrano, n° 117 28006 Madrid España
II-6	Estado de nacionalidad	ES
II-7	Estado de domicilio	ES
III-1	**Solicitante y/o inventor**	
III-1-1	Esta persona es:	Solicitante únicamente
III-1-2	Solicitante para	Todos los Estados designados
III-1-4	Nombre	Universidad Politécnica de Madrid
III-1-5	Dirección	C/ Ramiro de Maeztu, n° 7 28040 Madrid España
III-1-6	Estado de nacionalidad	
III-1-7	Estado de domicilio	ES

PETITORIO PCT

(original en formato electrónico)

III-2	**Solicitante y/o inventor**	
III-2-1	Esta persona es:	**Inventor únicamente**
III-2-3	Inventor para	**Todos los Estados designados**
III-2-4	Nombre (APELLIDOS, Nombre)	**NAVAS MERLO, Eduardo**
III-2-5	Dirección	**Consejo Superior de Investigaciones Cientificas (CSIC) Centro de Automática y Robótica C/ Ctra. de Campo Real Km 0,200 28500 Arganda del Rey (Madrid) España**
III-3	**Solicitante y/o inventor**	
III-3-1	Esta persona es:	**Inventor únicamente**
III-3-3	Inventor para	**Todos los Estados designados**
III-3-4	Nombre (APELLIDOS, Nombre)	**FERNÁNDEZ SAAVEDRA, Roemi Emilia**
III-3-5	Dirección	**Consejo Superior de Investigaciones Científicas (CSIC) Centro de Automática y Robótica C/ Ctra. de Campo Real Km 0,200 28500 Arganda del Rey (Madrid) España**
IV-1	**Mandatario o representante común; o dirección para la correspondencia** La persona identificada a continuación se nombra/ha sido nombrada para actuar en nombre del/de los solicitante(s) ante las administraciones internacionales competentes como:	**Mandatario**
IV-1-1	Nombre (APELLIDOS, Nombre)	**PONS ARIÑO, Angel**
IV-1-2	Dirección	**Glorieta de Ruben Dario, 4 28010 Madrid España**
IV-1-3	No. de teléfono	**+34 917007600**
IV-1-5	Correo electrónico	**patentesdpto@pons.es**
IV-1-5(a)	Autorización a utilizar el correo-e Se autoriza a la Oficina receptora, la Administración de búsqueda internacional, la Oficina Internacional y la Administración de examen preliminar internacional a utilizar esta dirección de correo-e para enviar notificaciones relativas a la presente solicitud internacional, si dichas oficinas así lo desean:	**por correo electrónico exclusivamente (no se enviará ninguna notificación en papel)**
V	**DESIGNACIONES**	
V-1	**Según la Regla 4.9.a), la presentación de este petitorio constituye la designación de todos los Estados contratantes vinculados por el PCT en la fecha de presentación internacional a efectos de todo tipo de protección disponible y, cuando proceda, de la concesión tanto de patentes regionales como de patentes nacionales.**	
VI-1	**Reivindicación de prioridad de una solicitud nacional anterior**	
VI-1-1	Fecha de presentación	**23 enero 2023 (23.01.2023)**
VI-1-2	Número	**P202330042**
VI-1-3	País o miembro de la OMC	**ES**

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VI-2	**Petición de documento de prioridad** Se ruega a la Oficina receptora que prepare y transmita a la Oficina Internacional una copia certificada de la(s) solicitud(es) anterior(es) identificada(s) supra como punto(s):	VI-1	
VI-3	**Incorporación por referencia :** cuando un elemento de la solicitud internacional mencionado en el Artículo 11.1)iii)d) o e) o bien una parte de la descripción, de las reivindicaciones o de los dibujos mencionada en la Regla 20.5.a), o bien un elemento o una parte de la descripción, de las reivindicaciones o de los dibujos mencionados en la Regla 20.5bis.a), no estén contenidos en otro lugar en esta solicitud internacional pero figuren íntegramente en una solicitud anterior cuya prioridad se reivindica en la fecha en la que uno o varios elementos mencionados en el Artículo 11.1)iii) fueron recibidos inicialmente por la Oficina receptora, ese elemento o esa parte, a reserva de confirmación según la Regla 20.6, se incorporarán por referencia en esta solicitud internacional a los efectos de la Regla 20.		
VII-1	**Administración encargada de la búsqueda internacional elegida**	Oficina Europea de Patentes (OEP) (ISA/EP)	
VIII	**Declaraciones**	Número de declaraciones	
VIII-1	Declaración sobre la identidad del inventor	-	
VIII-2	Declaración sobre el derecho del solicitante, en la fecha de presentación internacional, para solicitar y que le sea concedida una patente	-	
VIII-3	Declaración sobre el derecho del solicitante, en la fecha de presentación internacional, a reivindicar la prioridad de la solicitud anterior	-	
VIII-4	Declaración sobre la calidad de inventor (sólo para la designación de los Estados Unidos de América)	-	
VIII-5	Declaración sobre las divulgaciones no perjudiciales o las excepciones a la falta de novedad	-	
IX	**Lista de verificación**	Número de hojas	Fichero(s) electrónico(s) adjunto(s)
IX-1	Petitorio (incluidas las hojas de declaración)	5	✓
IX-2	Descripción	13	✓
IX-3	Reivindicaciones	3	✓
IX-4	Resumen	1	✓
IX-5	Dibujos	11	✓
IX-6a	Parte de la descripción reservada a la lista de secuencias	-	-
IX-7	TOTAL	33	

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	Elementos de acompañamiento	Documento(s) en papel adjunto(s)	Fichero(s) electrónico(s) adjunto(s)
IX-8	Hoja de cálculo de tasas	-	✓
IX-14	Traducción de la solicitud internacional al **inglés**	-	✓
IX-19	Otro	Archivo de preconversión Declaración (Instrucción 706): Esta es una copia completa y exacta de la solicitud internacional antes de su conversión en el formato de documento electrónico en el cual se presente.	✓
IX-19	Otro	TASAS	✓
IX-20	**Figura de los dibujos que debe acompañar el resumen**		
IX-21	**Idioma de presentación de la solicitud internacional**	español	
X-1	**Firma del solicitante , del mandatario o del representante común**	(PKCS7 Firma Digital)	
X-1-1	Nombre (APELLIDOS, Nombre)	PONS ARIÑO, Angel	
X-1-3	Calidad (si tal calidad no es obvia al leer el petitorio)	(Representante)	

PARA USO DE LA OFICINA RECEPTORA ÚNICAMENTE

10-1	**Fecha efectiva de recepción de la pretendida solicitud internacional**	
10-2	**Dibujos:**	
10-2-1	Recibido	
10-2-2	No recibido	
10-3	**Fecha efectiva de recepción, rectificada en razón de la recepción ulterior pero dentro del plazo, de documentos o de dibujos que completan la pretendida solicitud internacional**	
10-4	**Fecha de recepción, dentro del plazo, de las correcciones requeridas según el Articulo 11(2) del PCT**	
10-5	**Administración encargada de la búsqueda internacional**	ISA/EP
10-6	**Transmisión de la copia para la búsqueda diferida hasta que se pague la tasa de búsqueda**	

PARA USO DE LA OFICINA INTERNACIONAL ÚNICAMENTE

11-1	**Fecha de recepción del ejemplar original por la Oficina Internacional**	

Justificante de presentación electrónica de solicitud de patente

Este documento es un justificante de que se ha recibido una solicitud española de patente por vía electrónica utilizando la conexión segura de la O.E.P.M. De acuerdo con lo dispuesto en el art. 16.1 del Reglamento de ejecución de la Ley 24/2015 de Patentes, se han asignado a su solicitud un número de expediente y una fecha de recepción de forma automática. La fecha de presentación de la solicitud a la que se refiere el art. 24 de la Ley le será comunicada posteriormente.

Número de solicitud:	P202430011	
Fecha de recepción:	09 enero 2024, 16:13 (CET)	
Oficina receptora:	OEPM Madrid	
Su referencia:	ES1641.1942-PRIO	
Solicitante:	Consejo Superior de Investigaciones Científicas (CSIC)	
Número de solicitantes:	1	
País:	ES	
Título:	VÁLVULA NEUMÁTICA PARA EL CONTROL DE UN CAUDAL DE AIRE	
Documentos enviados:	Descripcion.pdf (7 p.)	package-data.xml
	Reivindicaciones.pdf (1 p.)	es-request.xml
	Dibujos.pdf (1 p.)	application-body.xml
	Resumen.pdf (1 p.)	es-fee-sheet.xml
	OLF-ARCHIVE.zip	request.pdf
Enviados por:	CN=OEPM	
Fecha y hora de recepción:	09 enero 2024, 16:13 (CET)	
Codificación del envío:	2D:64:3A:23:9E:58:D7:BC:22:8D:45:CF:3E:A1:AC:17:4D:CE:71:E9	

AVISO IMPORTANTE

Las tasas pagaderas al solicitar y durante la tramitación de una patente o un modelo de utilidad son las que se recogen en el Apartado "Tasas y precios públicos" de la página web de la OEPM (http://www.oepm.es/es/propiedad_industrial/tasas/). Consecuentemente, si recibe una comunicación informándole de la necesidad de hacer un pago por la inscripción de su patente o su modelo de utilidad en un "registro central" o en un "registro de internet" posiblemente se trate de un fraude.

La anotación en este tipo de autodenominados "registros" no despliega ningún tipo de eficacia jurídica ni tiene carácter oficial.

En estos casos le aconsejamos que se ponga en contacto con la Oficina Española de Patentes y Marcas en el correo electrónico informacion@oepm.es.

ADVERTENCIA: POR DISPOSICIÓN LEGAL LOS DATOS CONTENIDOS EN ESTA SOLICITUD PODRÁN SER PUBLICADOS EN EL BOLETÍN OFICIAL DE LA PROPIEDAD INDUSTRIAL E INSCRITOS EN EL REGISTRO DE PATENTES DE LA OEPM, SIENDO AMBAS BASES DE DATOS DE CARÁCTER PÚBLICO Y ACCESIBLES VÍA REDES MUNDIALES DE INFORMÁTICA.

Para cualquier aclaración puede contactar con la O.E.P.M.

/Madrid, Oficina Receptora/

Información de solicitud

Referencia de usuario

ES1641.1942-PRIO

(54) **Título de la invención**

VÁLVULA NEUMÁTICA PARA EL CONTROL DE UN CAUDAL DE AIRE

Partes intervinientes

(71) Solicitante 1

Nacionalidad

España

Categoría

Centro público de investigación español

Nombre de la organización

Consejo Superior de Investigaciones Científicas (CSIC)

NIF

Q2818002D

País

España

Provincia

Madrid

Código Postal

28006

Localidad

Madrid

Dirección

C/Serrano,117

Porcentaje de titularidad

100,00%

Declaración de derechos

El solicitante ha adquirido el derecho a la patente de la siguiente manera:

- [x] Invención laboral

74 Representante 1

Tratamiento

D.

Apellidos

Pons Ariño

Nombre

Ángel

Código de agente

0499/5

NIF

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Poder de representación

☑ Número de poder general otorgado por la OEPM

Poder general

20081765

72 Inventor 1

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05724847D

72 Inventor 2

Tratamiento

Dña.

Apellidos

Fernández Saavedra

Nombre

Roemi Emilia

Nacionalidad

España

NIF

01188823E

Dirección de notificación

Medio de notificación

Correo electrónico

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Madrid

Código Postal

28010

Localidad

Madrid

Dirección

Glorieta de Rubén Darío, 4

Correo electrónico

patentes_comunicaciones@pons.es

Declaraciones

Datos no proporcionados

Información sobre material biológico y lista de secuencias

Datos no proporcionados