Instituto Tecnológico y de Estudios Superiores de Monterrey

Campus Monterrey

School of Engineering and Sciences

DESIGN OF A SOFT GRIPPER WITH COMPLIANT MECHANISMS

A thesis presented by

Alfredo Puente Flores

Submitted to the
School of Engineering and Sciences
in partial fulfilment of the requirements for the degree of

Master of Science

In

Manufacturing Systems

Monterrey Nuevo León, December 1st, 2021

Dedication

First, I would like to give thanks to God because I strongly believe that if it were not for Him, I would not even be here. One way or another I have always felt His presence in my life and even when I felt the loneliest and did not seem to find a way out of the darkness that was consuming me, I could always manage to find my way.

I have many people to thank even from before the inception of this project. Clearly without my parents I would not even be here today. They have always, and I am sure will always, supported me unconditionally. Without their love, support, and encouragement the completion of this project would not have been possible.

I am sure I put my parents through a lot during my childhood since I loved to disassemble my toys and other things to see what they had inside just because I had the idea that a robot could be created out of the PCBs and other parts I could find inside them. What can I say? I wanted a friend. Despite my antics, they always loved me and even supported my "experiments". I suppose that had not it been for that, I would not have become an Engineer.

I must also thank my grandparents, Gustavo, and Esther because they played an important role in my life not to mention they also experienced the outcomes of my first electrical works as a kid – short circuits, of course. Unfortunately, my grandpa could not see me become an Engineer. However, I am sure that wherever he is, he knows what I am doing now.

In my life there are truly important individuals and I sincerely believe that without them, I would not have completed this work. I would like to thank 우리 누나 (임주리). Although she is not blood-related to me, in more than seven years she has been to me like the older sister I never had, and she always believes in me no matter what. 누나, 고마워요. 진짜, 진짜 고마워요.

To Алима and Мариам. Because they are special to me even if I do not tell them often. Both have been there for me during the past two to three years cheering me up, scolding me from time to time when necessary, and making me laugh. My days would not have been as cheerful without them. Алима, Мариам… спасибо за всё.

Finally, I would like to thank someone incredible who manages to colour my days with her spontaneity and warmth. What would have been of me without all your warmth, jokes, and toys you always find on the street while talking to me on the phone, Наталья? У меня нет слов чтобы выразить всё, что я хочу тебе сказать, но ты итак всё знаешь. Спасибо большое, Таша.

Thank you all for believing in me and being an important part of my life.

그만둬야겠다 생각을 하다가. 그 생각을 그만뒀다.

– Daniel Armand Lee, BLONOTE

On ne voit bien qu'avec le cœur. L'essentiel est invisible pour les yeux.
– Antoine de Saint-Exupéry, Le Petit Prince

Il ne faut pas oublier que toutes les grandes personnes ont d'abord été des enfants. C'est pour ça que je me demande toujours : « Le mouton oui ou non a-t-il mangé la fleur ? ».

Acknowledgments

It is impossible not to thank my thesis advisors, Professors – Armando, Pedro, and Kike. They were always there whenever I needed something and were always pushing me into the right direction so that the project could be successfully completed. Had not they been there, I would still be lost in a sea of articles trying to row in different directions at the same time. Also to Professor Carlos Vasquez who helped at the lab in order to perform the different testing with the grippers.

I would also like to thank Tecnológico de Monterrey and CONACyT for their support.

DESIGN OF A SOFT GRIPPER WITH COMPLIANT MECHANISMS

by

Alfredo Puente Flores

Abstract

Robotic manipulators can perform repetitive tasks at rates and accuracies that cannot be rivalled by those of human operators. Nowadays, they are rather ubiqitiuos and widely used in different fields. However, that is not all. Robotic manipulators have slowly started to incursion in fields other than manufacturing like that of medicine and agriculture. Because of the wide variety of fields that currently employ robotic manipulators, tasks can be more complex than the usual ones. For this reason, traditional mechanical grippers are not always adequate and there is currently a high demand for grippers that can effectively adapt to grasp a wider variety of objects – especially those that aree fragile or deformable – without damaging them.

Current grippers are mostly made of mechanical linkages what makes them stiff and non-adaptive, which is a disadvantage when attempting to grasp delicate objects. Soft grippers can be an adequate solution for this problem and have gained attention in recent years. Although some models have been presented in the literature, they have several drawbacks. This work presents the design of a novel soft gripper that can adapt to the shape of the object. Experiments were conducted to validate the proposal.

List of Figures

List of Tables

Contents

Chapter 1 Introduction

1.1 Motivation

Robots have grown to be highly diverse. Some walk and others fly; some are small while others are humongous, some have animal or human appearance while others resemble a human arm. Currently, robots are almost ubiquitous and are not used only for industrial purposes. The areas where they are being used have expanded over the years, and nowadays, there are even robots that can help a surgeon perform less invasive surgeries (Harada et al., 2001; Hoznek et al., 2008; Modine & Elarid, 2012; Schneider & Feussner, 2017; Boyraz et al., 2019; Song, 2020).

In a sense, robots can ease our lives. Nonetheless, their versatility and helpfulness come at a cost: they require humans to improve their proficiency by adding better sensors and more dexterous and versatile end effectors.

Modern manipulators can exceed humans in some tasks. They can lift heavier loads, have repeatability, and move faster. Their price has been slowly decreasing over the years compared to the cost of manual labor. These advantages have encouraged researchers to develop and design cheaper, more advanced, and precise robotic manipulators and grippers that can be used for a wider diversity of purposes.

1.2 Problem Statement and Context

Robotic grippers or end effectors interact with the environment to grasp and manipulate objects. Grasping can be defined as the ability to pick up and hold an object against any external disturbances (Shintake et al., 2018). On the other hand, manipulation is defined as the act of exerting forces on an object to cause either a rotation or displacement with respect to the reference frame of the manipulator (Shintake et al., 2018). Traditional grippers (i.e., mechanical grippers) consist of a set of rigid joints and links with actuators that can be housed within the links, joints, or at the base of the gripper. In some cases, sensors can be added to provide the robot with a way to obtain information from the outer world as seen in a few models in the literature.

Despite their ubiquity, mechanical grippers are not suitable for the task of manipulating/grasping delicate objects since they can damage objects (Venter & Dirven, 2017; Hussain et al., 2018; Milojevic et al., 2018; Elgeneidy et al., 2019; Nguyen et al., 2018; Homberg et al., 2015; R. Chen et al., 2019; Trivedi et al., 2008; Shintake et al., 2018). Therefore, for specific applications that require manipulating fragile objects, there is currently the necessity to design alternatives to rigid robots and grippers

Attempts to design more anthropomorphic grippers have been made to find more suitable types of end effectors; however, the complexity of those solutions is a considerable detriment that prevents them from being used. The quest to find less complex and universal grippers; brought the concept of soft robotics and made it gain popularity during recent years. While the idea of soft robotics has been around for a while, there is still room for improvement as can be seen in the following examples from literature.

Several attempts have been made to design a soft robotic gripper that can effectively grasp a wide variety of objects by adapting to their shape. However, further research is required due to the following reasons: difficult to build (Homberg et al., 2015), complex steps to assembly (Homberg et al., 2015), limited adaptability (Wang et al., 2016), limitations in the variety of objects that can be grasped (Wang et al., 2016), heavy/bulky (Wang et al., 2016),, do not provide feedback about the state of the material (Wang et al., 2016), few have real-time force feedback controllers (Wang et al., 2016), current designs cannot be escalated to the microdomain (Milojevic et al., 2018; Trivedi et al., 2008), expensive (Milojevic et al., 2018; Trivedi et al., 2008), no unique synthesis method (Milojevic et al., 2018; Trivedi et al., 2008), and reduced scalability for mass production (Milojevic et al., 2018; Trivedi et al., 2008).

Additionally, not all the different designs of soft robotic grippers presented in the literature have embedded sensors or can adapt their force to perform the grasping/manipulation tasks. Furthermore, under-actuation has been recognized as essential for grippers; however, the task of minimizing the number of actuators needed for one gripper remains unsolved, and it is considered a difficult task (Liu et al., 2019; Liu & Chiu, 2017).

Traditional mechanisms consist of rigid links that are connected to movable joints. While a traditional mechanism consists of rigid links connected to movable joints, a compliant mechanism gets mobility derived from the deflection of some or all of its members (i.e., components), rather than from joints (Howell et al., 2013). A complaint mechanism is thus a monolithic or quasimonolithic structure that can achieve force and motion transformation through elastic deformation of its members.

Compliant mechanisms have advantages that include: monolithic nature, reduced complexity, easy to manufacture (i.e., 3D printing), reduced or no assembly, friction-free motion hence no need for lubrication, and better scalability (Milojevic et al., 2018). The advantages that complaint mechanisms present make them desirable for designs of soft or adaptive grippers.

The applications where more adaptive grippers can be used are wide, and the need for more dexterous and compliant grippers is still there. Soft robots have unique advantages in environments that call for conformity and variable stiffness. Since compliant grippers can adapt to different shapes without specific control inputs, they can dramatically reduce the costs and complexity of any given robot's control systems while improving grasping performance and manipulation dexterity compared to mechanical grippers. From all the mentioned it can easily be inferred the impact of a potentially more universal design.

1.3 Research Questions

Considering the current necessity of a soft gripper capable of adapting to different objects to perform different tasks and the different disadvantages current soft grippers that can be found in the literature have:

- Is it possible to design a monolithic-single-actuated soft gripper with the use of compliant mechanisms that can be single actuated?
- Is it possible to design a monolithic-single-actuated soft gripper that can successfully adapt to different geometries by using a compliant mechanism?

1.4 Objectives

The main objective of this research thesis is to design a monolithic and single-actuated dexterous soft gripper with the use of compliant mechanisms which can adapt to different shapes.

As secondary objectives:

- Test the performance of the gripper mounted on a robot to perform actions of pick and place with different objects.
- To design a monolithic dexterous soft gripper that is not “bulky”.
- To design a scalable monolithic dexterous soft gripper.
- To validate and explore the feasibility of using compliant mechanisms to design a dexterous soft gripper.

1.5 Main Contributions

- Design and testing of a novel monolithic and dexterous soft robotic gripper capable of successfully adapting and grasping different geometries.
- Initial exploration of the feasibility of using metamaterials instead of compliant hinges for the original proposed geometry of a novel soft gripper.

1.6 Distribution Organization

The present document is organised in 5 chapters. A general introduction is given in Chapter 1. Chapter 2 contains all the pertinent to the literature review. Chapter

3 and 4 correspond to the design and the testing stages correspondingly and Chapter 5 Gives an account of further work that can be done and presents some simulations that were performed trying to incorporate metamaterials to the gripper so that different patterns could be used in different areas to achieve the desired behaviour.

Chapter 2 Literature Review

The literature review that serves as the basis for this research project is presented in this chapter.This chapter presents a review of existing soft grippers found in the available literature and an introduction to compliant mechanism.

2.1 Soft Robotic Grippers

2.1.1 Brief Overview of Soft Robotics

The field of robotics has already expanded beyond industrial settings to healthcare, cooperative human assistance, and agriculture; just to mention some (Majidi, 2014). These fields require robots to be more versatile and less rigid. These developments have made soft robotics become one of the fastest growing topics in the robotics community and academia. (Bao et al., 2018). Soft robotics has not only gained popularity among researchers and academics around the globe but also among the general public. This popularity can be understood as an indicator of the field's huge potential to impact the current role of robots in the modern world.

Although the future of soft robots is quite promising, the research on the topic still offers opportunities for new developments ~~is~~ by no means extensive. Attempts to design novel robots different from the coneventional ones started before the term soft robot was even coined (i.e., Efforts to develop a soft robot started in the 1950s, and the term was adopted until 2008.) (Bao et al., 2018). According to Bao et al., (2018), the first time the term soft robot was used was to investigate rigid robots with compliant joints and robots made of soft materials. After that, the term would be used to denominate a new multidisciplinary field that involved soft material robots that possessed compliance and deformable characteristics. Although the first scientific articles about soft robots were published during the nineties, it was not until recent years that soft robotics would become a trending topic for researchers (Bao et al., 2018).

2.1.2 Robotic Grippers

Tasks like picking and manipulating objects of different shapes, sizes, and materials are rather simple for humans; however, they pose a great challenge for robots (Brown et al., 2010). Robotic grippers reperesent an essential part of robotic manipulators because they serve, in a certain way, as their hands. Without them, robotc manipulators cannot perform tasks.

A gripper is a tool that is mounted at the end of a robotic manipulator and it being the last part of a robot, it is common to call those end effectors. End effectors have the purpose of interacting with the environment – that is, their job is to grasp, carry, manipulate, and place workpieces (Tai et al., 2016).

The first mechanical grippers were first commercialized as standard products around 30 years ago (Zhang, Xie, Zhou, Wang, & Zhang, 2020). Traditionally, they consist of several rigid joints and links with electric, pneumatic, or other types of actuators that are housed within the joints, links, or at the base of the whole structure to produce the desired movement. Traditional grippers cannot offer the dexterity of a human hand or grasp/manipulate soft and deformable objects easily.Moreover, human hands can grasp objects of various shapes and sizes and explore and perceive physical properties.

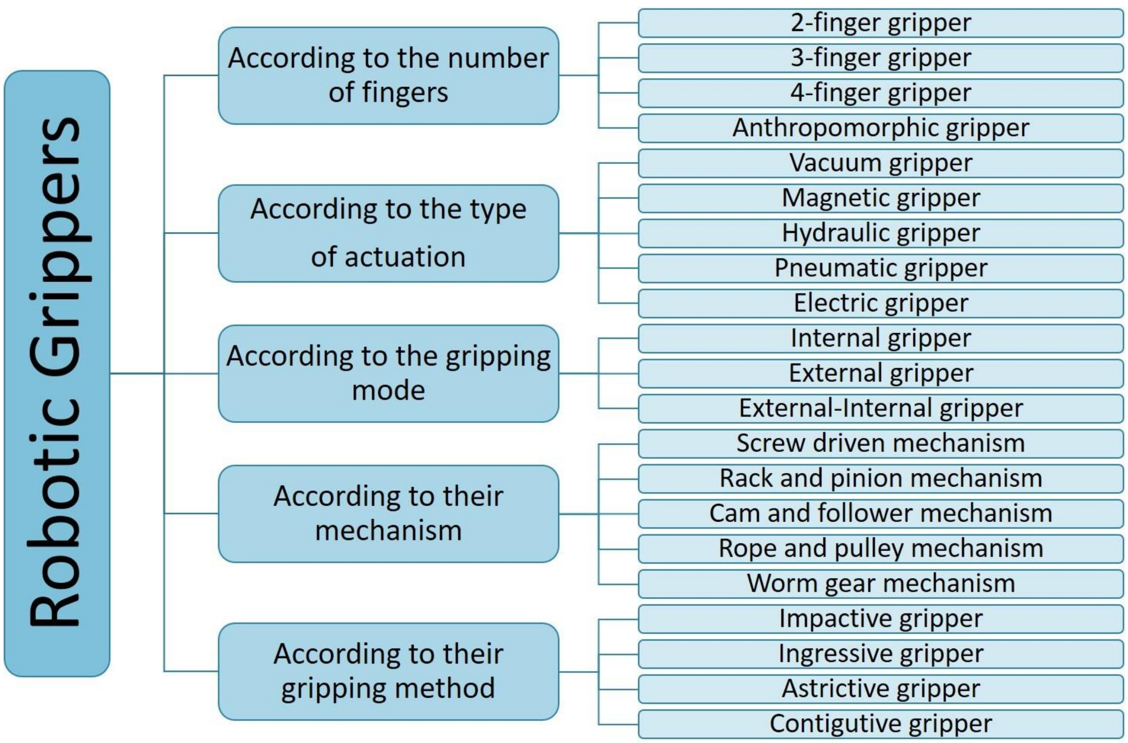


Figure 1 Gripper classification according to the different classifications that can be found in the literature (Adapted from: Zhang, Xie, Zhou, Wang, & Zhang, 2020).

In an attempt to try to give robots some awareness of the environment, robotic grippers can be equipped with proprioceptive sensors (Shintake et al., 2018) (e.g., mechanical, optical, magnetic, and electromagnetic encoders, torque sensors, Hall-effect sensors) to estimate the current position and velocity of the elements of the gripper (i.e., to give information about the gripper itself), and with exteroceptive ones (Shintake et al., 2018) (e.g., pressure sensors, optical sensors, conductive sensors) to gather information about the objects that are to be grasped/manipulated. Those significant changes are intended to make them more suitable and competitive in the modern world.

Due to the wide variety of settings where robots can be used, many robotic grippers have been tailor-made to suit all the different requirements of those settings.

Figure 1 shows a gripper classification that can help to better understand the vast diversity of existing grippers.

From the classification by number of fingers, it is essential to highlight that the most common is the 2-finger gripper (Birgen et al, 2018; Zhang, Xie, Zhou, Wang, & Zhang, 2020). Although it might come as something odd at first glance, it is nothing strange that those grippers are the most common because of the human hand design. According to some studies, around 65 % of human's grasping of objects with parallelepiped, pyramidal, and cylindrical shapes is performed with only two fingers (Hugo, 2013).

Also, it was found by Lee & Jung (2014) that in 95% of their trials, the five most common types of grasps were the 2P(TI), 3P(TIM), 4P(TIMR), 5P(TIMRL), and 5G(TIMRL). (In their classification P stands for "Pinching" and G for "Grasping". The fingers are abbreviated as follows: T, thumb; I, index finger; M, middle finger; R, ring finger; and L, little finger.)

While it is true that 2-finger grippers have disadvantages and that it would be more convenient to at least have 3-finger grippers, as the number of fingers in a gripper increases so does the complexity of the control and their price Figure 2.

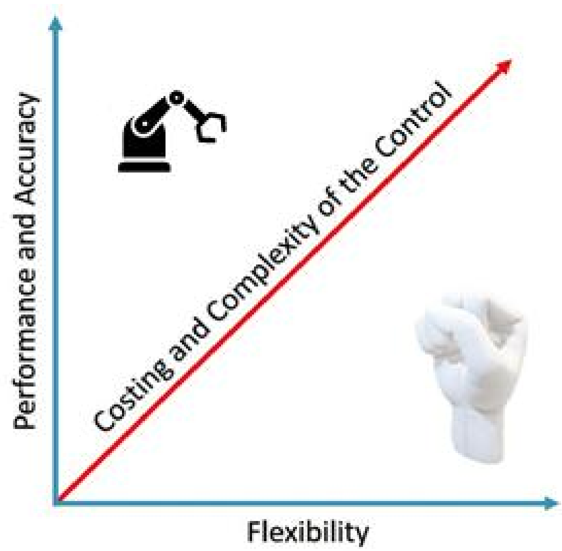


Figure 2 Performance, flexibility, affordability, and complexity of the control of grippers. (Adapted from: Basson, & Bright, 2019; Zhang, Xie, Zhou, Wang, & Zhang, 2020).

As seen in Figure 1, when grippers are classified by the nature of their actuators, there are five possible categories. From those categories, the most common actuators that have been reported for grippers are pneumatic and electrical ones.

Pneumatic actuators are commonly used whenever it is needed that the gripper provides a high gripping force; however, when a more precise control is the target, the high forces that can be obtained with such actuators is often sacrificed and electrical actuators are used instead.

On the same diagram referred above, it is possible to see other classifications that have been proposed; however, those classifications will not be discussed here. For further reference on those the reader can refer to (Zhang, Xie, Zhou, Wang, & Zhang, 2020).

Currently, the leading manufacturers and vendors of grippers are: SCHUNK®, SMC®, Festo®, IAI®, Parker®, Yamaha®, Zimmer®, Destaco®, SMAC®, Gimatic®, PHD®, and Camozzi® (Zhang, Xie, Zhou, Wang, & Zhang, 2020).

The most innovative models are currently those by Festo®. Most of those models found their inspiration in the natural world. Without geckos, octopuses, fish, and birds those models possibly would not have even existed and prove that nature has been and will always be an important source of inspiration for engineers and inventors to solve many scientific and technological problems for it is only there that the vastest source of information is.

It should be evident for the reader by now the way grippers have evolved from their primitive traditional forms and the inclination to design less-rigid grippers for different applications. However, to this day, the most ubiquitous grippers are the mechanical ones with two or three fingers due to their simplicity and low cost. The problem of those models is obvious: Unless carefully controlled, grasping with a traditional gripper might lead to damage of the grasped object or might end up pushing it out of the desired path. One common solution that is being used is to add compliant materials or soft pads to the gripping elements.

Something commonly done is that when a robotic manipulator is needed for the handling of fragile or easily deformable objects, mechanical grippers integrated with some compliant pads are adjusted and the control is calibrated so that the force employed by the actuator falls between an allowable range the object can take without breaking or deforming according to the case. This practice requires adjusting the robot control manually, thus it can be time consuming. In addition to this, some objects might still be damaged. More disadvantages of this practice in an industrial setting being evident for the reader from the facts that were just mentioned will not be listed here.

There is still no complete solution to make the ubiquitous mechanical grippers suitable for the handling of fragile or easily deformable objects. The idea of having a low-cost and simple robotic gripper that can manipulate both soft and fragile objects is what made academics and companies like Festo® strive to design less-rigid models as the ones mentioned above.

The story of the development of soft grippers can be traced back to the 1970s with tendon-driven-rigid-multi-link devices that explored the application of the "Active Cord Mechanism" inspired by the movements of the snake (Hirose & Umetani, 1978). This mechanism helped demonstrate the idea was feasible and set the path for the development of new models and concepts during the 1980s and 1990s like the model proposed in (Suzumori et al., 1991) where flexible micro-actuators (FMAs) are applied to a robotic mechanism. It is also during those years that memory foams and electroactive polymers (IPMCs) also started to be used for grippers (Shintake et al., 2018).

During the 2000s the advancements in research allowed researchers to develop more sophisticated grippers. However, the "gripper race" still continues and scientists around the world are still trying to find a design that can tackle some of the disadvantages current designs have.

Among the disadvantages existent soft grippers have are: Hard to build (Homberg et al., 2015), hard to assembly (Homberg et al., 2015), limited adaptability, the variety of objects that can be grasped is limited, heavy/bulky, no feedback about the state of the material, few have real-time force feedback controllers (Wang et al., 2016), current designs cannot be escalated to the microdomain, expensive, no unique synthesis method, numerous actuators (Liu et al., 2019; Liu Chiu, 2017), and reduced scalability for mass production (Milojevic et al., 2018; Trivedi et al., 2008).

2.1.3 Soft Gripper Classification

In 2018 Shintake et al., proposed three categories according to their gripping technologies into which soft grippers could be categorized: i) by actuation, ii) by controlled stiffness, and iii) by controlled adhesion. Although these categories are by no means exclusive since in some cases several technologies can be used, this categorization helps to better understand the technologies that are being used and even visualize the advantages and disadvantages of each.

In the present work only gripping by actuation will be reviewed due to the focus it has. However, information on the other categories can be found in the work previously mentioned and elsewhere.

2.1.3.1 Gripping by Actuation

In soft grippers, grasping can be achieved through the adaptation of compliant structures deformed by either external or internal actuators. Among the different actuator technologies, it is possible to count; passive structures with external motors, fluidic elastomeric actuators, electroactive polymers, and shape memory materials (Shintake et al., 2018).

Usually, the external motors approach is preferred and widely used in the field and industry due to the several advantages of it (Shintake et al., 2018). For starters, the actuator being external, it does not directly influence the size, and weight of the gripper, thus offering the designer a wide catalogue of actuators for se- lection. Some others include ease of integration, control, and implementation in different settings.

Soft manipulation can be achieved by means of compliant structures moved by external actuators and passively adapting to the object’s shape. The main characteristic of grippers that use this kind of approach or technology is the absence of active elements inside the gripper structure that is in contact with the object (Shintake et al., 2018).

There are two types of soft grippers using external motors: contact-driven and tendon-driven grippers. These two categories will be further introduced in the following sections.

2.1.3.1.1 Contact – Driven Deformation

There are several grippers that take advantage of compliant structures which can be forced by mechanical inputs as a strategy for grasping. One of the most popular examples are the grippers using the Fin Ray® effect (Crooks et al., 2016, Crooks et al., 2017, Basson Bright, 2019, Elgeneidy et al., 2019, Chen et al., 2019). In the case of the gripper by Chen et al., although - in principle - the Fin Ray effect is used, the gripper was enhanced by using electroadhesion.

Although the Fin Ray® effect is rather popular. There are other gripper models like the one proposed by Petkovic in 2013 and the models proposed by Liu and Chiu in 2017 that are also good examples of grippers with this actuation technology that is achieved by means of using compliant mechanisms.

Complaint mechanisms have opened new possibilities for contact-deformation grasping. These mechanisms will be further discussed in the following sections to greater extent and detail. However, for the reader’s sake, a brief explanation is provided: Compliant mechanisms – unlike traditional ones – do not consist of rigid links connected to movable joints. Instead, they gain mobility from the deflection of some of its members (i.e., components) rather than from joints (Howell et al., 2013). It is because of their nature that they can be exploited to explore new possibilities for contact-driven grasping.

Chih-Hsing Liu et al. (Liu & Chiu, 2018) designed three monolithic compliant grippers made of silicon rubber for applications where adaptability is necessary. Their grippers can be classified as 2-finger designs actuated by a single linear actuator. For their designs compliant mechanisms were used due to their monolithic nature. However, it is important to highlight that topology optimization methods were used to define the shape of their grippers.

Their designs were tested with concave and convex shapes as well as with objects such as a helicopter toy, a banana, a lemon, an apple, and a cucumber and it showed good adaptability. In addition to those tests, they performed a payload test, and the gripper was shown to withstand a maximum payload of 2.5 Kg.

Petkovic and Pavlovic (Petkovic et al., 2012) attempted to design a universal gripper that could be able to pick up familiar objects of a wide variety of shapes and surfaces. Their proposed design uses compliant mechanisms as well due to the several advantages they have.

Although their design is novel and can conform to different shapes, there are several drawbacks. The first one is that the design was made by press-cutting from silicone. Said process requires a mould as can be understood. Another drawback of their proposed design is that due to the gripper's high flexibility it is virtually impossible for it to hold heavy loads.

Another example of the contact-driven deformation approach that uses compliant mechanisms as well is the gripper proposed by Milojevic and company in 2018 (Milojevic et al., 2018). The group presented a shape morphing compliant structure that integrates actuators and sensors within it to be used as a soft robotic gripper. In their gripper, the embedded actuators that help the gripper achieve the desired movement are made of shape memory alloy wire – nitinol – and the sensors are formed by using conductive graphene.

In their work, they decided to use compliant mechanisms since they can deform smoothly and thus provide advantages for shape morphing and adaptability – desired characteristics in a soft robotic gripper. Also, by integrating actuators and sensors to the compliant mechanism they enhanced it for the desired purpose and attempted to emulate biological systems where the sensing and actuation is usually embedded in a single system. An example one of those systems being human hands where the sensors are "the senses" and the embedded actuation "the muscles and tendons".

The authors defend the idea of using several actuators within the compliant structure by stating this is necessary for the gripper to be able to adapt to multiple shapes when grasping. However, integrating several actuators that must be tailor-made for the application can impact the scalability and the feasibility of mass producing such a gripper. In fact, it has been noted in the literature that single actuation is preferred but still hard to achieve.

Although the model they have presented is novel, they have solely presented a single and a two-finger gripper that can move and sense. However, the system has not been tested as of yet for any applications to the author's knowledge.

As of now we have seen examples of grippers using compliant mechanisms in the macrodomain. However, currently there is an increasing demand for grippers capable of manipulating delicate objects in the microdomain. Manipulating objects in the microdomain is a considerable challenge since there is uncertainty in sizes and stiffness of the objects that are to be manipulated (Nguyen et al., 2018).

There have been several attempts to give a solution to this problem. Among the attempts it is possible to count the efforts by Shi and company (Shi et al., 2018). They presented a gripper based on compliant mechanisms. Their gripper is intended for manipulating opto-fiber and their work only analyses it analytically and with FEA analyses.

Duc-Chuong Nguyen et. al., presented a conceptual gripper which can maneuver objects of various sizes while preserving a constant gripping force using compliant mechanisms. In this design there is no necessity for sophisticated sensors or control systems since compliant mechanisms are used.

The authors used FEAs to characterize the design under static loading and they also presented a methodology to optimize their design shape based on GA (Nguyen et al., 2018).

Compliant mechanisms have been demonstrated to work well for the macro and micro domains when precise motions are required. In addition, complaint mechanisms offer advantages such as no backlash, no dry friction, no wear, and no tear.

Although soft grippers are intended to be entirely soft systems, there are cases where passive structures have been combined with rigid systems in the form of pads, fingertips, threads, and strips (Shintake et al., 2018). These systems are also taken as part of this classification.

2.1.3.1.2 Tendon – Driven

Tendon-driven structures recall the first designs that were explored to demonstrate the feasibility of soft grippers inspired by the way snakes move (Hirose & Umetani, 1978). However, the tendon drive itself might have found its origin in the way human fingers work.

These structures are and have been widely employed not only for grippers but for the design of robotic hands. The generality of those structures consists of a body with multiple degrees of freedom actuated by a single tendon (Shintake et al., 2018).

Tendon-driven grippers have traditionally consisted of rigid links, joints, and springs. However, those can be replaced by hinges made of elastic materials. By replacing them the systems can be simplified and even made to be monolithic; thus, avoiding the need for assembly and promoting the reduction of production costs.

There are different grippers that were designed based on this actuation technology listed by Shintake. Some of those designs were enhanced with tactile sensors and the inclusion of compliant materials or skin. It has been found those enhancements have shown some promising advantages for grasping. Nonetheless, the problem of miniaturization has not been solved and remains under study also, further work on these kinds of grippers is expected to focus mostly on control since the mechanics of these systems is already well understood.

2.2 Compliant Mechanisms

Nature has been, historically, the source of inspiration for engineers and inventors to solve many scientific and technological problems. It is in nature that it is possible to find countless examples of how to efficiently achieve controlled motion. From it we learn that most moving components are flexible, and the motion is achieved due to bending of flexible parts instead of rigid parts connected with hinges.

Nowadays when someone thinks about mechanisms, they usually picture some rigid parts connected to hinges or sliding joints. However, in the past the first mechanisms and tools that humans fabricated were compliant mechanisms. A clear example of this are bows. It can be assumed this was because early humans were closer to nature and all the compliant mechanisms that can be found in it.

Howell mentions in his book (Howell, et. al, 2013) that something that bends in order to achieve what it is meant to do is compliant and that if said flexibility also helps that something accomplish something useful, then that is when something becomes a compliant mechanism.

While a traditional mechanism consists of rigid links connected to movable joints a compliant mechanism is a mechanism which gets its mobility from the deflection of some of its members (i.e., components), rather than from joints (Howell et al., 2013).

Although compliant mechanisms are difficult to design, nowadays there is a tendency to design less-rigid mechanisms due to the new necessities of the contemporary society. The advancements in knowledge have made this tendency possible. Especially those advancements in material's science.

The advantages of compliant mechanisms over their traditional counterparts include: the possibility of being made only of one layer of material – particularly useful for MEMS –, lack of assembly (monolithic), compactness, friction-free motion – due to the fact these mechanisms gain their motion from the deflection of flexible members –, wear-free motion – particularly helpful for devices that are required to undergo a considerable number of motion cycles –, no need for lubrication, high precision and reliability.

The last two characteristics make them especially desirable for positioning mechanisms like the 3D-printed three degrees of freedom spatial motion compliant parallel mechanism to be used for high precision manipulation developed by Min Tuan Pham and his team (Pham et al., 2017).

Although compliant mechanisms have many advantages, it is impossible not to mention there are several challenges or disadvantages to their use. A clear one is their dependency on the mechanism's material properties – in some cases those properties can be somewhat obscure. Other challenges include; their nonlinear motions, fatigue due to repeated loading, and a somewhat difficult design process.

Fatigue life is of particular interest when it comes to compliant mechanisms since their movement comes from the bending of flexible parts and stress usually concentrates on such locations. Although there are already methods to analyze and test fatigue life, special attention and effort is required to ensure the mechanism's life even when exposed to repeated loading.

Although compliant mechanisms have been extensively studied during the past decades, there is no accepted general methodology for designing them. Thus, developing a methodology for designing compliant mechanisms still remains an open area (Zhang & Zhu, 2018). Despite a common method being non-existent, several approaches have been developed and perfectioned over the years.

Among the first approaches used for designing compliant mechanisms there are the ones based in converting an analogous rigid-body mechanism into a complaint one (i.e., kinematics-based approach) (Howell et al., 2013; Wang et al., 2019; Yu et al., 2011).

This methodology helps to quickly explore a variety of feasible compliant mechanisms and select the most viable design. This technique might be a quick way of designing a compliant mechanism. Howbeit, it is important to highlight that a great deal of intuition and involvement on the part of the designer is required. Not to mention some of the mechanisms created using this approach, more often than not, might end up having lumped compliance (Zhang & Zhu, 2018).

Most of the compliant mechanisms we see nowadays, especially the ones designed by using the kinematic approach are built based on flexure hinges or flexural pivots. These, provide a relative rotation between two adjacent rigid members through a bending mechanism as their homologous (i.e., rigid joints) would.

Since flexure hinges are the main points where stress concentrates in a compliant mechanism because of the cyclic bending. Fatigue life is something that should be considered when designing a compliant mechanism, especially since their motion comes from the bending of flexible parts (Howell et al., 2013).

Another method for the design of compliant mechanisms is topology optimization (Zhang & Zhu, 2018). This method is often complemented with FEA methods to consider as many possible ways as possible of distributing material within the mechanism's design domain. This methodology has the potential to find designs that otherwise would not be easily discovered by other means.

There are already some methods to assess the life a given mechanism is expected to have (Howell et al., 2013; Zhang & Zhu, 2018). Finite element methods are the most powerful and general methods available to analyze compliant mechanisms (Howell et al., 2013). However, a marked tendency to avoid the use of kinematics-based approaches, so as to try to overcome the disadvantages those pose, has appeared due to the emergence of more topology optimization methods like the one presented by (Zhang & Zhu, 2018).

The linear optimization method proposed by (Zhang & Zhu, 2018) is a novel, easy, and efficient method for the design of compliant mechanisms as demonstrated by them in the examples that can be found in the aforementioned work and (Zhu et al., 2013). The non-linear model of the same methodology was also recently presented (Q. Chen et al., 2019).

2.3 Fabrication Methods of Compliant Mechanisms

There are different ways a complaint mechanism might be manufactured. Among the different methods that can be used it is possible to find conventional and unconventional manufacturing methods. Among the conventional manufacturing methods, milling, 3D printing, and moulding are the most common methodologies that can be found in the literature that are able of producing a monolithic compliant mechanism or structure.

It is, however, possible to find non-conventional methods like electro erosion machining, chemical and electrochemical machining, laser beam processing, and electron beam with plasma or waterjet. It is also possible to find other manufacturing methods when it comes to the production of MEMS, which are compliant mechanisms. Nonetheless, one of the most common methods found in literature for the manufacturing or prototyping of compliant mechanisms is 3D printing for the advantages it offers and ubiquity (Daniel Lates, et. al, 2016).

Several advantages of 3D printing for the manufacturing of compliant mechanisms are; the low complexity, the low cost, the ability to create pieces with a complex shape, and the ability to quickly create and test parts (Daniel Lates, et. al, 2016).

Chapter 3 Gripper Design

3.1 Gripper Design

For the design of the gripper several variables play a role: distance between the tips, thickness of the gripper – because of the use of compliant mechanisms –, location and kind of flexural hinges, actuator, and manufacturability. In the beginning all the efforts were put towards identifying a possible shape that could be suitable for the gripper.

In order to generate a suitable a suitable geometry, reviewing what had already been done in previous works as well as the already commercially available soft grippers and what is already available in nature was of the utmost importance so as to understand what had been done before. While in this process, the necessity of picking a form that could be single-actuated and entirely 3D printed in one piece – monolithic – so as to avoid any assembly was one of the goals that could not be forgotten.

All together, the process of selecting a suitable shape was not an easy task. Among the first shapes that were tested there are horseshoe inspired forms, some arcs, complex shapes inspired in Chinese characters, and one form inspired in crustaceans' claws (Fig. 3).

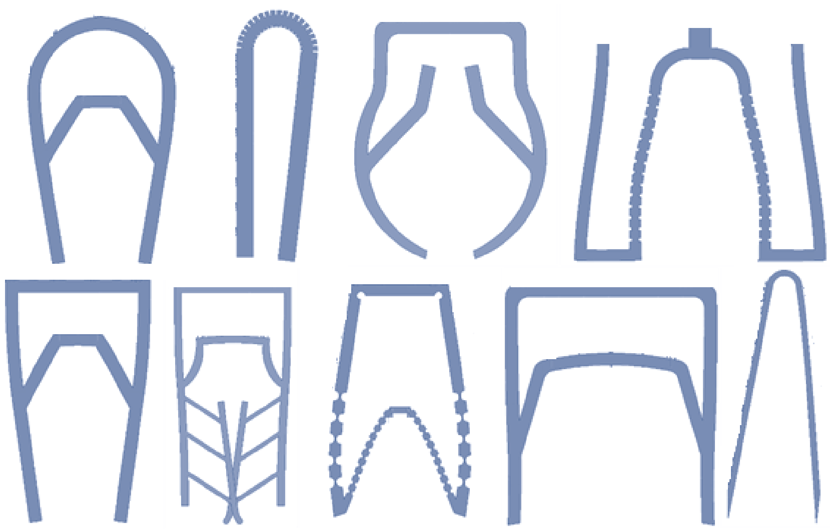


Figure 3 Some of the shapes that were explored

The different options were designed entirely intuitively taking as inspiration different shapes available in daily used objects and language as mentioned above. The shapes that inspired these designs were shapes that more or less could behave like a gripper or like “pincers” in some cases. This last because it is the desired and expected behaviuor of a gripper.

In order to understand the way, the different shapes that were proposed were behaving, linear FEA simulations in SOLIDWORKS® were performed. The simulations constrain the upper part of the gripper and apply a force of $\mathbf{200}\ \boldsymbol{N}$ at the magenta arrow as shown in Fig.4 and the material selected was ABS. Among the shapes that were explored, the one that apparead to be the most suitable – based on the displacement obtained at the tips and possibilities of actuating it with a single actuator – for adapting to different objects was that inspired by crustacean’s claws.

As can be seen, this shape, unlike the others, is the one with the most potential for adapting to different objects if some compliance is achieved in the inverted-middle “V” part of the “claw”. However, the other shapes could also be further explored for the manipulation of small objects since the way they behave is similar to the way “pincers” do and they also show some potential.

Once the design inspired by crustacean’s claws was selected due to the potential that was seen in the FEA simulations the focus was entirely given to that shape and the problem changed from “What form?” to “How to achieve the desired movement/effect with this shape?”. To solve this problem the behaviour of the shape had to be better understood.

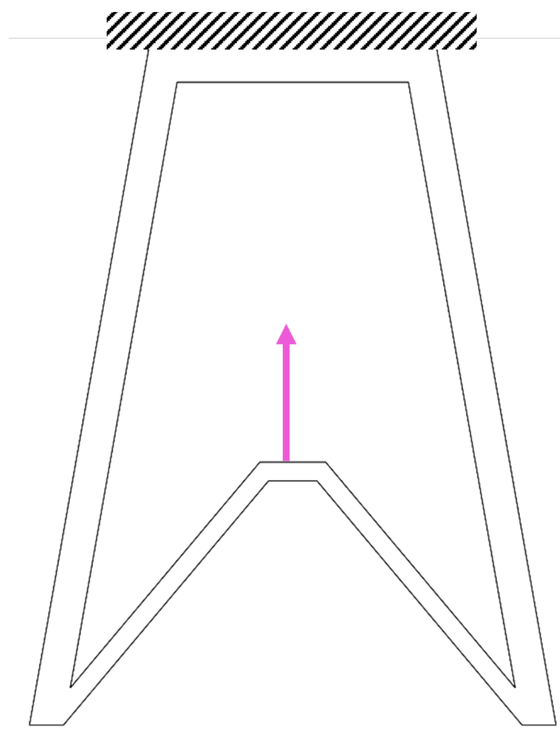


Figure 4 Original solid design of the selected shape

The original solid design of the shape was that shown above (Fig. 4). The first step that was taken was to better understand the way the structure was behaving with the help of linear FEA simulations and a K-means cluster analysis.

The clustering was performed in order to attempt to map the gripper in different regions according to the displacement that the points were experiencing. This was done with the purpose of possibly dividing the geometry in different sections as done in a work presented by Ion et al., in 2016; as well as to better understand the different sections of the gripper.

The simulation was performed in SOLIDWORKS®. A linear static FEA study was selected and, as above, a force of $\mathbf{200\ N}$ was applied at the magenta arrow while the upper part was constrained. The material selected for the simulation was ABS.

From the results of the study the data was exported and with it a K-means cluster analysis was run both for the Von Mises Stress and the displacement. The graphs with the clusters that were obtained can be seen in (Fig. 5).

For the graphs, four clusters were obtained for each study. The displacement graph suggests a way in which the gripper can be segmented according to the displacements the different points are undergoing. The Von Mises Stress one shows the parts of the gripper where the maximum stresses are. The parts where stresses are concentrated later would be proven to be where the first 3D printed designs commonly failed.

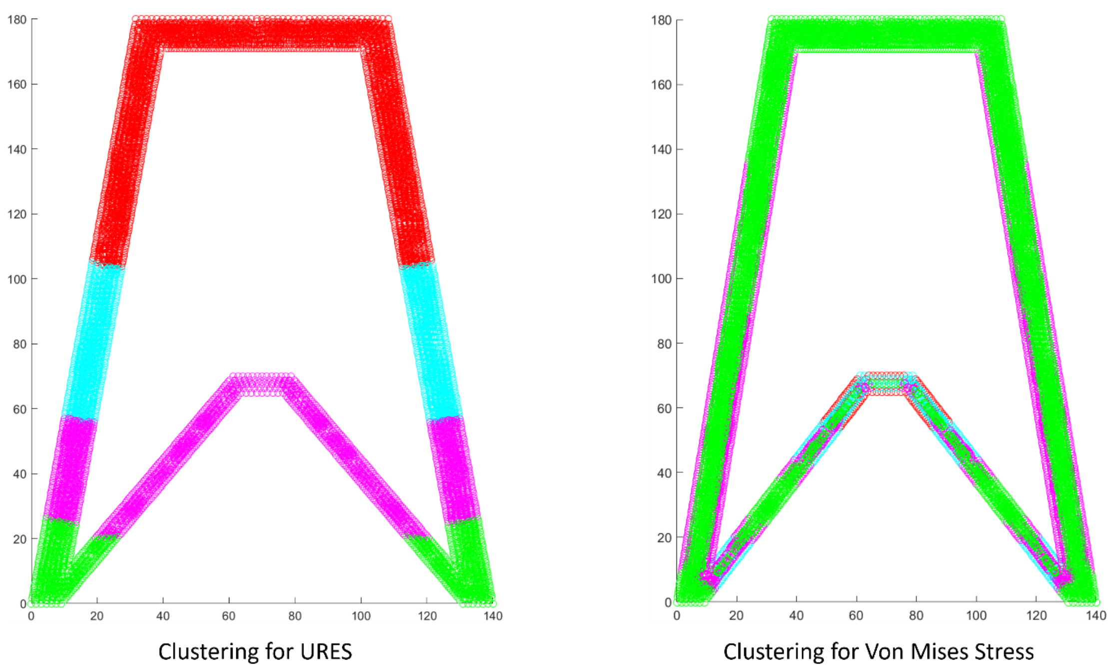


Figure 5 K-means clustering analysis for displacement and Von Mises Stress

As can be understood the solid structure would not have enough displacement on the tips so as to work as a gripper. Therefore, a way to give specific points on the structure more flexibility had to be found. Two alternatives were possible: material distribution as in (Ion et al., 2016) or compliant mechanisms. The second alternative was the one to be mainly explored. However, an insight on the possible advantages of material distribution / metamaterials is given in the second section and suggested as future work.

Compliant mechanisms were the logical alternative due to the advantages they have. Same which include; monolithic nature, reduced complexity, easy to manufacture (usually by FMD 3D printing), reduced or no assembly, friction-free motion hence no need for lubrication, and better scalability (Milojevic et al., 2018).

Among the different approaches used for designing compliant mechanisms it is possible to find those based on converting an analogous rigid-body mechanism into a complaint one (i.e., kinematics-based approach) (Howell et al., 2013; Wang et al., 2019; Yu et al., 2011). Said approach helps to quickly explore a variety of feasible compliant mechanisms and select the most viable design. Howbeit, it is important to highlight that a great deal of intuition and involvement on the part of the designer is required.

Apart from the kinematics-based approaches there are also popular topology optimization methods like the one proposed by (Zhang & Zhu,2018) or the popular MATLAB® - Fortran® implementation of the method of moving asymptotes by Krister Svanberg.

For the present work a kinematics-based approach was used due to the advantages it poses over optimization algorithms in terms of time and clearness of the design process.

As an initial approach to start exploring the possibilities compliant mechanisms could offer the first step was to add well-known flexure hinges to the geometry that was selected. At this stage several notch felexure hinges like the right-circular, the leaf, the corner-filleted, elliptic, hyperbolic, parabaolic, v-shaped, and ycloidal were used.

To better understand what kind of flexure hinge and what parameters could render the higher displacement at the tips detasFLEX MATLAB® tool by (Henning et al., 2018) was used (Fig. 6).

According to the tool, one of the most suitable notched hinges for our application was the right-circular flexure hinge. Also, Ning Xu et al., published a study in 2017 where they compared elliptic, circular, parabolic, and hyperbolic hinges and the results showed that the circular hinge offered the most compliance after the elliptic, but the ecliptic’s precision falls below the one a circular one can offer. For that reason, the exploration began by using right-circular flexure hinges.

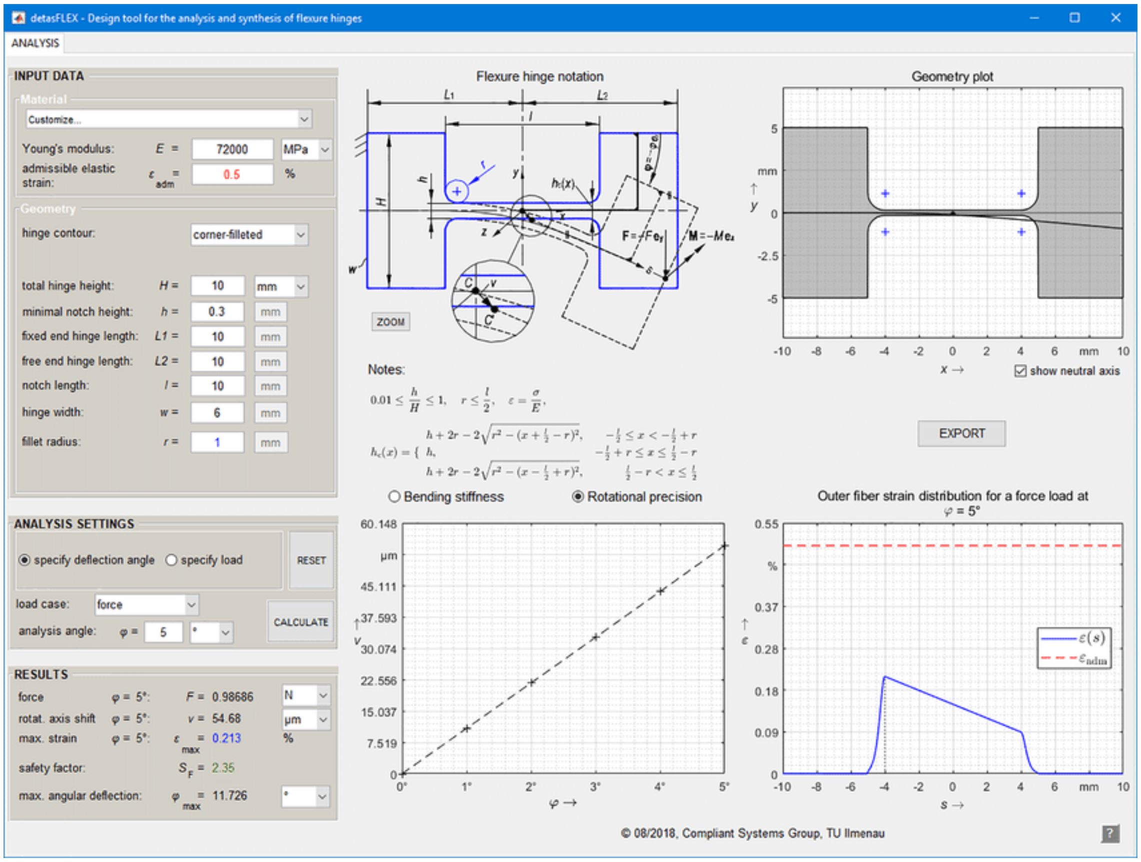


Figure 6 detasFLEX tool by Henning et al., 2018

Although at this stage of the design process the kind of notch flexure hinge that was to be used to initially explore the potential of the original structure had and the feasibility of a gripper being designed by means of using compliant mechanisms; it had to be understood where it was possible to add a flexure hinge so that the structure could move as desired.

For the reason stated above and following the idea of the kinematic-based approach for the design of compliant mechanisms, the original structure had to be understood as a traditional mechanism with joints so as to understand where movement was necessary to perform the expected function. In (Fig. 7) the selected geometry is depicted as if it were a traditional mechanism so as to better observe and understand where movement was necessary.

As can be seen, joints at different points of the structure could help achieve the desired movement. However, no adaptability or compliance to the grasped object is ensured. In order to obtain some kind of adaptability, the form of artisanal wooden snake toys is recalled. Thinking about those toys the idea of adding a chain to the lower parts of the gripper so as to allow it to be adaptable was conceived.

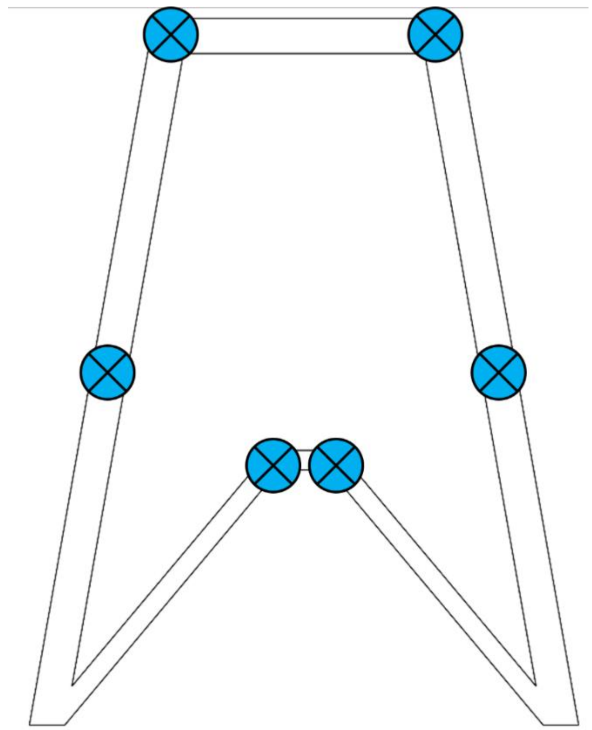


Figure 7 Gripper design depicted as if it were a traditional mechanism with rotational joints to move as expected.

From the K-means analysis (Fig. 5) it was possible to conclude at what points it was viable to add flexure hinges and FEA simulations were performed with the same parameters as the ones mentioned above but this time in Fusion360® to determine which configuration rendered the most displacement at the tips before breaking.

In the figure below (Fig. 9) some of the configurations that were obtained are shown in the upper part.

Although good results were obtained from the simulations of gripper designs with flexure hinges and displacements at the tips as high as the one shown by G5 in (Fig. 11) it is possible to find in the literature designs of complaint laparoscopes where thin members/beams and/or slots are used like in the one presented by (Lassooij et al., 2012). For this reason, it was decided to explore this possibility for the gripper.

In (Fig. 11) the best configurations and variations of the original model for the gripper are presented and compared. As can be seen, some configurations were entirely based on circular flexure hinges, but combinations of what was found worked for laparoscopes (i.e., thin flexure beams or slots) and circular hinges can be found.

In order to have a parameter to compare the different models, the geometric advantage was computed. Where the output displacement was that experienced at the tips and the input displacement the one where the force was applied.

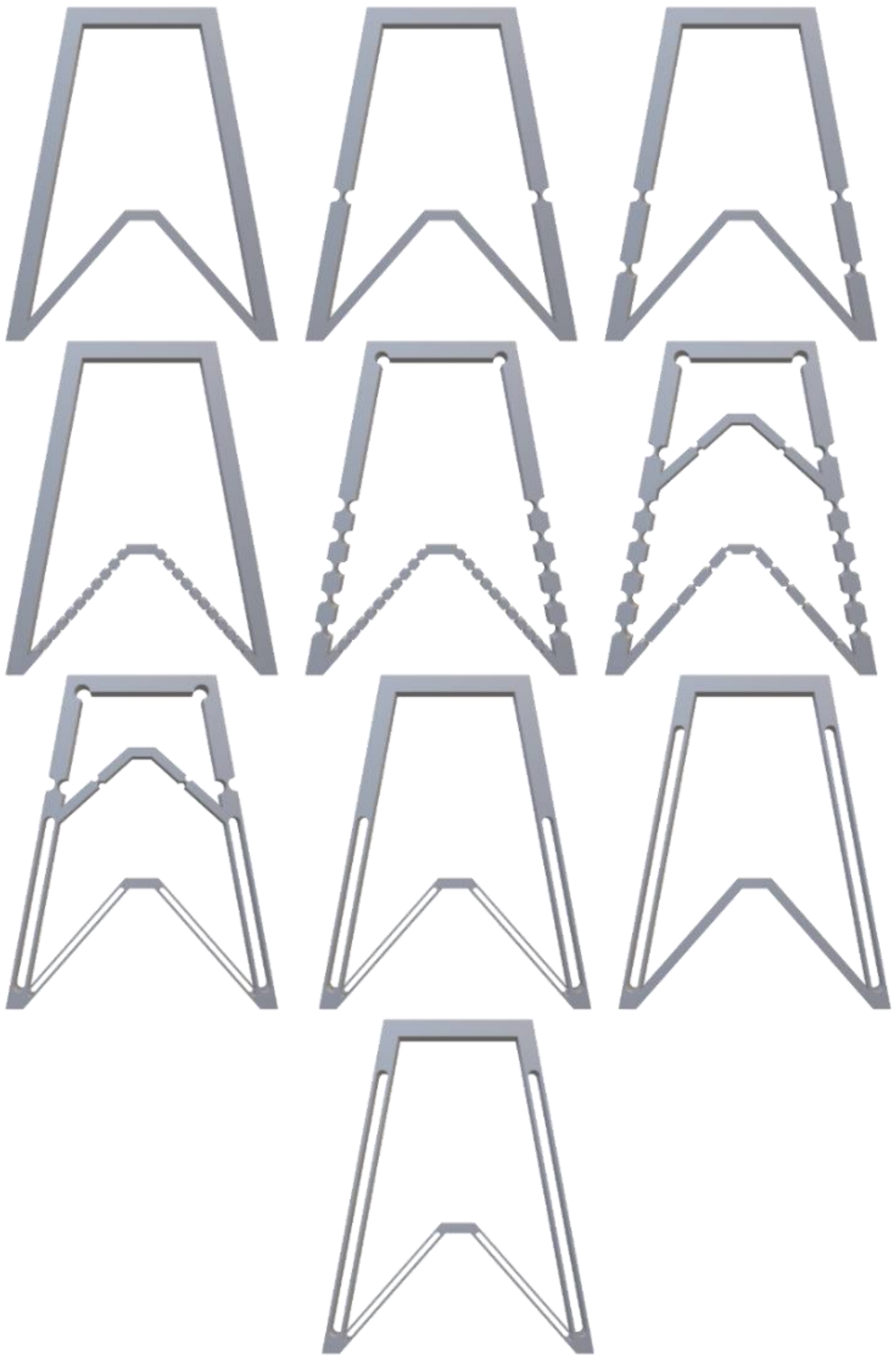
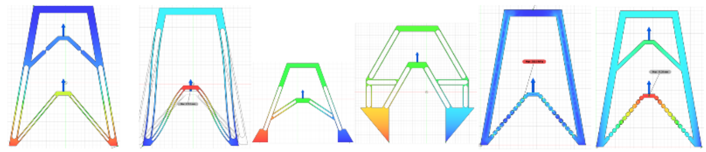


Figure 8 Some configurations of the compliant gripper

$$GA = \frac{OUTPUT\ DISPLACEMENT}{INPUT\ DISPLACEMENT}$$



200 N		G1	G2	G3	G4	G5	G6
Von Mises Stress (Mpa)	MIN	0.027775	0.03293	2.63E-04	0.001679	0.04439	0.01235
	MAX	284.2	422.8	193.5	158.7	263.8	133.4
Displacement X (mm)	S1	186.1	272.1	28.74	76.46	49.35	25.07
	S2	187.2	269.2	27.49	80.87	49.49	25.17
Displacement Y (mm)		125.1	180.8	28.95	42.8	33.9	17.26
GA		1.492006395	1.496958	0.971157	1.8379673	1.457817	1.455388

Figure 9 Best configurations and variations found and comparisons

Figure 10 3D printed design

The best twelve models were 3D printed in PLA and manually tested as seen in (Fig. 9 and 10) to have a better idea or their experimental behaviour.

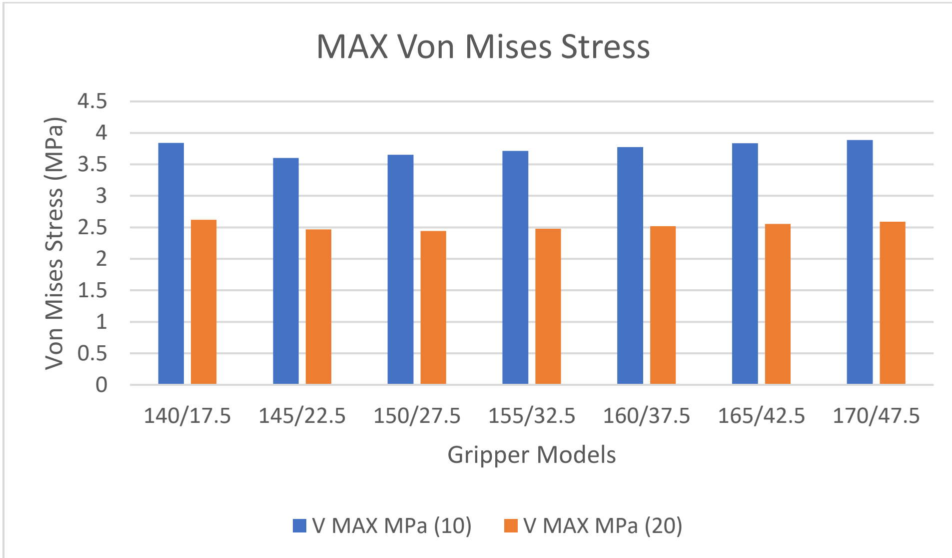
Figure 11 Manual testing of the grippers with medicine boxes

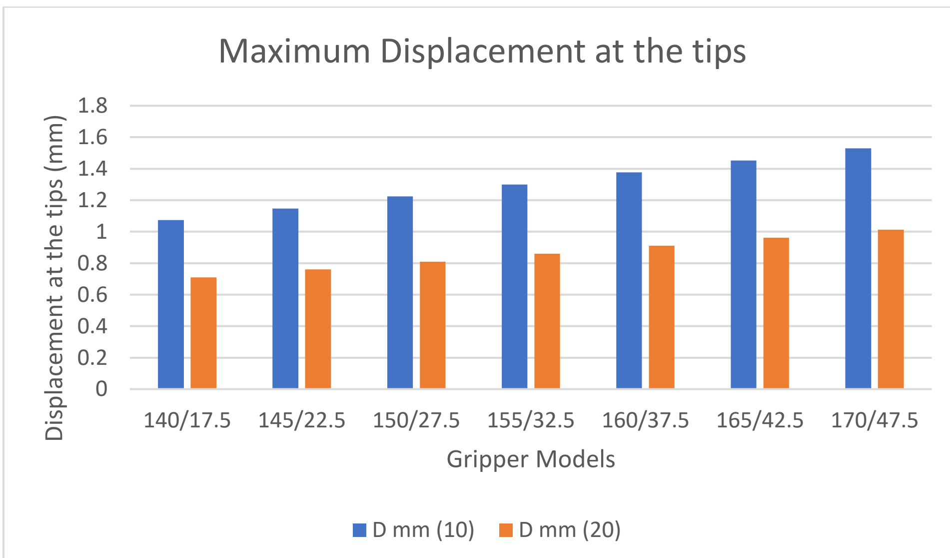
As expected, the model G2 was the one that could grasp objects more easily than the other models since the displacement at the tips was greater. For this reason, it would be decided to further explore possibilities like increasing its thickness, different lengths from tip to tip, as well as modifying the length from center to center of the slot.

Simulations in Fusion360® with the same conditions established above except for an applied force of $\mathbf{10\ N}$ at the magenta line was applied and the following results were obtained for variations in thickness and transversal length.

L	V MAX MPa (10)	V MAX MPa (20)	V MIN MPa (10)	V MIN MPa (20)	D mm (10)	D mm (20)
140/17.5	3.84	2.621	3.57E-04	2.06E-04	1.074	7.11E-01
145/22.5	3.602	2.47	3.24E-04	1.97E-04	1.147	7.60E-01
150/27.5	3.655	2.445	2.83E-04	1.57E-04	1.225	8.10E-01
155/32.5	3.716	2.481	2.46E-04	1.32E-04	1.299	8.60E-01
160/37.5	3.774	2.517	2.12E-04	1.15E-04	1.376	9.11E-01
165/42.5	3.835	2.555	1.63E-04	8.75E-05	1.453	9.62E-01
170/47.5	3.889	2.592	1.44E-04	7.00E-05	1.529	1.013

Table 1 Results obtained for variations in thickness and transversal length





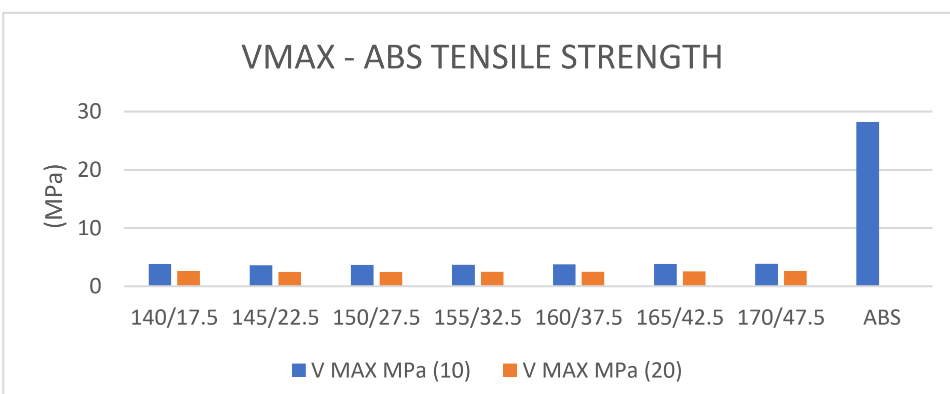


Figure 12 Maximum Von Mises Stress and Displacement at the tip's graphs with variations in thickness and transversal length and comparison between the Maximum Von Mises Stress of all models and the ABS' tensile strength.

As can be seen from the data in Table 1 and Fig. 12, the results suggest that as thickness increases, the less displacement at the tips it is possible to get. It is also possible to conclude that the relationship between the Maximum Von Mises Stress and the length from tip to tip slightly follows the shape of a second order polynomial. From this follows that the longer the length from tip to tip the higher the displacement experienced at the tips – something that is consistent with basic concepts of mechanics since the bending experienced by the middle segment is higher as long as its length increases.

In the last graph presented in Fig. 12, it is possible to see a comparison of the Maximum Von Mises stress found in the different models and ABS' tensile strength. It is possible to see that all configurations are at least 5 times below the value of the tensile strength.

3.2 Gripper Design and Addition of Metamaterials

Nature is the most complete and extense database we have to our days of succesful solutions to many scientific and technological problems. It is not strange that ideas from nature have majorly inspired and influenced mankind to innovate or solve problems (Zhang et al., 2015). In nature, it is possible to find a variety of porous structures that play important roles for the successful function of different organisms. Needless to mention that the most artificial designs on porous materials have all been inspired by nature or can find their roots in patterns found originally in nature.

Cellular materials – often referred to as "lattice materials" – consist of an interconnected network of solid struts or plates and have complex architectures with voids. Among these, it is possible to find two-dimensional (2D) honeycombs, three-dimensional (3D) lattice truss structures, randomly structured foams, and porous materials (Liu et al., 2020).

Cellular structures have gained popularity and recognition due to their mechanical properties such as light weight, low moduli, and large variation of Poisson's ratio (Liu et al., 2020). All of those characteristics are usually inaccessible with ordinary materials. These same qualities are the ones that augure huge potential for them as core structures in different fields; included that of soft robotics where patterns with good flexibility are gaining notoriety.

Due to the characteristics of cellular materials, it would be convenient to explore the feasibility of using cellular structures to provide the flexibility and some degree of adaptability to the compliant gripper designs found just in the way flexure hinges would.

In the literature it is possible to find cellular materials that have been applied successfully to compliant grippers (Ion et al., 2016; Kaur et al., 2019; Janbaz et al., 2019) and other structures where morphing abilities are required (Heo et al., 2013; Jenett et al., 2017; Ren et al., 2020)

For the principal design that was found, several cellular patterns were tested to explore the feasibility of using them.

3.2.1 Truss

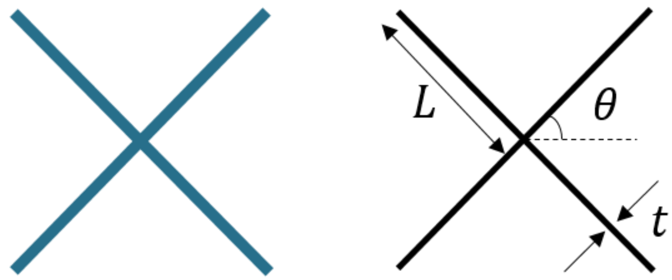


Figure 13 Truss unit cell and its parameters

In a work that compares truss, conventional hexagonal honeycomb, and re-entrant hexagonal honeycomb core sandwiches, it was found that truss core sandwiches have the largest flexural stiffness and the re-entrant honeycomb core sandwich the lowest and largest bending deflection (Li et al., 2017). From that, it can thus be easily understood that the latter posses a lower Young's modulus

These characteristics made this pattern desirable for the gripper in places where rigidity and weight reduction in comparison to the original solid structure were desired.

3.2.2 Metamaterial Architecture from a Self-Shaping Plant

There is a wide variety of designs that has been inspired by nature itself and this novel presented structure is not the exception. The movements that carnivorous plants can do have trigguered the curiosity of many.

This particular carnivorous plant has long leaves that can fold around different preys. According to the information they presented in their research. This plant exhibits and incredible adapting behaviour that makes it ideal for catching insects thanks to its thin filaments and adhesive secretions (La Pota et al., 2019).

Mechanically speaking, those plants are capable of actuating their capture mechanisms by means of storing elastic energy that is later released through rapid buckling or unbuckling (according to the necessity) instability.

Recently, La Porta et al., have studied the leaves of the carnivorous plant Drosera capensis L. which slowly fold around insects trapped on their sticky surface to ensure their digestion.

After understanding the form in which it behaved, they managed to design a metamaterial to bend reversibly under homogeneous stimuli. Said configuration is a combination of an auxetic and a non-auxetic pattern.

The design of the upper layer of their unit cell is entirely based on the reentrant hexagonal lattice, which is known to have an auxetic behaviour while the lower lattice structure has a similar geometry but with an additional horizontal link (Fig. 14).

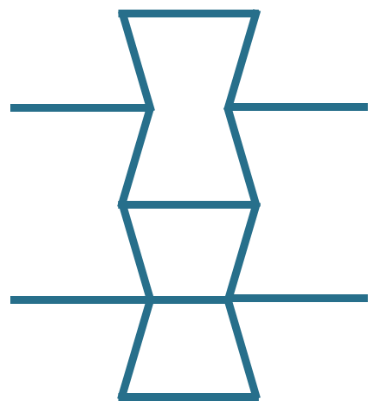


Figure 14 Proposed configuration to emulate the Drosera capenis L.

As the proposed structure by La Porta and his team deforms under compression, the upper auxetic layer contracts, while the lower nonauxetic layer expands perpendicular to the long axis of the structure, resulting in a curvature being induced in the whole bilayer structure (La Porta et al., 2019).

The behaviour of the proposed structure makes it especially attractive for applications in soft robotics. For said reason, it was decided to test a lattice in the inner inverted "V" part of the gripper to see if the behaviour of the lattice could benefit the adaptability of the gripper in some way as well as the displacement experienced at both "tips".

3.2.3 Kirigami-Based Open Hexagonal Honeycomb

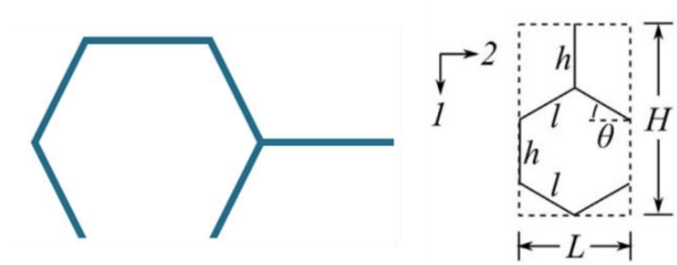


Figure 15 Unit cell of the Kirigami-based open hexagonal honeycomb

Although not used 3D printed but as cutting patterns for sheets. Adapting that lattice to be 3D printed might show a similar behaviour to that of the cut patterns shown by Huang et al., in 2017 and Neville et al, in 2016. For that reason, the cell of the open hexagonal honeycomb proposed by Huang et al., in 2017 (Fig. 15) was adapted to be 3D printed and not cut nor folded.

3.2.4 Re-entrant Hexagonal Honeycomb

Figure 16 Unit cell of the re-entrant hexagonal honeycomb

Because of the significant low-weight and tunnable in-plane and out-of-plane mechanical performances, honeycomb structures have attracted attention in various engineering fields during recent years (Huang et al., 2017). Cellular structures similar to regular and irregular honeycombs and re-entrants are known to be lighter, have a high-level of flexibility and to be more efficient materials (Yalçın et al. 2018). (In the case of out-of-plane flexibility for the re-entrant hexagonal honeycomb it has been shown that by adding a thin plate to the design of the honeycomb it is possible to achieve it (Huang et al., 2017)).

This structure has potential applications in morphing applications due to its compliance and morphing behaviour provided by the re-entrant hexagons. About the flexibility, the flexibility of this kind of cellular structure is high and that is the reason why it has been used in air-morphing wings as the core with promising results (Ren et al, 2020). The 3D version of this cellular structure has been used for a smart compliant robotic gripper (Kaur et al, 2019).

Having found in the available literature this cellular structure has potential for morphing applications but also good flexibility while keeping the stresses low, it was decided to test it in both the inner and outer inverted “V” parts of the gripper.

3.2.5 2D Chiral

The 2D chiral cellular structure presented by Liu et al., in 2020 owns the characteristics of both; low elastic moduli and large global-local strain ratios, which makes it suitable – and has been suggested – to be used for morphing applications

The authors' suggestions come from the low in-plane moduli as well as the large maximum global local strain ratios that the lattice exhibits which suggest there is an important in-plane elasticity and potential for morphing capabilities.

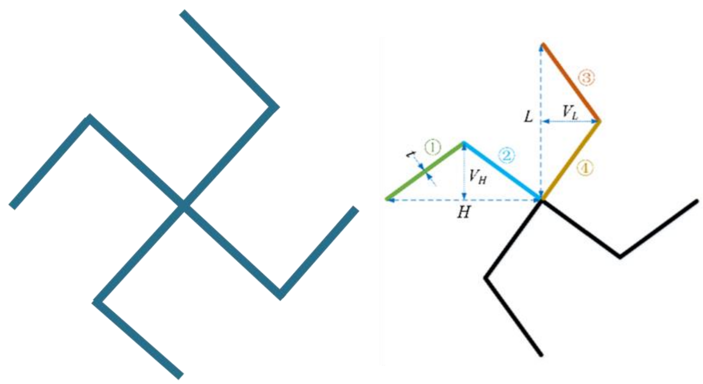


Figure 17 Unit cell of the 2D chiral cellular structure proposed by Liu et al., 2020

In their study, the chiral cellular structure is proposed as a potential alternative for the core of flexible skins or the inner support of flexible structures. For said reasons, this structure was used for the outer inverted "V" part.

Although it would have also been convenient to implement the same structure for the inner one, the current dimensions of the gripper structure are rather prohibitive for this to be applied. Nonetheless, this lattice advantages might be able to show the behaviour that is required for the outer inverted "V" beams of the gripper.

3.2.6 FEA Tests

3.2.6.1 Upper Part of the Design

As mentioned above, a truss cellular structure was applied to the upper part of the gripper. The expected outcome was to maintain to some extent the stiffness had with the original solid shape, weight reduction, and a subtle increase on the displacement experienced at the tips.

After the simulations, the comparison of the original solid structure and the one to which the truss was applied rendered a 16.98% increase in the displacement experienced at the tips and a 33.19% increase in the maximum von Mises stress in the structure. Although the increase in the von Mises seems considerable, the structure still has a safety factor of 5.

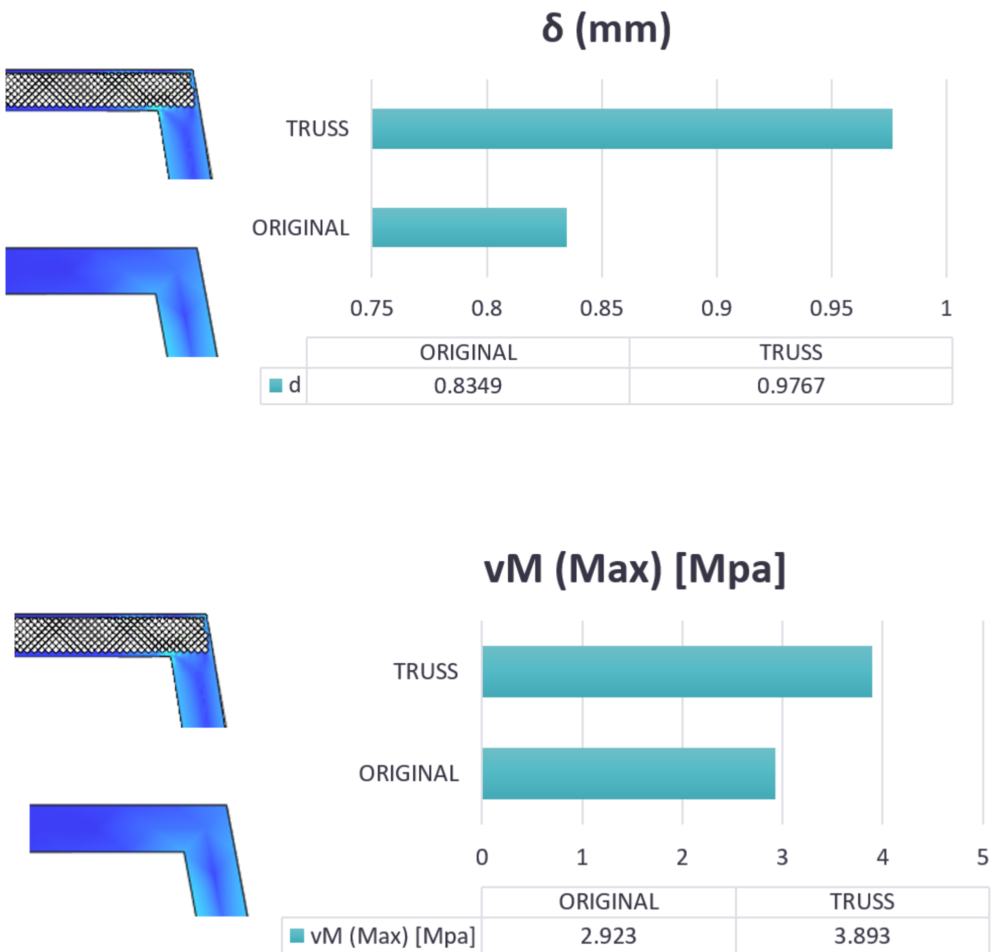


Figure 18 Comparison of the original gripper and the one to which the truss cellular structure was added

3.2.6.2 Inner Inverted "V" Part of the Design

The inner part of the gripper is both peculiar and important. If a cellular structure with a low Young's modulus is applied naturally the displacement that is experienced at the tips of the gripper is high. However, there is a cost, the stresses increase considerably.

In this area, low stiffness is desired; nonetheless, it is the part where the highest stresses are experienced, and an increase is undesired.

For the inverted "V" part of the gripper three cellular structures were tested and compared against the original gripper and one with slots that work as if they were flexure hinges. The three cellular structures that were used were; the metamaterial architecture from a self-shaping carnivorous plant, a re-entrant hexagonal honeycomb, and the Kirigami-based open hexagonal honeycomb (Fig. 19).

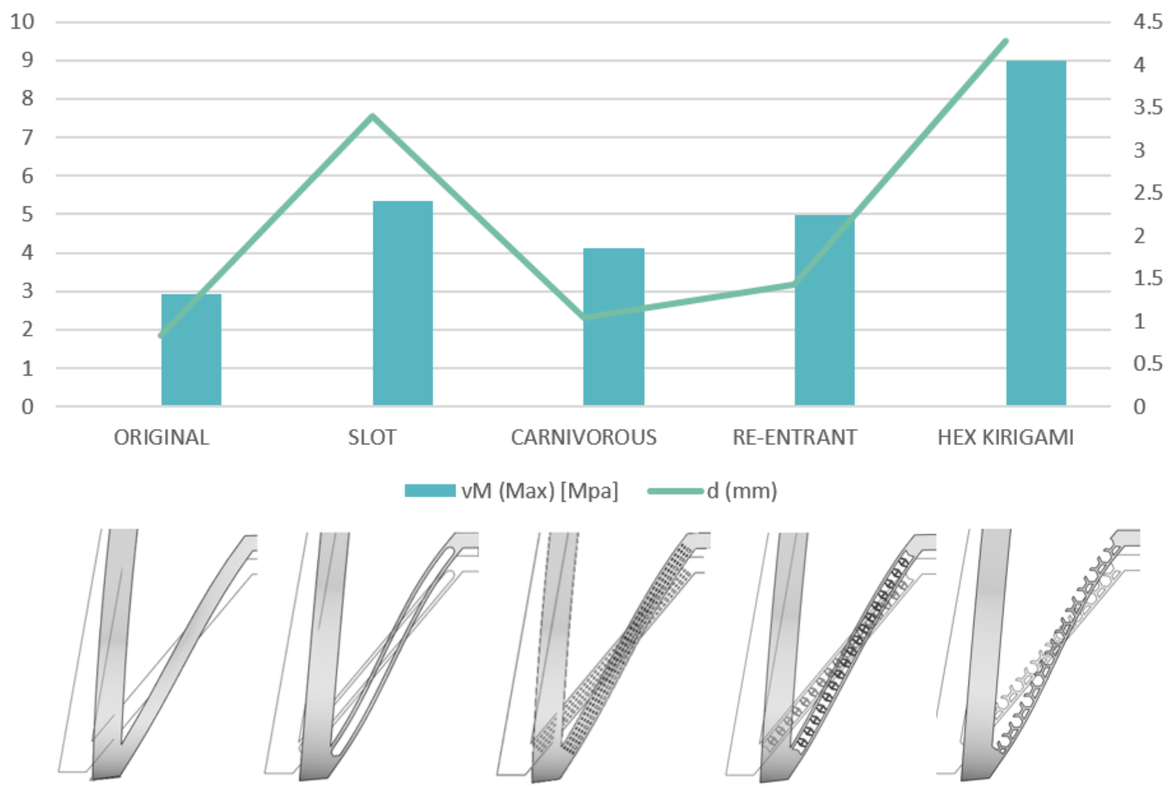


Figure 19 Variations of the inner "V" part and comparison graph

Since both to minimize the stresses experienced in this area and maximize the displacement that can be experienced at the tips, the best option would be to use the slot. However, the re-entrant honeycomb might also be used in cases where large displacements are not desired.

3.2.6.3 Outer Inverted "V" Part of the Design

The outer inverted "V" part of the gripper, several specimens were designed, tested, and compared against the original (Fig. 20). Cellular structures like the Kirigami-based open hexagonal honeycomb, 2D chiral, and the re-entrant hexagonal honeycomb were used. All these were also compared to the original one found previously and some models with a thin beam at different positions.

The specimen that yielded the largest displacement was one of the cellular ones; that is that of the Kirigami-based open hexagonal honeycomb cellular structure. As means of validating the results obtained from the FEA simulations in Fusion360® the torsional $\boldsymbol{Ks}$ for different specimens were obtained by using the PRB model for the design of compliant mechanisms proposed by Howell et al. in 2011.

SPECIMENS	vM (Max) [Mpa]	vM (Min) [Mpa]	d	K
ORIGINAL	2.923	2.00E-03	0.8349	49.356
SLOT	3.05	7.62E-04	0.9896	9.871
HEX KIRIGAMI	6.089	1.04E-04	2.675	0.844
2D CHIRAL	4.034	2.45E-04	1.172	15.186
CENTER BEAM	5.545	4.26E-04	2.317	4.9356
UP BEAM	6.045	2.96E-04	2.548	4.9356
LOW BEAM	4.639	8.78E-04	2.071	4.9356
RE-ENTRANT HEX HONEYCOMB	3.742	4.39E-04	1.043	18.983

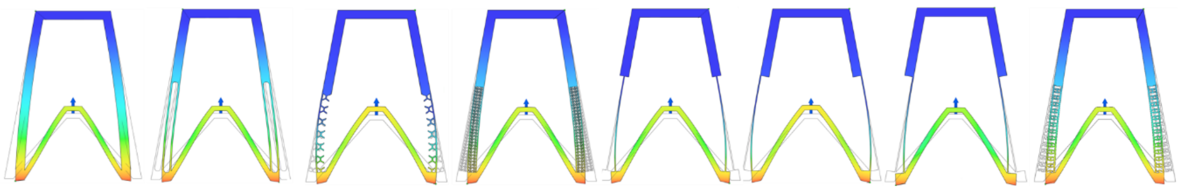


Figure 20 Specimens used, data obtained from them, and torsional Ks obtained from the PRB model for a cantilever beam

To compute the values of the torsional $\boldsymbol{Ks}$ for the different cellular structures that were compared, the apparent Young's moduli $\langle \boldsymbol{E} \rangle$ were necessary. To obtain these values several latticed beams of $\mathbf{10}\,\boldsymbol{mm}\,\boldsymbol{x}\,\mathbf{90}\,\boldsymbol{mm}\,\boldsymbol{x}\,\mathbf{10}\,\boldsymbol{mm}$ (dimensions of the area where the lattices were applied in the gripper) were designed to later perform iterative linear FEA simulations for bending while reducing the length of the beam. The data obtained is presented in (Table 5).

From plotting $\boldsymbol{L}^2$ against $\frac{\boldsymbol{\delta}}{\boldsymbol{L}}$ it is possible by using linear regression to obtain an equation in the form of $\boldsymbol{F}(\boldsymbol{x}) = \boldsymbol{mx} + \boldsymbol{b}$. Said equation can be equated to Eq. (1)

$$\frac{\boldsymbol{\delta}}{\boldsymbol{L}} = \frac{\boldsymbol{F}}{3\langle \boldsymbol{E} \rangle \boldsymbol{I}} \boldsymbol{L}^2 + \frac{\boldsymbol{FA}}{\boldsymbol{K}\langle \boldsymbol{G} \rangle} \qquad \boldsymbol{Eq.}(\mathbf{1})$$

By now, it is plain that $\boldsymbol{m} = \frac{\boldsymbol{F}}{3\langle \boldsymbol{E} \rangle \boldsymbol{I}}$ and the apparent Young's modulus $\langle \boldsymbol{E} \rangle$ can be obtained in a straightforward fashion and be applied to Eq. (2) to compute the torsional $\boldsymbol{K}$ of the PRB model.

$$\boldsymbol{K} = \frac{\mathbf{2.278} * \boldsymbol{EI}}{\boldsymbol{l}} \qquad \boldsymbol{Eq.}(\mathbf{2})$$

The lower the obtained $\boldsymbol{K}$, the higher the flexibility of the structure is. Thus, the lower the obtained $\boldsymbol{K}$ the lower the Young's modulus is. The $\boldsymbol{Ks}$ obtained from the PRB model are somewhat consistent with the FEA results. Nonetheless, it is still necessary to obtain the PRB model for the whole gripper for further validation.

REENTRANT			
L	L^2	d/L	d
100	10000	0.04655	4.655
81	6561	0.033	2.673
78	6084	0.031385	2.448
71	5041	0.027338	1.941
57	3249	0.020456	1.166
50	2500	0.017618	0.8809
36	1296	0.012964	0.4667
19	361	0.009879	0.1877
8	64	0.008481	0.06785

HEX KIRIGAMI			
L	L^2	d/L	d
100	10000	8.67E+00	8.67E+02
85	7225	6.20E+00	5.27E+02
70	4900	4.21E+00	2.95E+02
60	3600	3.01E+00	1.80E+02
48	2304	1.88E+00	9.01E+01
40	1600	1.30E+00	5.18E+01
35	1225	9.45E-01	3.31E+01
20	400	2.85E-01	5.703
15	225	1.58E-01	2.363
9	81	2.00E-02	0.1803

2D CHIRAL			
L	L^2	d/L	d
100	10000	6.57E-02	6.57E+00
90	8100	5.82E-02	5.24E+00
80	6400	5.11E-02	4.09E+00
70	4900	4.46E-02	3.12E+00
60	3600	3.83E-02	2.30E+00
50	2500	3.39E-02	1.69E+00
40	1600	2.89E-02	1.15E+00
30	900	2.36E-02	0.708
20	400	1.65E-02	0.3301
10	100	8.74E-03	0.08736

Table 2 Data obtained from the iterative FEA simulations for a beam in bending

Chapter 4 Experimental Testing

In this chapter a complete account of the materials for the integration gripper-actuator-robot is given as well as an explanation and results of the experimental testing are presented.

4.1 Integration, Control, and Setup

For the experimental testing of the gripper two variations of the same model were 3D printed in a Zortrax M300 3D printer in Z-HIPS filament which has the following mechanical properties (Table 3) as reported by the manufacturer of both, the 3D printer and filament.

Mechanical Properties	Metric	Test Method
Tensile Strength	16.90 MPa	ISO 527:1998
Breaking Stress	13.02 MPa	ISO 527:1998
Elongation at max Tensile Stress	1.87 %	ISO 527:1998
Elongation at Break	7.75%	ISO 527:1998
Bending Stress	29.30 MPa	ISO 178:2011
Flexural Modulus	1.18 GPa	ISO 178:2011
Izod Impact, Notched	4.82 kJ/m^2	ISO 180:2004

Table 3 Mechanical Properties of Z-HIPS as reported by the manufacturer

The two variations of the model that were 3D printed correspond to two models G2 140/17.5 - T10 mm - with different slot length. These two, are shown in (Fig. 24) and correspond to variations in the length of the slot present on the outer sides of the gripper. The first showing a mechanical advantage in the FEA simulations of 1.508 and the second of 1.504.

As can be understood by modifying the length of the slot more or less displacement can be obtained at the tips depending on the length from center to center of the slot. The greater the length, the greater the displacement experienced at the tips (Fig. 25). The equation describing the tendency can be written as follows:

$$\boldsymbol{displacement\ at\ the\ tips = (0.0743 * lenght) + 2.9836}$$

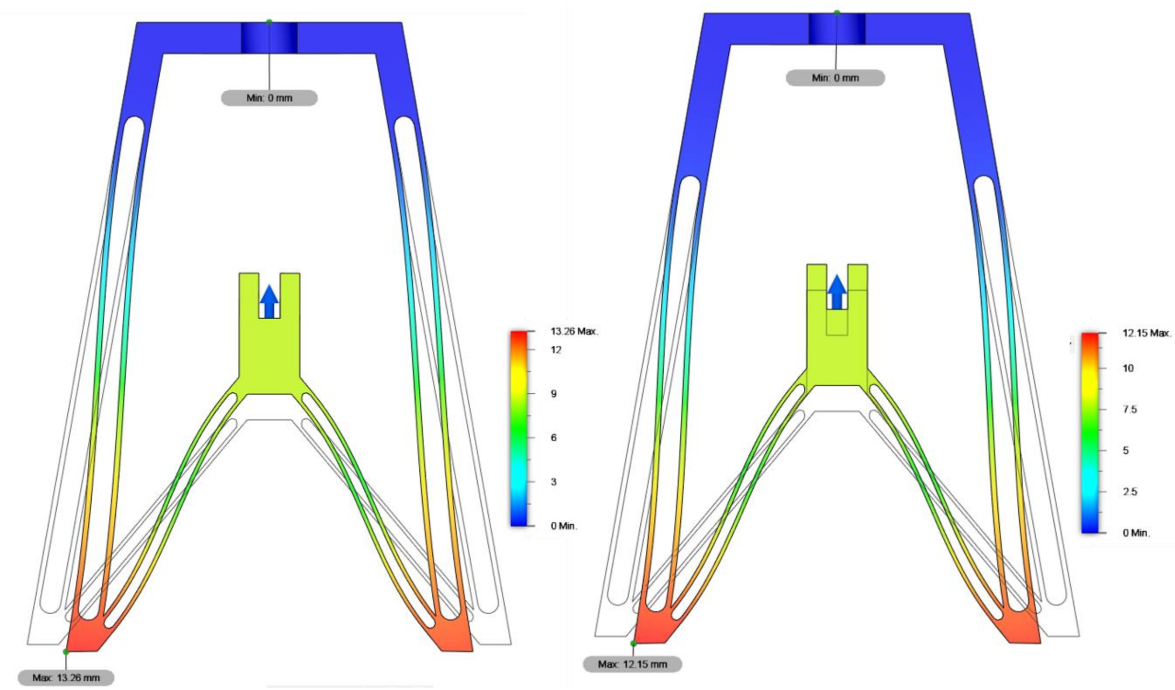


Figure 21 Models G2 140/17.5 – 10 mm with different slot length

The STL files were processed to generate the G-Code for 3D printing in the Z-Suite program available for the Zortrax 3D printers. All parameters were set as default. The only exceptions being the infill pattern and the infill percentage. For the infill pattern a linear one (i.e., PATT 0) was selected with a corresponding infill percentage of 40%. Each 3D-printed model taking around 5 hours to be fully printed.

The gripper was mounted on an UR10 robot for the experimental testing. For this a coupler for the robot and the gripper was designed and it was decided that the gripper should be mounted at a 45° angle so as to avoid reaching singularities in the workspace of the robot.

The actuator used for the gripper was a 12V electric linear actuator manufactured by Morai Motion (MMPL12-100-100) with a force of 100N and a maximum stroke 100 mm. The advantage of using this linear actuator was that due to its compact-size it was possible to easily integrate it with the gripper and the payload of the robot is not reduced by a great extent by the end of the arm tool (EOAT) since the whole assembly weights 225g and the actuator itself only 76g.

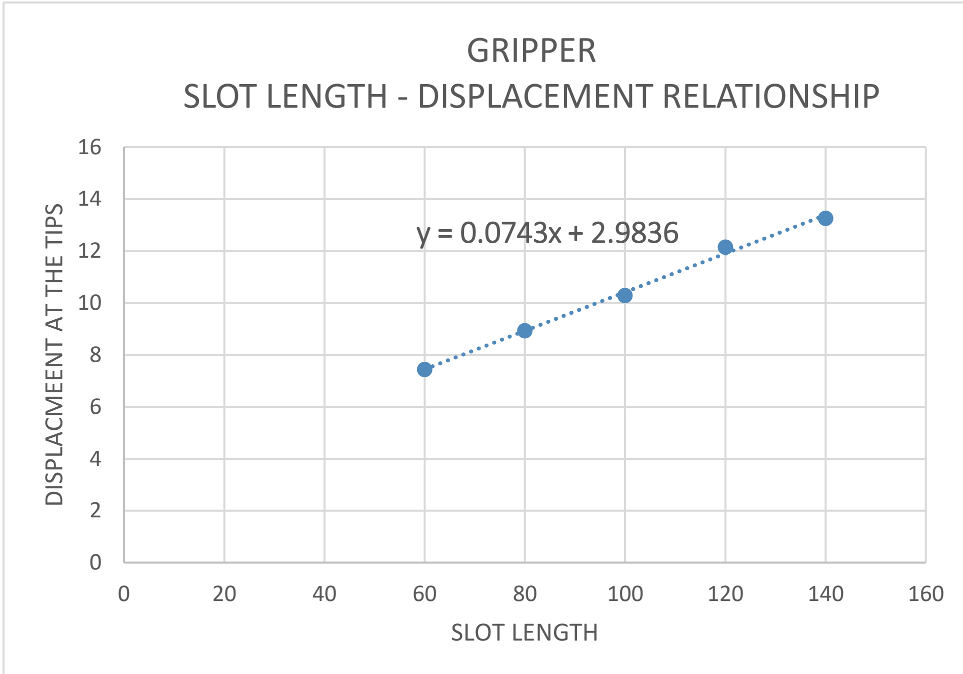


Figure 22 Gripper Slot length - displacement relationship

The final assembly of components for integrating the robot with the actuator and the gripper can be seen in (Fig. 23).

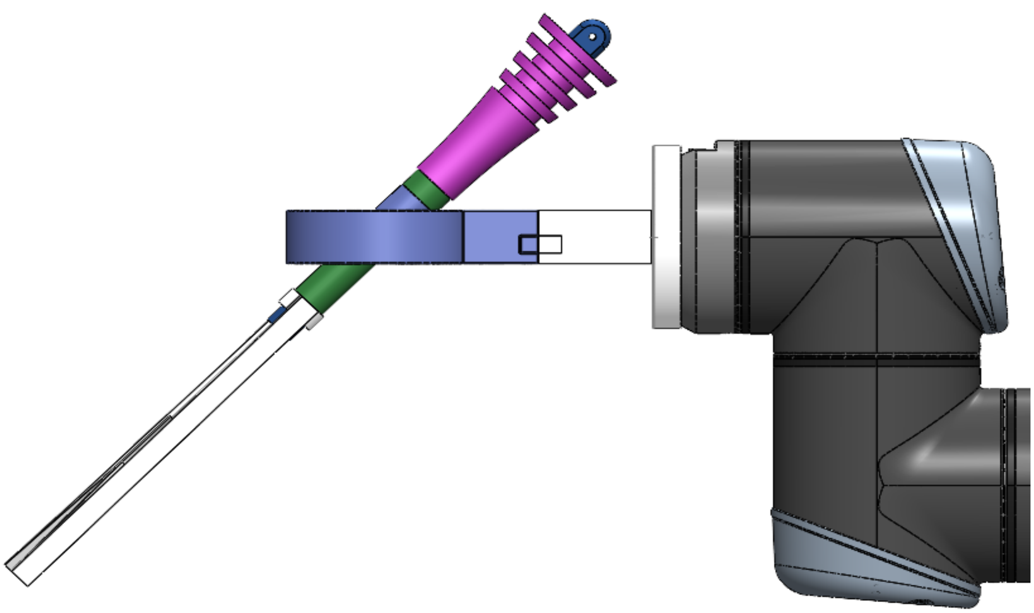


Figure 23 Side view of the gripper mounted on the UR10

In order to actuate the gripper and control the linear actuator an Arduino MEGA® with a L293D motor shield was used. The Arduino was powered by a computer in the lab and the linear actuator by a generic external power supply of 12V / 10A.

As can be understood, the control of the actuator and the robot is done independently, and they only communicate until a signal from the robot is sent from both the opening and closing of the gripper.

4.1 Experiments

In order to test the gripper mounted on the robot and see how it worked with different common solids of different shapes, it was decided to 3D print the following prisms and spheres of different sizes (Table 4):

SOLID	DIMENSIONS	WEIGHT
CUBE	$50\ mm\ x\ 50\ mm\ x\ 50\ mm$	$40.65g$
	$40\ mm\ x\ 40\ mm\ x\ 40\ mm$	$22.840g$
	$30\ mm\ x\ 30\ mm\ x\ 30\ mm$	$11.068g$
CYLINDER	$r = 25\ mm\ h = 60\ mm$	$36.509g$
	$r = 20\ mm\ h = 60\ mm$	$24.933g$
	$r = 15\ mm\ h = 60\ mm$	$15.4072g$
PARTIAL SPHERE	$r = 25\ mm\ h = 45.50\ mm$	$22.704g$
	$r = 20\ mm\ h = 35.50\ mm$	$12.5854g$
	$r = 15\ mm\ h = 25.50\ mm$	$5.938g$

Table 4 Solids: Dimensions and weights

To do the testing the UR10 robot was programmed from its teach pendant so that it would follow certain points and perform a pick and place operation. The test would be considered successful whenever the robot could pick the target object from the starting position and move it without letting it fall.

Both models of the gripper were able to successfully grasp the cubes, cylinders, and partial spheres described in Table 4 (Fig.24). Due to this success, it was decided to experiment with medicine boxes and a tomato, an avocado, an orange, a lemon, and, to add something more challenging – an egg.

Figure 24 Gripper Model G2 - 140/17.5 - T10 – 140 mm grasping a partial sphere, a cube, and a cylinder.

The decision to include a fruit such as a tomato was due to the frailty of its skin. Unlike the orange and lemon, the skin of the tomato is rather delicate. If the gripper succeeded in grasping the tomato without damaging its skin, it was likely that other fruits with delicate skins could also be grasped without being damaged.

In order to parametrize the different boxes used for the testing and the fruits and egg used for further reference, weights, and dimensions (only for the medicine boxes) are provided in table 1 in the annexes section. The boxes were measured with an electronic caliper and the weights were obtained by means of an OHAUS® PA214 electronic scale.

Although both models were capable of grasping successfully all the objects one of the 3D printed specimens of slot length 120 mm failed and broke when attempting to grasp one of the objects. It is assumed this was due to a 3D printing defect. However, further research is advised to determine what could have caused it to fail. In figure 29 it is possible to see the gripper models successfully grasping some of the objects.

4.2 Results Analysis and Discussion

From the success obtained with the two models that were tested on the robot grasping objects of different shapes it is possible to say that the soft compliant gripper shape that is presented in this work is capable of adapting to several geometries and grasp objects that are usually considered fragile and hard to grasp.

The gripper models were capable of successfully grasping objects of up to approximately $\mathbf{200}\ g$. This suggests the gripper can be successfully implemented in situations where a robot is required to perform actions of pick and place of small objects. It is seen that the robotic gripper can be successfully implemented in collaborative applications due to the nature of the materials that were used for it.

Although, as Howell mentions through many of his works, compliant mechanisms are seen as not reliable by the general public since they are bending parts that might give the appearance of being fragile. It is possible to say that this becomes one strength for the model presented here since it gives it the potential to be used at home settings or settings where some degree of security is needed. In this case plastic minimizes the possibilities of hurting someone.

Although one of the specimens of the model with shorter slot length failed and broke. It can be said this was due to manufacturing defects since the other two samples did not present the same problem.

In the linear FEA simulations the model with less sloth length has less displacement at the tips and eventually offers some degree of less compliance because the members are more rigid. However, it is seen that both could achieve the desired movements. It is safe to say that different slot lengths can be applied to the structure depending on a particular application and the range of displacement at the tips that is desired.

Figure 25 Grippers successfully grasping objects. From right top to left bottom: Lemon, egg, tomato, Fluoxetine, QUAL®, and Fluoxetine medicine boxes.

Chapter 5 Conclusions and Further Work

From the in-lab experimentation it can be concluded that the FEA simulations were rather consistent as to predict which gripper model of those tested would behave better. That is, the model that showed the more displacement at the tips is the one that was found to offer more adaptability. Although as mentioned before, both models were able to successfully grasp all the tested objects, one of the 3D printed models with the shorter slot (less displacement at the tips) broke.

There is basis to believe it might be due to the 3D printing process. For said reason more testing is advised and further work should be more dedicated to the in-lab testing, but not only of these models; other parameter variations should be tested. It is also advised that 3D printed probes with different infill patterns, percentages, and in different printing directions are tested so as to perform new simulations with the experimental results and compare them to the previous ones as seen in works of different nature to this one.

As in other works available in the literature, the mechanical advantage of both grippers that were tested is presented in previous chapters. Nonetheless, it would be convenient to use sensors in the lab and perform different experiments to measure other parameters like the output forces at the tips and contact areas with the grasped objects. Usually, works like this one do not test for those parameters and rather focus on whether or not the gripper can passively comform to different objects. Nonetheless, an index could be proposed based on different measures that could possibly be obtained by more experimentation and precise sensors and cameras. For instance, the displacement at the tips experimentally obtained can be obtained with laser sensors and compared to that of the simulations.

In terms of adding metamaterials to the gripper, based on all the FEA simulations that were performed and the comparisons presented in Chaper 3, it is possible to conclude that the best configuration for the selected gripper shape would be to use a truss lattice on the top part, an open hexagonal Kirigami lattice on the outer inverted “v” part, a slot on the inner inverted “v” part, and the rest let it be solid (Fig. 30). It is important to highlight that in place of the slot it is possible to use 2D a re-entrant hexagonal honeycomb lattice. However, only for applications where large displacements are not needed at the tips.

The latticed grippers that were tested cannot easily be 3D printed by FMD. Therefore, it is necessary to either, re-scale the gripper or look for feasible ways in which it can be manufactured. It would also be important to test different unit cell parameters for the lattices. If the gripper is re-scaled, it might be possible to do so and successfully 3D print the models by FMD.

Optimization algorithms like the one presented by Ren et al., in 2020 are gaining popularity to optimize cellular structures for morphing applications (and others, depending on the objective function). Taking those works as precedents, it might be possible to optimize a cellular structure for the proposed gripper geometry.

To do this, popular existent topology optimization algorithms for compliant mechanisms can be used. Among the popular topology optimizers, it is possible to count the method of moving asymptotes by Krister Svanberg, the BESO, and the

SOBESO methods; however, others like those proposed by (Zhang et al., 2018; Zhu et al., 2013; Zhu et al., 2020) could also be adapted for cellular materials.

It might also be worth exploring geometries based in Kirigami and that of the self-actuated shells presented by Guseinov et al. in 20210 and ways in which they can be adapted and applied to the design.

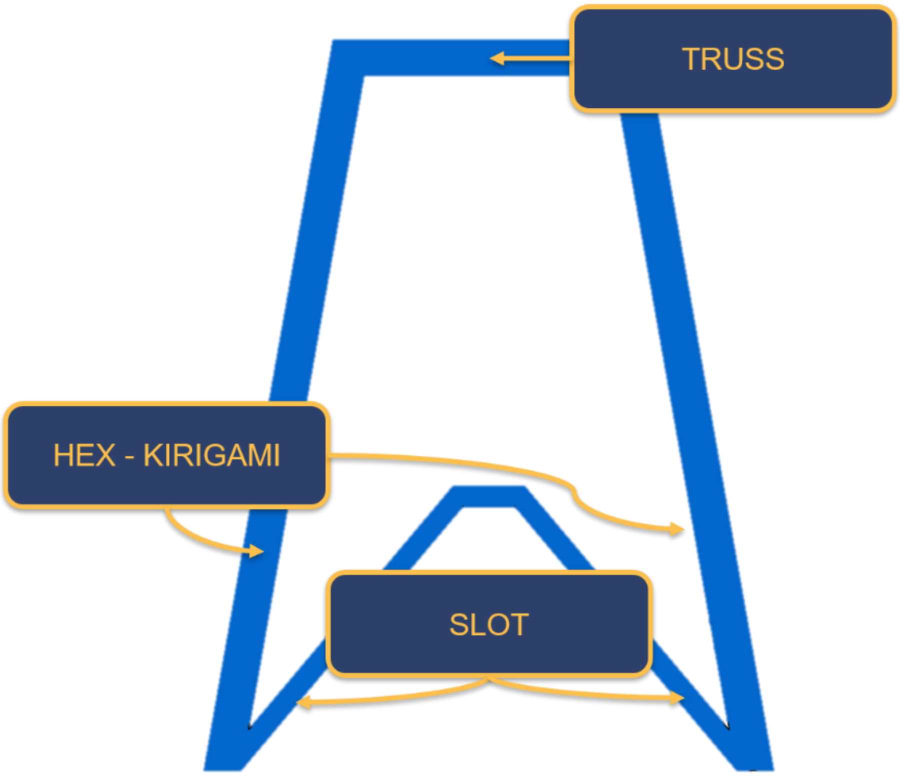


Figure 26 Best configuration found

Apart from what is described above, since most of the grippers similar to the one presented here do not include sensors, it would be convenient to explore the possibility to integrate sensors into the robotic gripper. It is also well known that the way a part is 3D printed has an effect on the mechanical properties of it (Ouhsti et al., 2018). For said reason, it would be convenient to further explore the effects of 3D printing and orientation in the gripper.

It is also important to mention that all the simulations of the work are limited since they were linear. For this the non-linear displacement was neglected and assumed to be small. For more accurate results, non-linear simulations might be implemented. Nonetheless, the linear simulations were capable of giving a good understanding of the behaviour of the structure with different configurations and offered enough information to compare the designs presented here.

References

[1] Venter, D., & Dirven, S. (2017). Self-morphing soft-robotic gripper for handling and manipulation of delicate produce in horticultural applications. *2017 24th International Conference on Mechatronics and Machine Vision in Practice (M2VIP)*, 1-6. https://doi.org/10.1109/M2VIP.2017.8211516

[2] Hussain, I., Renda, F., Iqbal, Z., Malvezzi, M., Salvietti, G., Seneviratne, L., Gan, D., & Prattichizzo, D. (2018). Modelling and Prototyping of an Underactuated Gripper Exploiting Joint Compliance and Modularity. *IEEE Robotics and Automation Letters*, *3*(4), 2854-2861. https://doi.org/10.1109/LRA.2018.2845906

[3] Milojevic, A., Linb, S., Cojbasic, Z., Handroos, H., Luostarinen, L., & Zentner, L. (2018). Adaptive Soft Robotic Gripper Based on Shape Morphing Compliant System. *2018 International Conference on Reconfigurable Mechanisms and Robots (ReMAR)*, 1-10. https://doi.org/10.1109/REMAR.2018.8449831

[4] Elgeneidy, K., Lightbody, P., Pearson, S., & Neumann, G. (2019). Characterising 3D-printed Soft Fin Ray Robotic Fingers with Layer Jamming Capability for Delicate Grasping. *2019 2nd IEEE International Conference on Soft Robotics (RoboSoft)*, 143-148. https://doi.org/10.1109/ROBOSOFT.2019.8722715

[5] Nguyen, D.-C., Phan, T.-V., & Pham, H.-T. (2018). Design and Analysis of a Compliant Gripper Integrated with Constant-Force and Static Balanced Mechanism for Micro Manipulation. *2018 4th International Conference on Green Technology and Sustainable Development (GTSD)*, 291-295. https://doi.org/10.1109/GTSD.2018.8595638

[6] Homberg, B. S., Katzschmann, R. K., Dogar, M. R., & Rus, D. (2015). Haptic identification of objects using a modular soft robotic gripper. *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 1698-1705. https://doi.org/10.1109/IROS.2015.7353596

[7] Chen, R., Song, R., Zhang, Z., Bai, L., Liu, F., Jiang, P., Sindersberger, D., Monkman, G. J., & Guo, J. (2019). Bio-Inspired Shape-Adaptive Soft Robotic Grippers Augmented with Electroadhesion Functionality. *Soft Robotics*, *6*(6), 701-712. https://doi.org/10.1089/soro.2018.0120

[8] Trivedi, D., Rahn, C. D., Kier, W. M., & Walker, I. D. (2008). Soft robotics: Biological inspiration, state of the art, and future research. *Applied Bionics and Biomechanics*, *5*(3), 99-117. https://doi.org/10.1080/11762320802557865

[9] Shintake, J., Cacucciolo, V., Floreano, D., & Shea, H. (2018). Soft Robotic Grippers. *Advanced Materials*, *30*(29), 1707035. https://doi.org/10.1002/adma.201707035

[10] Wang, F., Liang, C., Tian, Y., Zhao, X., & Zhang, D. (2016). Design and Control of a Compliant Microgripper with a Large Amplification Ratio for High-Speed Micro Manipulation. *IEEE/ASME Transactions on Mechatronics*, *21*(3), 1262-1271.

[11] Howell, L. L., Magleby, S. P., & Olsen, B. M. (Eds.). (2013). *Handbook* of compliant mechanisms. John Wiley & Sons, Inc.

[12] Ion, A., Frohnhofen, J., Wall, L., Kovacs, R., Alistar, M., Lindsay, J., Lopes, P., Chen, H.-T., & Baudisch, P. (2016). Metamaterial Mechanisms. Proceedings

of the 29th Annual Symposium on User Interface Software and Technology. https://doi.org/10.1145/2984511.2984540
[13] Kaur, M., & Kim, W. S. (2019). Toward a Smart Compliant Robotic Gripper Equipped with 3D-Designed Cellular Fingers. Advanced Intelligent Systems, 1(3), 1970032. https://doi.org/10.1002/aisy.201970032
[14] Janbaz, S., Bobbert, F. S., Mirzaali, M. J., & Zadpoor, A. A. (2019). Ultra-programmable buckling-driven soft cellular mechanisms. *Materials Horizons*, *6*(6), 1138–1147. https://doi.org/10.1039/c9mh00125e
[15] Heo, H., Ju, J., & Kim, D.-M. (2013). Compliant cellular structures: Application to a passive morphing airfoil. *Composite Structures*, *106*, 560–569. https://doi.org/10.1016/j.compstruct.2013.07.013
[16] Jenett, B., Calisch, S., Cellucci, D., Cramer, N., Gershenfeld, N., Swei, S., & Cheung, K. C. (2017). Digital Morphing Wing: Active Wing Shaping Concept Using Composite Lattice-Based Cellular Structures. *Soft Robotics*, *4*(1), 33–48. https://doi.org/10.1089/soro.2016.0032
[17] Lv, J., Ren, X., Song, C., & Zhang, H. (2020). Two-Scale Topology Optimization of the 3D Plant-Inspired Adaptive Cellular Structures for Morphing Applications. *Journal of Aerospace Engineering*, *33*(4), 04020032. https://doi.org/10.1061/(asce)as.1943-5525.0001119
[18] Zhang, Q., Yang, X., Li, P., Huang, G., Feng, S., Shen, C., Han, B., Zhang, X., Jin, F., Xu, F., & Lu, T. J. (2015). Bioinspired engineering of honeycomb structure – Using nature to inspire human innovation. *Progress in Materials Science*, *74*, 332–400. https://doi.org/10.1016/j.pmatsci.2015.05.001
[19] Li, T., & Wang, L. (2017). Bending behaviour of sandwich composite structures with tunable 3D-printed core materials. *Composite Structures*, *175*, 46–57. https://doi.org/10.1016/j.compstruct.2017.05.001
[20] La Porta, C. A., Lionetti, M. C., Bonfanti, S., Milan, S., Ferrario, C., Rayneau-Kirkhope, D., Beretta, M., Hanifpour, M., Fascio, U., Ascagni, M., De Paola, L., Budrikis, Z., Schiavoni, M., Falletta, E., Caselli, A., Chepizhko, O., Tuissi, A., Vailati, A., & Zapperi, S. (2019). Metamaterial architecture from a self-shaping carnivorous plant. Proceedings of the National Academy of Sciences, 116(38), 18777–18782. https://doi.org/10.1073/pnas.1904984116
[21] Luo, Q., & Tong, L. (2013). Adaptive pressure-controlled cellular structures for shape morphing I: design and analysis. *Smart Materials and Structures*, *22*(5), 055014. https://doi.org/10.1088/0964-1726/22/5/055014
[22] Neville, R. M., Scarpa, F., & Pirrera, A. (2016). Shape morphing Kirigami mechanical metamaterials. *Scientific Reports*, *6*(1). https://doi.org/10.1038/srep31067
[23] Huang, J., Zhang, Q., Scarpa, F., Liu, Y., & Leng, J. (2017). In-plane elasticity of a novel auxetic honeycomb design. Composites Part B: Engineering, 110, 72–82. https://doi.org/10.1016/j.compositesb.2016.11.011
[24] Yalçın, B., Ergene, B., & Karakılınç, U. (2018). Modal and Stress Analysis of Cellular Structures Produced with Additive Manufacturing by Finite Element Analysis (FEA). *Academic Perspective Procedia*, *1*(1), 263–272. https://doi.org/10.33793/acperpro.01.01.52

[25] Kaur, M., & Kim, W. S. (2019). Toward a Smart Compliant Robotic Gripper Equipped with 3D-Designed Cellular Fingers. *Advanced Intelligent Systems*, *1*(3), 1970032. https://doi.org/10.1002/aisy.201970032
[26] Liu, W., Li, H., Yang, Z., Zhang, J., & Ge, X. (2020). In-plane elastic properties of a 2D chiral cellular structure with V-shaped wings. *Engineering Structures*, *210*, 110384. https://doi.org/10.1016/j.engstruct.2020.110384
[27] Zhang, X., & Zhu, B. (2018). *Topology Optimization of Compliant Mechanisms*. Springer Singapore. https://doi.org/10.1007/978-981-13-0432-3
[28] Zhu, B., Zhang, X., & Wang, N. (2013). Topology optimization of hinge-free compliant mechanisms with multiple outputs using level set method. *Structural and Multidisciplinary Optimization*, *47*(5), 659-672. https://doi.org/10.1007/s00158-012-0841-1
[29] Zhu, B., Zhang, X., Zhang, H., Liang, J., Zang, H., Li, H., & Wang, R. (2020). Design of compliant mechanisms using continuum topology optimization: A review. *Mechanism and Machine Theory*, *143*, 103622. https://doi.org/10.1016/j.mechmachtheory.2019.103622
[30] Guseinov, R., McMahan, C., Pérez, J., Daraio, C., & Bickel, B. (2020). Programming temporal morphing of self-actuated shells. *Nature Communications*, *11*(1). https://doi.org/10.1038/s41467-019-14015-2
[31] Hirose, S., & Umetani, Y. (1978). The development of soft gripper for the versatile robot hand. Mechanism and Machine Theory, 13(3), 351–359. https://doi:10.1016/0094-114x(78)90059-9
[32] Suzumori, K., Iikura, S., & Tanaka, H. (1991). Development of flexible microactuator and its applications to robotic mechanisms. Proceedings. 1991 IEEE International Conference on Robotics and Automation. https://doi:10.1109/robot.1991.131850
[33] Lee, K.-S., & Jung, M.-C. (2014). Common patterns of voluntary grasp types according to object shape, size, and direction. International Journal of Industrial Ergonomics, 44(5), 761–768. https://doi:10.1016/j.ergon.2014.08.005
[34] Tai, K., El-Sayed, A.-R., Shahriari, M., Biglarbegian, M., & Mahmud, S. (2016). State of the Art Robotic Grippers and Applications. Robotics, 5(2), 11. https://doi:10.3390/robotics5020011
[35] Lassooij, J., Tolou, N., Tortora, G., Caccavaro, S., Menciassi, A., & Herder, J. L. (2012). A statically balanced and bi-stable compliant end effector combined with a laparoscopic 2DOF robotic arm. *Mechanical Sciences*, *3*(2), 85–93. https://doi.org/10.5194/ms-3-85-2012
[36] Henning, S., Linß, S., & Zentner, L. (2018). DetasFLEX – a computational design tool for the analysis of various notch flexure hinges based on non-linear modeling. Mechanical Sciences, 9(2), 389–404. https://doi.org/10.5194/ms-9-389-2018
[37] Liu, C.-H., & Chiu, C.-H. (2018). Design and prototype of monolithic compliant grippers for adaptive grasping. 2018 3rd International Conference on Control and Robotics Engineering (ICCRE). https://doi:10.1109/iccre.2018.8376432
[38] Petković, D., & Pavlovic, N.D. (2012). Object grasping and lifting by passive compliant gripper.

[39] Lassooij, J., Tolou, N., Tortora, G., Caccavaro, S., Menciassi, A., & Herder, J.L. (2012). A statically balanced and bi-stable compliant end effector combined with a laparoscopic 2DoF robotic arm. *Mechanical Sciences, 3*, 85-93.
[40] Lateş, D., Căşvean, M., & Moica, S. (2017). Fabrication methods of compliant mechanisms. Procedia Engineering, 181, 221–225. https://doi.org/10.1016/j.proeng.2017.02.377
[41] Liu, C.-H., & Chiu, C.-H. (2017). Optimal design of a soft robotic gripper with high mechanical advantage for grasping irregular objects. 2017 IEEE International Conference on Robotics and Automation (ICRA), 2846-2851. https://doi.org/10.1109/ICRA.2017.7989332
[42] Liu, C.-H., Chiu, C.-H., Hsu, M.-C., Chen, Y., & Chiang, Y.-P. (2019). Topology and Size–Shape Optimization of an Adaptive Compliant Gripper with High Mechanical Advantage for Grasping Irregular Objects. Robotica, 37(08), 1383-1400. https://doi.org/10.1017/S0263574719000018
[43] Pham, M. T., Teo, T. J., Yeo, S. H., Wang, P., & Nai, M. L. S. (2017). A 3-D Printed Ti-6Al-4V 3-DOF Compliant Parallel Mechanism for High Precision Manipulation. *IEEE/ASME Transactions on Mechatronics*, *22*(5), 2359-2368. https://doi.org/10.1109/TMECH.2017.2726692
[44] Majidi, C. (2014). Soft robotics: A perspective—current trends and prospects for the future. *Soft Robotics*, *1*(1), 5–11. https://doi.org/10.1089/soro.2013.0001
[45] Basson, C. I., & Bright, G. (2019). Geometric conformity study of a fin ray gripper utilizing active haptic control. *2019 IEEE 15th International Conference on Control and Automation (ICCA)*. https://doi.org/10.1109/icca.2019.8899497
[46] Bao, G., Fang, H., Chen, L., Wan, Y., Xu, F., Yang, Q., & Zhang, L. (2018). Soft robotics: Academic insights and perspectives through Bibliometric analysis. *Soft Robotics*, *5*(3), 229–241. https://doi.org/10.1089/soro.2017.0135
[47] Zhang, B., Xie, Y., Zhou, J., Wang, K., & Zhang, Z. (2020). State-of-the-art robotic grippers, grasping and control strategies, as well as their applications in Agricultural Robots: A Review. *Computers and Electronics in Agriculture*, *177*, 105694. https://doi.org/10.1016/j.compag.2020.105694
[48] Shiu, E. Y., Leung, N. H., & Cowling, B. J. (2019). Controversy around airborne versus droplet transmission of respiratory viruses. *Current Opinion in Infectious Diseases*, *32*(4), 372–379. https://doi.org/10.1097/qco.0000000000000563
[49] Wang, F., Liang, C., Tian, Y., Zhao, X., & Zhang, D. (2016). Design and Control of a Compliant Microgripper With a Large Amplification Ratio for High-Speed Micro Manipulation. *IEEE/ASME Transactions on Mechatronics, 21*, 1262-1271
[50] Yu, J., Li, S., Su, H.-jun, & Culpepper, M. L. (2011). Screw theory based methodology for the deterministic type synthesis of flexure mechanisms. *Journal of Mechanisms and Robotics*, *3*(3). https://doi.org/10.1115/1.4004123
[51] Crooks, W., Vukasin, G., O'Sullivan, M., Messner, W., & Rogers, C. (2016). Fin Ray® effect inspired soft robotic gripper: From the RoboSoft Grand Challenge toward optimization. *Frontiers in Robotics and AI*, *3*. https://doi.org/10.3389/frobt.2016.00070
[52] Crooks, W., Rozen-Levy, S., Trimmer, B., Rogers, C., & Messner, W. (2017). Passive gripper inspired by Manduca sexta and the Fin Ray® effect. *International*

Journal of Advanced Robotic Systems, *14*(4), 172988141772115. https://doi.org/10.1177/1729881417721155
[53] Xu N, Dai M, Zhou X. Analysis and design of symmetric notch flexure hinges. Advances in Mechanical Engineering. November 2017. doi:10.1177/1687814017734513
[54] Hugo P.O. (2013) Industrial Grippers: State-of-the-Art and Main Design Characteristics. In: Carbone G. (eds) Grasping in Robotics. Mechanisms and Machine Science, vol 10. Springer, London. https://doi.org/10.1007/978-1-4471-4664-3_5
[55] Chen, Q., Zhang, X., & Zhu, B. (2019). A 213-line topology optimization code for geometrically nonlinear structures. *Structural and Multidisciplinary Optimization*, *59*(5), 1863-1879. https://doi.org/10.1007/s00158-018-2138-5
[56] Brown, E., Rodenberg, N., Amend, J., Mozeika, A., Steltz, E., Zakin, M. R., Lipson, H., & Jaeger, H. M. (2010). Universal robotic gripper based on the jamming of granular material. *Proceedings of the National Academy of Sciences*, *107*(44), 18809–18814. https://doi.org/10.1073/pnas.1003250107
[57] Ouhsti, M., El Haddadi, B., & Belhouideg, S. (2018). Effect of printing parameters on the mechanical properties of parts fabricated with open-source 3D printers in PLA by Fused Deposition Modeling. *Mechanics and Mechanical Engineering*, *22*(4), 895–908. https://doi.org/10.2478/mme-2018-0070
[58] Boyraz, P., Dobrev, I., Fischer, G., & Popovic, M. B. (2019). Robotic surgery. Biomechatronics, 431–450. https://doi.org/10.1016/b978-0-12-812939-5.00015-x
[59] Harada, K., Masamune, K., Sakuma, I., Yahagi, N., Dohi, T., Iseki, H., & Takakura, K. (2001). Development of a micro manipulator for minimally invasive neurosurgery. Human Friendly Mechatronics, 75–80. https://doi.org/10.1016/b978-044450649-8/50014-0
[60] Hoznek, A., Salomon, L., & Abbou, C.-C. (2008). Extraperitoneal laparoscopic robotic-assisted radical prostatectomy. Robotics in Urologic Surgery, 63–67. https://doi.org/10.1016/b978-1-4160-2465-1.50012-2
[61] Modine, T., & Elarid, J. M. (2012). Minimally invasive cardiac surgery, port-access and robotic surgery. Minimized Cardiopulmonary Bypass Techniques and Technologies, 229–244. https://doi.org/10.1533/9780857096029.3.229
[62] Schneider, A., & Feussner, H. (2017). Mechatronic support systems and Robots. Biomedical Engineering in Gastrointestinal Surgery, 387–441. https://doi.org/10.1016/b978-0-12-803230-5.00010-5
[63] Song, S.-E. (2020). Robotic interventions. Handbook of Medical Image Computing and Computer Assisted Intervention, 841–860. https://doi.org/10.1016/b978-0-12-816176-0.00039-9

Annexes

Table 1: Objects for the in the in-lab testing details same wich the grippers could successfully grasp while mounted on the UR10 manipulator.

OBJECT	DIMENSIONS	WEIGHT
Tomato	-	$104.164g$
Avocado	-	$200.493g$
Orange	-	$118.035g$
Lemon	-	$39.010g$
Egg	-	$48.083g$
Medicine Boxes		
Transtec ® (Buprenorphine) 	$105.3\ mm\ x\ 108\ mm\ x\ 16.6\ mm$	$24.452g$
QUAL® (Paracetamol, Dextropropoxyphene, Diazepam) 	$75.8\ mm\ x\ 61\ mm\ x\ 18.7\ mm$	$22.189g$
AMSA® Fluoxetine 	$61.7\ mm\ x\ 85\ mm\ x\ 17.2\ mm$	$12.229g$
BIOMEP® Fluoxetine	$69.8\ mm\ x\ 60.7\ mm\ x\ 17.7\ mm$	$7.743g$

		
Sinfonil® (Oxcarbazepine) 	$111.6\ mm\ x\ 52.6\ mm\ x\ 24.2\ mm$	$23.216g$
Neosporin® (Neomycin, Polymyxin B, Bacitracin) 	$147.7\ mm\ x\ 37.8\ mm\ x\ 28.9\ mm$	$26.234g$
Creon® [50] (Pancreatin) 	$124\ mm\ x\ 76.2\ mm\ x\ 44.1\ mm$	$29.119g$
Creon® [20] (Pancreatin) 	$123.9\ mm\ x\ 76.9\ mm\ x\ 27.5\ mm$	$19.760g$
Systane™ ULTRA	$33\ mm\ x\ 67.4\ mm\ x\ 29.7\ mm$	$10.820g$

		
AMSA® Pantoprazole 	$93.3\ mm\ x\ 44.4\ mm\ x\ 15.6\ mm$	$7.881g$
ULTRA® (Sucralfate) 	$r = 25\ mm\ \ h = 86.7\ mm$	$62.900g$
ESPABION® (Trimebutine) 	$149\ mm\ x\ 66\ mm\ x\ 18.2\ mm$	$15.094g$
Micropore® 	$55.6\ mm\ x\ 55.9\ mm\ x\ 27.4\ mm$	$15.141g$