GRADO EN INGENIERÍA EN TECNOLOGÍAS INDUSTRIALES

DESCRIPTIVE REPORT

DESIGN OF A SOFT WALL CLIMBING ROBOT WITH DIELECTRIC ELASTOMER ACTUATORS AND ELECTROADHESION

Author: Ana Ordóñez Urteaga

Supervisor: Yong Huang

Co-Supervisor: Song Kaidong

Madrid

June 2020

Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título

Diseño de un robot blando trepador con actuadores dieléctricos de elastómero y electro adhesión

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Fdo.: Ana Ordóñez Urteaga Fecha: 17/06/2020

Autorizada la entrega del proyecto

EL DIRECTOR DEL PROYECTO

Fdo.: Yong Huang Fecha: 17/06/2020

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DISEÑO DE UN ROBOT BLANDO TREPADOR CON ACTUADORES DIELÉCTRICOS DE ELASTÓMERO Y ELECTROADHESIÓN

Autor: Ordóñez Urteaga, Ana.
Director: Huang, Yong.
Entidad colaboradora: University of Florida

RESUMEN DEL PROYECTO

Los robots blandos surgen de la necesidad de reproducir los movimientos de los seres vivos como las plantas, animales y humanos. Hasta el momento, los únicos robots que existían se producían con materiales rígidos como los plásticos duros y metales. La introducción de materiales blandos para la producción de robots permite los movimientos de deformación elástica y la formación de curvaturas, además de los movimientos de traslación y rotación en las tres dimensiones. El objetivo principal de este proyecto consiste en aprender sobre la materia, sobretodo sobre los materiales blandos y los agentes externos capaces de estimular los mismos y, por último, encontrar una función útil para el diseño y producción de un robot blando.

Palabras clave: Actuador dieléctrico de elastómero, electro adhesión.

1. Introducción

El estudio de materiales blandos con el fin de crear robots es relativamente nuevo. Al contrario que los robots convencionales, hechos de materiales duros, estos robots tienen la capacidad de imitar partes de organismos vivos como las plantas, animales y humanos, tanto estéticamente, como de manera funcional. Varios estudios desvelan que los usuarios prefieren interactuar con robots que se asimilen a sí mismos. Además, el uso de estos materiales proporciona un uso seguro de los robots de forma intrínseca.

2. Definición del proyecto

La principal razón por la cual se eligió este tema como foco central de esta investigación es la posibilidad de innovar y desarrollar trabajos pioneros. Es decir, dado que el área de estudios de los robots blandos es relativamente nueva, la cantidad de publicaciones sobre el tema es reducida, lo cual da paso a poder crear nuevos productos con facilidad. El único inconveniente que surge de esta novedad es la falta de información existente, ya que no hay modelos teóricos ni matemáticos ni algoritmos que definan el comportamiento de los robots blandos ni de los materiales que se emplean.

3. Descripción del modelo y herramientas

La parte más importante de los robots blandos es el actuador, dado que es el responsable de transformar el efecto del estímulo del agente externo en movimiento. La variedad de materiales blandos disponibles para fabricar estos actuadores es bastante limitada con las tecnologías de hoy en día. Para esta investigación en particular, se decidió usar un actuador dieléctrico de elastómero y, consecuentemente, energía eléctrica para estimularlo. Los materiales necesarios para fabricar el actuador son cinta adhesiva VHB 4910 para la membrana de elastómero, láminas acrílicas para pre – estirar la cinta adhesiva y lubricante de carbono para formar los electrodos.

Durante el proceso creativo surgió la idea de fabricar un robot blando con la capacidad de trepar por las paredes. Para poder llevar esto acabo se necesita incluir la idea de las fuerzas de electro adhesión para el diseño de los pies del robot. Los materiales necesarios para fabricarlos son cinta adhesiva VHB 4910 y láminas acrílicas otra vez, y folios de papel normales y un lápiz 2B para crear capas de grafito. Los pies, al igual que el actuador, necesitan energía eléctrica para su funcionamiento.

Dado que el proceso de fabricación es artesanal, es decir, hecho a mano, las herramientas necesarias para ello son relativamente comunes. Entre ellos se encuentran tijeras, cuchillas de precisión, reglas, rotuladores permanentes, espátulas, hilos de cobre, cinta adhesiva, etc. Como se puede ver, tanto las herramientas como la materia prima necesaria para fabricar el robot son poco costosas. El único elemento más costoso y de carácter más técnico es el amplificador de tensión, que es necesario ya que que proporciona la energía eléctrica tanto a los actuadores como los pies. El último elemento que destacar sería el software usado para el diseño gráfico del robot. En este caso se han usado dos: SolidWorks 3D y Shapr 3D.

4. Resultados

Después de varios meses aprendiendo sobre el desarrollo de los robots blandos, su diseño, fabricación, creación y experimentos llevados acabo, los resultados han sido bastante satisfactorios. Durante estos procesos, los actuadores y los pies electro adhesivos se han tratado de forma individual para luego juntarlos al final. Las prestaciones que han desempeñado cada uno en los experimentos realizados al final del proyecto han demostrado el cumplimiento de los objetivos establecidos al comienzo de su desarrollo. El diseño final del robot se puede apreciar en la siguiente imagen.

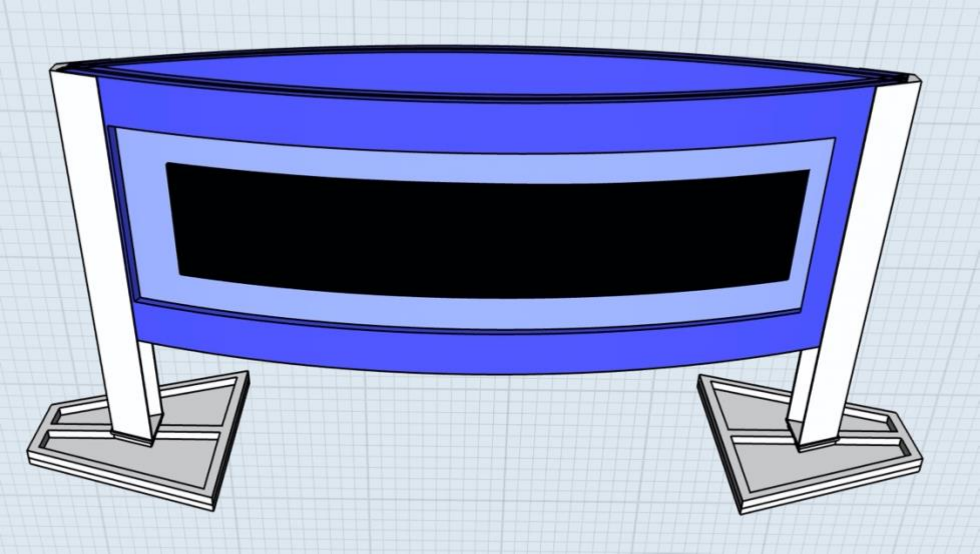

Figura I – Diseño final del robot blando trepador

5. Conclusiones

Para concluir, cabe destacar que todos los objetivos propuestos se han cumplido a lo largo del desarrollo del proyecto. Los procesos de diseño y fabricación han tenido como resultado un robot estéticamente agradable y funcionalmente correcto y útil, lo cual se ha demostrado durante los experimentos llevados a cabo hacia el final del proyecto. Para una futura mejora del modelo actual, sería necesario someter el robot a más experimentos con el fin de encontrar sus puntos débiles y modificarlos para su mejora. Además, añadir dispositivos externos daría pie a la producción de diferentes versiones del robot, cada uno con su respectiva función, lo cual sería una buena solución. Como nuevo objetivo tras finalizar este proyecto, se propone automatizar el proceso de fabricación con el fin de poder distribuir y comercializar el producto final.

6. Referencias

[1] Goldberg, Peter. “Studies Show Humans Prefer Interacting with Hyper-Realistic Human-like Robots.” *HERE 360*

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ABSTRACT

The relatively new field of soft robotics was born from the need and desire to build robots that mimicked living organisms such as plants, animals and humans not only aesthetically but also functionally. The inherent and structural compliance of soft smart materials allow soft robots to deform (stretching and compressing) and store energy. That is, besides the three dimensional translational and rotational motions, soft robots are able to deform and bend resembling the anatomy of animals and human beings. The ultimate goal of this project is to become familiar with the soft robotics field, study the soft smart materials and external agents that stimulate them and finally, come up with an application or function and design and manufacture a robot to perform it.

Key words: Dielectric elastomer actuator (DEA), electro adhesion (EA)

1. Introduction

The soft robotics field arises from the need to develop robots with the ability to perform human and animal like movements. Hard robots have been around decades before soft robots; however, their inherent rigidness prevent them from performing strain deformation and bending motions. The introduction of soft smart materials has allowed the scientific community to work on and cultivate this field of study.

2. Project definition

The main reason why this field of study was chosen over others for the development of this project is its room for innovation. Since there are very few investigations and published papers on the topic, there is a greater chance of creating an original application for a soft robot. The drawback to this newness is the lack of background, specifically the lack of theoretical, mathematical models and algorithms that define the behavior of soft robots and soft smart materials.

This project aims to create a soft robot from beginning to end. That is, learning about soft robotics, finding a useful function or application for the robot, designing it, manufacturing it and experimenting with it to produce the optimal model.

3. Model and Tool description

The most important part of a soft robot is its actuator, which is able to transform the external stimulus into motion. The choice of soft smart materials to build these is limited with the current technologies. For this specific research, the decision was made to build a dielectric elastomer actuator made of VHB tape as the dielectric membrane, acrylic sheet cut outs used to pre-stretch the membrane and carbon grease for the electrodes. As a result of choosing a dielectric material for the actuator, the external stimulus required must come from a source of electric supply.

During the creative process the idea of building a soft wall climbing robot was brought up. In order to do this, another important element had to be included in the model: electro adhesive feet. These are made of the acrylic sheet cut outs, regular paper, graphite and once again the VHB tape. Electro adhesion forces also require power supply. They are necessary to hold the robot to the walls as it climbs.

Since the manufacturing process is hand based, the tools required are very common and easy to find. Some of the ones that are used are scissors, cutters, permanent markers, soft copper wire, pencils, palette knives, etc. These tools and the raw materials used to build the robot are relatively cheap. Nevertheless, the voltage amplifier used to power the dielectric elastomer actuators and the electro adhesive feet is a more technical and expensive tool, essential for the robot’s functioning. The last tools used for the project were the design computer softwares. These are easy to use and provide excellent results, but a regular handmade sketch would be valid too.

4. Results

After several months of learning, thinking, designing, manufacturing and testing, the results were very satisfactory. The dielectric elastomer actuators and electro adhesive feet were treated individually throughout most of these processes and then assembled. The performance achieved by both elements complied with the expectations and objectives set at the beginning of the investigation. The final robot design can be seen in the figure below.

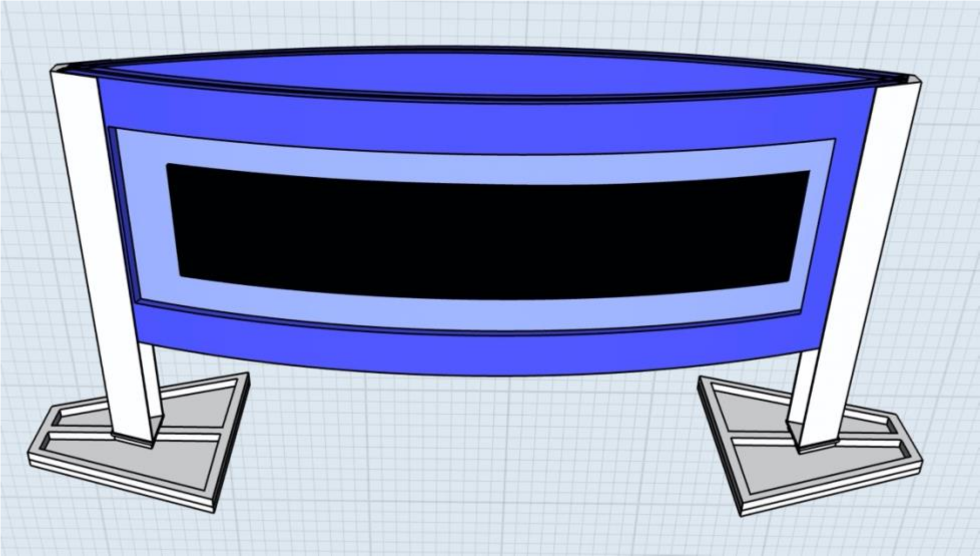

Figure I – Final design of the soft wall climbing robot

5. Conclusions

All in all, the objectives set were successfully achieved. The design and manufacturing processes led to a visibly pleasing looking robot and the experiments and tests run demonstrated efficient performance and behavior of the different elements. For future works based on this project, more experiments and tests would help modify and improve the current design. Moreover, adding external features and gadgets and/or modifying the original model to create different versions of it to perform different functions would be a good solution. The new objective once this project is finished is to help other researchers in the soft robotics field with this paper and possibly automatizing the robot's production to be able to market and distribute it.

6. References

[1] Goldberg, Peter. "Studies Show Humans Prefer Interacting with Hyper-Realistic Human-like Robots." *HERE 360*

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CHAPTER 1 – INTRODUCTION

Robots in their most simple form are programable machines which perform automated functions. The basis for the development of the robotics research field was set by Norbert Wiener with his studies that gave birth to the principles of cybernetics in 1948. Early robots consisted on simple mechanisms that performed basic automated actions and were mainly used as part of supply chain processes to improve and help bulk production. However, the vast technological advance that occurred during the second half of the 20th century completely revolutionized the traditional concept of robotics. Even though every programmed, automated machine can be considered a robot under the original definition, the general public currently thinks of robots as human like machines that are able to perform the same actions as people automatically. It is true that the rapid advance in programming, automatization, manufacturing, engineering and technology as a whole has driven researches and professionals to design these machines having as an aim to mimic the human anatomy. In fact, the manufacturing of these kind of robots has been an evident success, researches are currently taking the next step by making their appearance more human like both for aesthetic and functional purposes through the use of the new subfield of soft robotics.

Traditional robotics, also known as hard robotics, consist, as it is implied in their own name, of automated machines made of hard materials for their body, links and joints, essentially metallic parts. These robots highly effective for certain applications and functions, including bulk production, supply chains, etc. due to their fast and precise systems. However, when it comes to robots principally designed for human use, that are meant to perform under harsh environments or that require high adaptability, hard robotics fails to comply. When facing this limitation to hard robots, researchers worked on developing robots made of soft materials, which have the qualities necessary to overcome the problems listed.

All in all, soft robotics arises from two different specific needs in the industry. In the first place, some applications call for human friendly use and interaction. On the second hand, soft robots in contrast to hard robotics are able to deform, that is, stretch and compress under external stimuli. The principal source of inspiration is in fact from living organisms, including plants and animals, specifically the human body. Given that one of the ultimate goals of these robots is to perform human like actions, there is no better basis. Pioneer designs to meet such needs use the combination of hard and soft materials, but professionals are currently working with the design of robots manufactured exclusively with soft materials. Besides the use of soft materials, there is an additional challenge to soft robots since the manufacturing processes also differ from those used in hard robot production. Engineers have had to come up with new techniques to assemble these robots as the materials are far more delicate. As it can be seen, soft robotics requires of the collaboration of different departments, for instance: manufacturing engineers, programmers, electronic engineers, physiologists, materials engineers, biomedical engineer or pharmaceutics, depending on each robot's specific application. For this research particularly, the focus will be put on the design, choice of materials and manufacturing of the soft robot.

The competitive advantage of soft against hard robots is predominantly due to the choice of materials and its properties. For instance, soft materials are able to undergo large strain under different forms of external stimuli, that is, it can stretch and compress under the action of an external agent. Due to their compliant structure that allows molecules to move collectively and the material to deform, this one can also store and release energy. The same way, they can be easily bended. Their natural density makes the assembled structures exceptionally light weight, especially compared to metals. Moreover, from an economic perspective, the fabrication methods developed for soft robots are more cost effective and allow for both bulk and customized production at low cost per unit. In addition, the economic investment for the purchase of raw materials is significantly lower too in general terms. Going back to the material properties, they show a very fast response to external stimuli and quickly perform the induced motions. Finally, one of the most valuable features of soft materials and soft robots is their ability to reach multiple degrees of freedom in terms of motion. In other words, their movement spectrum is larger than that of hard robots. These last ones are limited to the six principal movements in three dimensions: three translations and three rotations. However, due to their bending and deformation properties, the degrees of freedom reached by soft robots are simply higher.

All these properties add together allow for soft robots to perform functions that traditional, hard robots were uncapable of. Soft materials make the robots highly adaptable to different surfaces and, extrapolating, to different, harsh environments. For example, some soft robots are meant to act under water, over delicate surfaces such as crystal or in uneven, rough surfaces to which they are able to adapt, once again due to their light weight, bendability, deformability and multiple degrees of freedom. In addition to their adaption to new working environments, surfaces and external objects, their aesthetics and soft structure make these robots and their use very human friendly, as they look and feel very similar to the point where they are able to perform body functions and adapt to human body parts that allows them to create prothesis and orthopedic body parts.

All in all, and having highlighted the advantages of soft robots, it is worth stating that neither hard nor soft robots are better or worse. Instead, each of them is designed for their specific functions and application in which their stronger qualities are exploited and taken advantage of. In fact, soft robotics arose from certain needs that hard robots were not capable of fulfilling. Nevertheless, and all this being said, their coexistence and complementary use is most beneficial to society.

In relation to this research particularly, the main objective is to get familiar with the soft robotics field and learn as much as possible from previously published works and research to develop a soft robot from start to finish. To rapidly summarize, this process, as it will reviewed in depth later, starts with getting acquainted with the materials used to manufacture soft robots. Manufacturing small and simple structures and stimulating them with the external agents provides with the knowledge needed for the creative process involved in developing new functions and applications for the robots. After learning about the material behavior, several designs will be developed as candidates for the final official product. Once some designs are discarded due to lack of resources, uselessness, lack of innovation and degree of difficulty, the remaining are manufactured and tested to identify the most efficient one both from a functionality and ease of manufacture perspective. For the chosen robot idea, several sketches and 3D renders are presented varying in shape, size, assembly and configuration once again to choose the best one. With the optimal design, multiple prototypes are manufactured using different materials in order to choose those that better adapt to it. The best configuration manufactured will then run through several tests under the external stimuli to gather data and produce an effective functional range regarding the different parameters modified.

The design that was chosen after running all the tests, experiments and evaluation was the soft wall climbing robot. This robot will be stimulated by electric and power supplies and will move through the expansion and contraction of the robot's body. Its feet will walk and climb thanks to the phenomenon of electro adhesion. The robot will be designed, manufactured and tested for optimal functional conditions and parameters and the final product will be studied from different aspects including sustainable, economic and application perspectives.

CHAPTER 2 – TECHNOLOGY DESCRIPTION

The technologies and tool used for this research can be classified into the three different stages of the soft robot's production: design, manufacturing and stimuli, being the choice of materials for the manufacturing part the most important for its development.

Firstly, for the design process, besides simple 2D sketches, the use of two different tools were needed to develop the 3D model renders: SolidWorks 2008 for Microsoft Windows and Shapr 3D CAD modeling Version 3.40 app for iOS. Both were used to design the multiple proposals for the manufacturing of the final soft robot. The use and results of these two tools will be studied more in depth later but they are essentially two computer-aided design (CAD) platforms for industrial design meant to be used by engineers.

Following comes the most important part of the production process, choosing the right materials for the manufacturing of the picked design. The soft robot can be divided into four parts: body, actuator, electro adhesive feet and connections to the power supply. For the body, which primal functions are to pre-stretch the actuator membrane and hold all parts (feet, actuator and wiring) together, the material chosen was an acrylic sheet to be shaped with a conventional cutter. Its design is simple for easy manufacturing and keeping the structure basic.

For the manufacturing of the actuators, there is a limited range of soft materials suitable for its function of transforming the external stimuli into motion. The different types available currently include, but are not restricted to: shape memory alloys (SMAs), fluidic elastomer actuators (FEAs), dielectric electroactive polymers (DEAPs), electromagnetic actuators (EMAs), shape morphing polymers (SMPs) and pneumatic artificial muscles (PAMs). After studying their different behaviors under the several types of external stimuli, their possible combination with the designed body and considering the resources available, dielectric elastomers were chosen to manufacture the actuator to be incorporated in the final soft robot produced.

Dielectric elastomers can be defined as smart materials that have the ability to transform electric stimulus into motion, technically defined as electromechanical transductors. The main advantages to the use of this material against the rest mentioned are its simplicity, low cost fabrication, wide range of stiffnesses and strains, large deformation and bendability and intrinsic softness [Perline 2008]. The commercial products used to manufacture the dielectric elastomer actuator include VHB tape (4910 and 4905), distributed by 3M for the membrane and carbon grease (846-80G) distributed by MG Chemical to increase electric conductivity between the membrane and soft wires.

VHB tapes consist of transparent acrylic double-sided adhesive foams. The difference between the two types used is their thickness, 4910 is 1mm thick whilst 4905 is 0.5mm thick. These two types are specifically designed to adhere to high surface energy materials. The tapes are designed to be durable, strong and elastic and their behavior can be defined as viscoelastic, resembling viscous liquids or elastic solids and they maintain their properties under a wide range of temperatures (- 40ºC, 90ºC) [VHB 3M 2013].

Figure 1 – VHB double sided adhesive foam [21]

For the actuator to be completed, some carbon grease is coated over the VHB tape to increase the electric conductivity of uneven and rough surfaces, ideal for the soft materials since it remains effective under deformation and strain. Moreover, it is safe to use with plastic surface, for instance, the elastic membrane. For the specific model and brand chosen, 846-80G by MG Chemicals, the grease has a resistivity of 114Ω·cm, ensures electrical contact between loose and vibrating parts and prevents arching, pitting, hotspots and welds [MG Chemicals 2008].

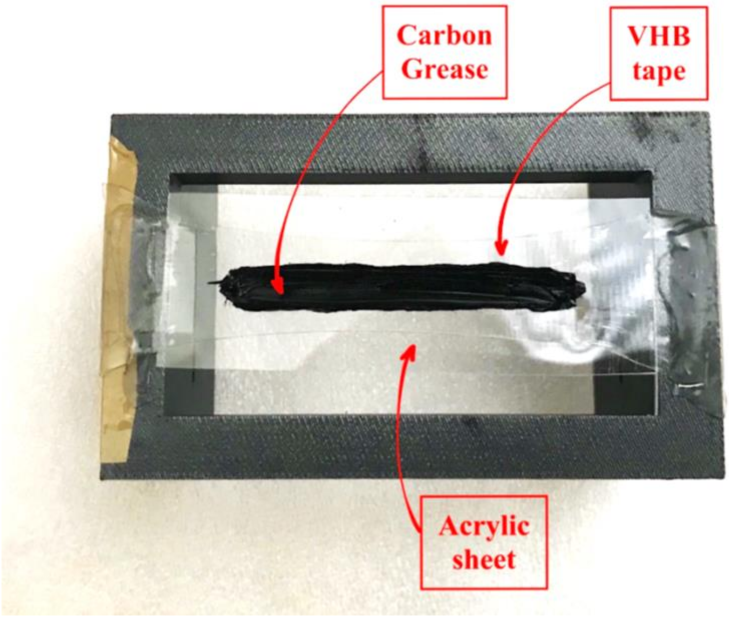


Figure 2 – Built in actuator in body

In the figure above it can be seen how the carbon grease is painted over the VHB tape to create the actuator, which is adhered to the acrylic sheet used for the robot's body. This picture was taken in the laboratory during the investigation process in which it is easy to depict and isolate each of the elements involved in the production of the robot as for the materials used.

To stimulate the actuator, the power supply is connected to the carbon grease electrodes through soft wires that are placed and coated on top with an extra carbon grease layer to ensure efficient electric conductivity. The reasons these soft copper wires are used instead of conventional wires are its light weight and small size. The soft robot's configuration is too delicate to manipulate with conventional wires under which the structure could collapse. Moreover, traditional wires would be hard to connect to the grease and hold on to it while the actuators deform.

The last elements of the soft robot's body are the electro adhesive feet. There is three essential parts that assemble to form its structure: an electro adhesive pad, VHB tape and the acrylic foot connector. The electro adhesive part can be subdivided into two components: a traditional sheet of paper and a graphite layer.

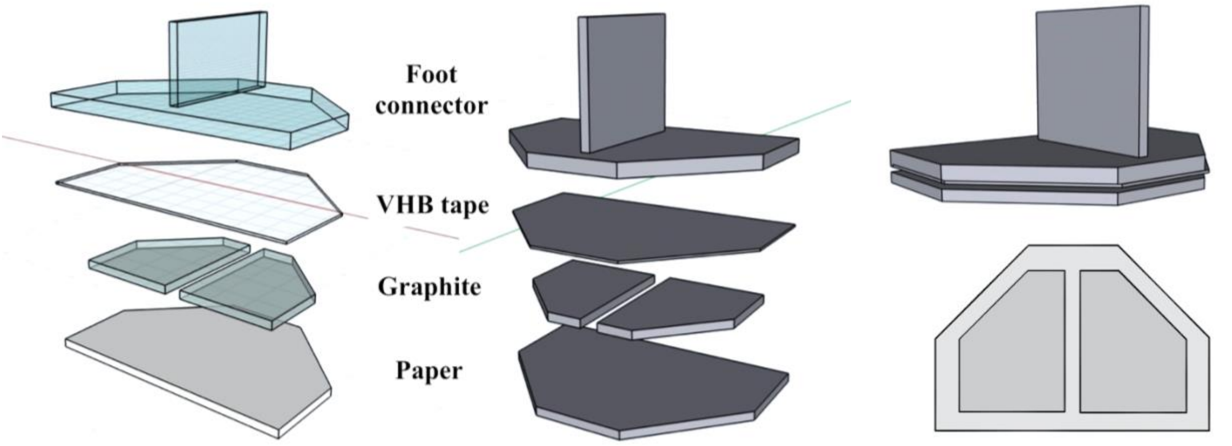


Figure 3 – Electro adhesive feet structure

Figure 3 is designed to depict the electro adhesive feet configuration from different perspectives and isolating each of the layers as well as the final product for a reader's easier understanding. As it can be seen, a 2D model is created for the foot's sole and a piece of regular UNE A4 paper is cut with its shape. Following, the two darker depicted areas are filled in using a 2B pencil which will also be connected to the power source and act as electrodes like the carbon grease in the soft actuator. The graphite layer needs to be thick to ensure electric conductivity as this is proportional to the level of coverage.

A piece of the VHB tape (4910) used for the soft robot previously will also be cut into the foot sole's shape and stuck to the piece of paper with the graphite layer, it is important to place the soft wires in between these two layers to ensure conductivity. Moreover, the adhesion properties of the VHB tape strengthen the wire connection. Lastly, the foot connector will be placed on top of the VHB tape, which acts as a link for the whole structure. This connector is made with the same material as the soft robot's body, and acrylic sheet.

The final technological device needed for the development of the soft robot is the power supply. Soft actuators and the different materials that can be used to manufacture it respond to several types of stimuli. Some of these are electric, chemical, solar (light), thermal, magnetic, pressure, etc. Once the type of material was chosen for the actuator to use for this specific robot design, the external stimuli that was thought to be more effective was electric. Moreover, since the feet required an electric stimulus too, the decision was made to use the same power supply for both. The specific device used is the Glassman FX20P15 High Voltage DC Power Supply (Positive Polarity). Its nominal values are 20kV, 15mAmp and 300W. As it has been previously mentioned the connection will be done through soft wires for both the actuator and the feet, set as independent power sources for each.

CHAPTER 3 – BACKGROUND

3.1 HISTORY AND ORIGINS OF SOFT ROBOTICS

Relative to the time frame in which the study field of robotics has been growing, more than seven decades by now, soft robotics is only an emerging discipline that has only been established as a research field in material studies in the 1990s. Given its short lifetime, the exact definition for what classifies as a soft robot is not definite, instead, it embraces a large range of machines. Liyu Wang from the Biomimetic Millisystems Lab at the University of California Berkeley defines the field of research as "robotics that encompasses solutions that interact with environment relying on inherent or structural compliance", Rossiter and Hauser give a similar definition stating that "soft robotics is an umbrella term that covers all types of active and reactive compliant system" in their paper.

Nevertheless, the first research papers to every be published on soft robotics date back to the 1970s by Cardaun, Schmidt and Perovskii with a special focus on grippers manufactured with granulated materials. However, the origin of soft robotics as it is known now belongs to Wilson and Mahajan, the first to use elastomers for its deformation properties. As for the current situation, the potential for soft robotics has boosted. The main reason for this besides the undeniable advance in technology, is the use of artificially synthesized materials, which are designed to comply with the characteristics and include the properties demanded by researchers. Along with the need for new soft materials aimed for the growth of soft robotics came the need to come up with new manufacturing techniques to manipulate such delicate materials. One of the most relevant techniques that has revolutionized and fueled the production of soft robots is 3D printing, given its easy prior design process, ability to manufacture with soft and light materials and accuracy to produce small sized and detailed structures.

Other reasons that make soft robotics a more extense and developed research field now a days compared to when it was first introduced are its current lower cost and the possibility to integrate different devices in the robot that either enhance their functionality or give it further types of applications, some examples are: microelectronic circuit systems, sensors, actuators, etc.

As it has been mentioned before, soft robotics is born from the need to mimic animal – like movements and to provide a user – friendly robot that is both easy and safe to handle by consumers. It is true that hard robots are better to perform repeated automated functions in traditional manufacturing and supply chain processes. They are also easily defined with mathematical modelling unlike soft robotics, mainly due to their nonlinear deformation and response to external forces. However, hard robots are becoming obsolete for applications designed exclusively for human interaction.

The natural properties of soft robots make them highly adaptable to multiple surfaces, fit in and squeeze through smaller spaces (also depending on their size), and most importantly, they are able to function both in delicate and severe environments including liquid, extremely high and low temperatures or under pressure. If made of human tissue they can even function inside the human body.

In relation to the current research in the field of soft robotics, it can be easily classified into two different types. Firstly, there are those who focus on investigating, improving and enhancing the properties of soft robots. For instance, gathering data on the response of the different types of materials to the different types of stimuli, trying to improve the soft materials themselves, working on optimal configurations for the robot's body and actuators, etc. Overall, this is the groundwork essential for those who focus on the second type of research in the field. Their work basically consists on using the findings from the previous group to work on the robots' possible functions and applications. These researchers are in charge of coming up with the robot's purpose and designing and manufacture it for its function. The process for this part of the investigation allows for additional gadgets in the designed, including sensors, cameras, microelectronic circuits or, in relation to this specific research, the electro adhesive feet. These last group is also in charge of developing the modus operandi of their designs. That is, gathering the data necessary to determine optimal working conditions and parameters involved. Furthermore, some overachieving and ambitious researchers like to work on the whole process, from improving and selecting the simplest form of a soft robot, including its properties and behavior, to designing and manufacturing the final product giving it a specific function, purpose or application.

3.2 SOFT MATERIALS

There is a major obstacle in the development of soft robotics involving discontinuous material behavior. The soft materials have nonlinear as well as time dependent response to external stimuli. There are many external variables that are hard to control that largely affect the soft material behavior and, subsequently experiment results. This makes mathematical modeling a hard task, and is the main reason why the behavior of soft smart materials cannot yet be put into an algorithm that widely apply. Nevertheless, there are a few simple and basic models used, that define some material behaviors broadly. For instance, the Maxwell and Zener models describe the material relaxation. The Maxwell model predicts spring behavior with the equation below where σ is stress, ε is strain, R is the spring constant, t is time and η is the damping coefficient

$$\sigma = \varepsilon R e^{-Rt/\eta}$$

The Zener model in contrast defines the behavior of a viscous damper (R_2) parallel to an elastic spring (R_1) by the following equation

$$\sigma = \varepsilon \left(R_1 + R_2 e^{-\frac{R_2 (R_1 + R_2) t}{R_1 \eta}} \right)$$

These two examples propose simple models with the use of a single equation, which unfortunately is not enough to fully describe and define material behavior. Moreover, these models are based on multiple assumptions like material isotropy. Other models that treat the behavior of soft materials similarly are the Kelvin or the Burger. The basis for all these models were set by Mullins in 1940, who asserted that the repeated stretching of these soft materials deteriorates them. This is clearly not a problem for hard robotics since metals and hard plastics follow Hooke’s law meticulously and are therefore easy to work with.

Many researchers are working on gathering data on the behavior of soft materials and make it available and accessible with the aim of promoting and improving the production of soft robots.

Jennifer C. Case, Edward L. White and Rebecca K. Kramer do an important job in trying to model and describe the behavior of soft materials applied to robotics with their published paper “Soft Material Characterization for Robotic Applications”. They put focus on investigating the behavior of three different elastomers that are frequently used in the study field and run five different experiments on each of them to gather data on their behavior under strain. For each of the experiments the materials are shaped equally and treated as closely as possible for greater accuracy. The experiments are:

1. Pull-to-failure: variable strain rate – This experiment consists on stretching the material in one dimension at a constant rate until breakage using three different strain rates for each type of elastomer.
2. Pull-to-failure: batch-to-batch consistency – In this case the materials are also stretched to breakage under one constant strain rate multiple times. The objective of this experiment is to determine whether there are inconsistent material properties that result in inconsistent behavior and response to external stimuli within one same batch of elastomer.
3. Pull-to-failure: effect of pre-strain – It is a very common practice in the soft robotics field to pre-stretch the soft material to achieve better results. However, there is a big tradeoff between these desired results and its effect on the material’s and essentially the robot’s lifecycle and decay speed.
4. Cycle loading test – Robots in general are designed to be used multiple times, sometimes repeatedly. This is easy with hard robotics, however, soft materials lose their efficiency at a very large pace with each use. This experiment shows the deteriorating behavior of the three types of elastomer after each use.
5. Stress relaxation use – The last experiment gathers data on the behavior of the elastomers as they relax after being stretched for 3 hours, at different constant relaxation rates.

The conclusions they have come across with this investigation are that material properties depend on strain rates, that they are sensitive to production variations, that pre-stretch leads to irreversible material alternation and that cyclical or repeated loading in fact deteriorate the material. To summarize, the field of soft robotics faces a great obstacle regarding the determination of material parameters and coefficients. The process requires of repeated experimentation and testing, and the results are not always consistent between different sets of the same material. This prevents the development of generalized mathematical models and algorithms.

3.3 SOFT ROBOT APPLICATIONS

Once all the research necessary to define the soft material's behavior is over, the creative process begins. This involves the search for a purposeful function or application for the robot followed by the design and manufacture of the product to implement it. In some cases too, this process includes the implementation of an additional gadget for the performance of further, specific functions.

As it has already been stated, soft robotics was born out of the need to produce automated machines that mimic the anatomy of living organisms. Hence, not only are robots influenced by their structure, but some even attempt to produce complete copies of such. The simplest forms of this type of soft robots usually try to resemble smaller animal organisms such as swimming frogs and fish, annelids or multiple legged arthropods as can be seen in the figure below.

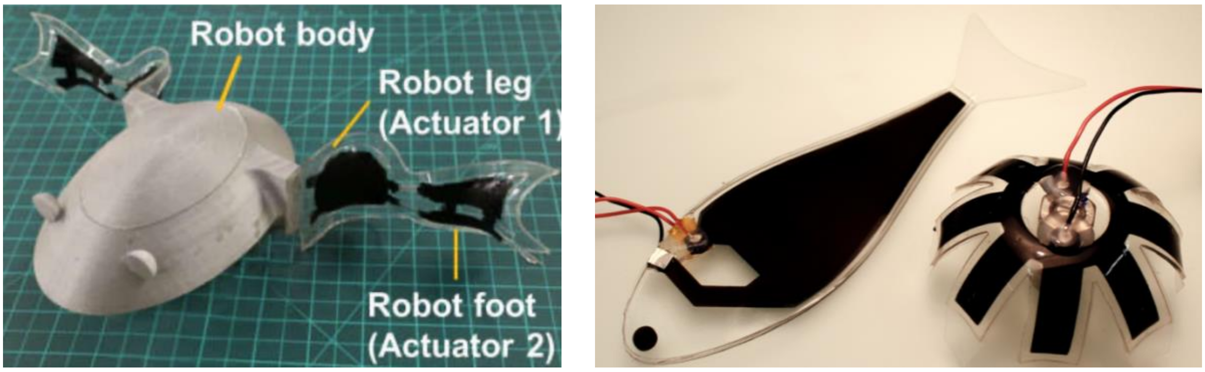


Figure 4 – Soft robotics applications: swimming frog [18] and fish [9]

Other researchers have focus on the human body instead and have been able to develop eyeballs, lens and ultimately, prothesis for different body parts. Even though prothesis have been around for a long time as hard robots, the aim of these kind of studies is to develop body parts with a higher resemblance to the originals, both for an aesthetic and functional purpose.

The most common trend right now is set on the reproduction of hands. Compared to the previously mentioned applications of living organisms, these types of products require a more complex level of design and manufacturing. Moreover, for them to be utile as prothesis in real patients, there needs to be different disciplines and professionals involved in its development, including engineers and doctors. The technical detail and complex structure required is clearly shown in the figure below.

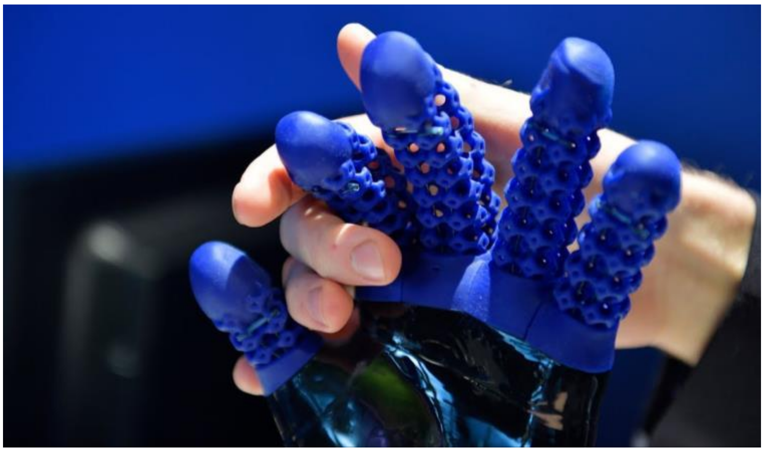


Figure 5 – Hand prothesis soft robot [4]

This hand specifically has the ability to respond to the external stimuli of pressure, and bends to perform a gripping action when it detects contact in the palm as it is being depicted in the picture.

To conclude the review of the applications of soft robotics it is worth mentioning the latest achievement in the research field: Octobot. This is a soft robot that resembles an octopus, and it is the first autonomous robot, that is, it is capable of untethered functioning, something investigators in the field have been trying to achieve since the origins of soft robotics. Its launch is relatively new, dating of August 2016. Thanks to its study, conducted by Robert Wood and Jennifer A. Lewis in Harvard University, many others have learnt to make their own robots untethered, promoting the general growth of the research field of soft robotics. The robot's body is made of silicon and pneumatic cavities are introduced in it as part of the same 3D printing manufacturing process. The external stimulus to which the robot responds is chemical, resulting of the gas released from the reaction of platinum and hydrogen peroxide, that expands the tentacles. This is just the beginning of an ongoing investigation in which researches are working on enhancing the robot to perform further functions and giving the product certain purposes. The following figure shows its fancy design and internal structure thanks to the translucent properties of the silicone.

Figure 6 – Octobot [16]

This is one of the latest trendiest soft robots developed, and as far a soft robotics concerns, one of the greatest achievements given its independence to function. On the medical side of soft robotics applications, there is still ongoing working professionals who are contemplating the use of human tissue to produce further robots to make them completely compatible with the human body. The development of this specific research aims to use all the information commented as a basis from which to develop its own innovative robot.

CHAPTER 4 – PROJECT DEFINITION

4.1 RATIONALE

4.1.1 INNOVATION

The fundamental reason why this investigation is based in the research field of soft robotics is its newness and current growing continuum. That is, since the study field is relatively new, many researchers are becoming engaged with it and the challenges it proposes and are collaborating towards the common goal of helping expand the general knowledge on soft smart materials and robots. However, this newness has two sides to the same coin. Both its advantages and disadvantages have been the reason why the research pursues the development of a soft robot.

In the first place, soft robotics offers much room for innovation. In contrast to other fields of study under the scope of engineering where everything has been studied, presented and evaluated, and everything is already out there, the soft robotics field still has a lot of room for growth. Hence, this research aims to be creative and innovative, and will hopefully result in the creation of a new device, application, or any improvement to soft robotics.

The downside to this newness is the lack of a solid basis from which to work upwards. As it has been mentioned, there is no go to mathematical model or algorithm that defines or characterizes the behavior of soft materials under external stimuli. Likewise, there is no established procedure to the creation and programming of the robots. This can make the investigation process hard, specially coming up with the initial idea. Once there is an idea to be developed, the design and manufacturing process will require many experimentation and testing process, and a lot of trial and error, going forwards and backwards through iterative processes until optimal or desired results are achieved.

Nevertheless, having no strict guidelines, rules or procedures to the development of soft robots, gives researchers the freedom to create, experiment and ultimately contribute to the science community, which should be extremely gratifying intrinsically and seeking social gratitude.

This ties with the following reason why this type of research was chosen. Being able to contribute to the science community with a relevant investigation would be very rewarding. As there is still plenty to be discovered with soft robots, there is a high chance for this to occur. With the study conducted for this specific paper, there are many areas which could be considered useful for future researchers. For instance, the analysis of soft materials and external stimuli, the characterization methods used for the dielectric elastomer actuator and the electro adhesive feet as well as the data gathered in the later experiments and tests that describe the robot's motion: climbing, crawling and turning. The research also describes the optimal parameters and controlled range of values used for the power supply both for electro adhesion and the actuator. All this information can be used for further improvement of the designed robot, or used individually for the development of different devices and applications. It is a comforting to contribute to the science community even with a gesture as small as the publishing of this research.

Going back to the downside of the 'newness' of the topic involving the lack of a solid groundwork and theoretical background, the research was taken as a challenge, which is indeed a big motivator. Joining this venture provides stimulation and presents inspiring problems which have not been dealt with before, making the process insightful and encouraging and the results extremely satisfactory.

4.1.2 APPLICATIONS

The aim of this research is to develop a fully functional soft, wall climbing, tethered robot through the analysis of materials, design and manufacturing and future experimenting process that describes its functionality. The final result will be the first version of the wall climbing robot, which can be later worked with to add supplementary features that give it different purposes or applications or simply to improve the original model. This matter would be addressed by further research and analysis, and will be commented in the last section of this research. The following are some of the possible applications that could be achieved by the modification and alteration of the original version of the robots. Some require of more dedication and technical work while others just need the implementation of an additional piece to the robot's body.

The soft wall climbing robot can reach heights unreachable by humans and squeeze through very small holes and gaps, and can be programmed to do it automatically and individually as long as it is connected to power. With the use of additional devices that could be easily attached to the robot's body such as cameras, microphones and sensors, the robot could perform endless tasks. For instance, they could be used for surveillance in buildings, for mapping and tracing of caves or downfalls, to find people under debris in case of natural disasters, for transporting small items, etc. If suited with pipettes, tweezers or small vacuum, it could also be used for sampling. Moreover, it could be coated with silicon or soft plastic to make it waterproof and make it function underwater.

All the applications previously mentioned are attainable to a certain extent with the current external stimulus. However, the number of applications and the robot's effectiveness in performing them would be immensely improved if the robot was untethered. This would be a hard task given that not only the actuator is powered by the voltage supply, but also the electro adhesive feet. Nevertheless, it could be possible to design and manufacture with the use of batteries and microelectronic circuits or with a system similar to that of the Octobot. All in all, these multiple applications and improvements would be achieved through further investigation and work over the original prototype.

4.1.3 COMMERCIALIZATION

There is three main ways in which the original soft wall climbing robot can be launched into the market making it available to society both for individual or bulk use and distribution. Besides the economic profits this can generate, which will be commented as part of the economic plan and forecasting, this section provides a summary on how the product can be made available to the general public.

Since this research is centered on the production of the original soft wall climbing robot, which results in a very simple and somehow limited mechanism, people might be reluctant to use it as it is given that it does not have a specific application of performs purposeful functions besides crawling and climbing. Hence, the distribution and commercialization process are hindered and must be thought of thoroughly.

The first idea and most simple from the production point of view is to patent the model and make it available for the general public to buy and alter as they wish to perform the different functions desired. The patent can also be used by other researchers to use as a basis and work on improving it and giving it specific purposes. This is a very feasible option which makes the soft robot available to everyone willing to pay for it. However, it requires too much on the client's side to manufacture. That is, the market segment attracted to this option would be too small given the knowledge and technologies involved in its production. The forecast in fact expects an enormously larger group interested exclusively in the use of the soft robot rather than its making.

For this larger target market, the commercialization idea that adapts to their needs is that of customization on demand. For some people it might be just fun and enjoyable to have and use the simple, basic version of the soft robot. However, thinking realistically, the soft wall climbing robot is not designed to be a toy, and a very little amount of people will regard it as so. Therefore, customized production would be another attainable method of distribution. This leaves clients in charge of coming up with the desired function of application based on their own wants and needs. They would then transmit the desired features to the production team, and these would be analyzed to determine whether they are feasible and if so, how it could be done. Customization, besides leaving the creative process up to the clients, allows for large economic income given the individual treat given to each customer. This process involves working over the original model, adding supplementary elements and modifying it to fit the required outcome.

Finally, batch of bulk production could be considered too with some modifications made to the robot. If many clients are asking for similar features on the robot for related applications, a general model could be designed and produced at bigger scales and sold to the general public. This process once again requires working over the original model, and therefore would involve further work to what is addressed in this specific research. Besides doing a unified model for similar requests from clients, some models could be created for the applications mentioned on the previous section, including surveillance, mapping, tracing, sampling, etc. These models would be produced in batches to sell individually and their quantities would be adjusted based on the demand they generate.

There is another option that combines the previous two solutions: customization and bulk production. For instance, an individual client might ask for a customized design with the idea of purchasing large amounts of such product. For example, a mining company might want to buy a soft wall climbing robot that takes samples inside caves before they allow mineworkers to go inside. They would need to buy a large number of robots for the different mines. This would apply to many other cases where there is a specific need and a large demand in terms of quantity of such product.

All in all, these are some of the ways in which the soft robot could be distributed and made available to society. All the options mentioned are far from exclusive, in contrast, they can be used simultaneously as they are perfectly complementary and compatible. Using all of them at the same time is the best solution both for clients and from an economic point of view if making the soft wall climbing robot profitable ever becomes an objective, since it comprehends a larger target market.

4.1.4 IMPACT TO SOCIETY

Tying in with the different methods of distribution comes the impact the soft robot will have in society. If all the distribution channels are used, it is likely that the robot will be available for a large amount of people and eventually, it can become a known, and hopefully useful and purposeful to those who purchase it.

Moreover, with the applications that were thought of for future versions of the original robot, these could become useful not only for individuals, but for big organizations, businesses or even the government. For instance, one of the applications that was previously mentioned, crawling through and recording under the debris after natural disasters, could be useful to firemen or the military as they look for trapped people and animals, speeding the process and elevating their efficiency.

To summarize, helping society in these and other issues, or simply helping people as individuals, making them happier by making the robot available to them is the most rewarding and uplifting compensation to all the involvement required for the development of the products. In addition, with the use of the distribution methods mentioned, other researchers from the soft robotics field can take advantage of the original model to build on it and develop further versions that will also have a positive impact both in the scientific community and society as a whole.

4.2 PROJECT OBJECTIVES

The first step in the development of any project is getting to know the field of study. Hence, the first thing to do is get acquainted with all the previous research done in the soft robotics field. Learning from the background and groundwork from which to build on is key to avoid underperforming and to take advantage of what has already been studied. Setting a clear basis and foundation as the starting point is important for a virtuous further development of the project.

Following comes the study of the soft smart materials used both for the robot's body and the actuator, as well as the different types of external stimuli to which the actuator responds. Getting to know the materials' behavior and properties, how well they function together and specifically, how the actuator transforms the external stimulus into motion is essential for the creative process to start. Without understanding how the materials work, coming up with applications or designs for the robot might result in wasted time and effort since their manufacturing might not be possible.

Once familiarized with the materials and their behavior it is possible to begin thinking of applications and designs that are coherent and consistent with this type of materials. The objective here is to come up with multiple design options from which to choose the best and most feasible one with the technologies available to give way for the manufacturing process. Once the best choice is defined, several designs will be generated for such preferred application.

The following objective involves the production of the robot itself based on the chosen design. The idea is to treat this process with trial and error. At this point the original design undergoes small modifications based on tests and experimentation in which different materials are used. The intention of this specific objective is to find the perfect dimensions for the robot's configuration and design as well as the selection of the materials and external stimulus that allow for optimal behavior.

Once the robot is manufactured using the chosen structure and materials, it needs to go through several testing and experimenting processes in order to determine several sets of data. Some of these are designed to establish a range of values for the voltage and power supply under which the actuator and electro adhesive feet can operate, and, ultimately find their optimal values through iterative analysis. Other experiments are needed to describe the robots' behavior. Since there is no theoretical model established for the functioning of the smart materials due to their nonlinear behavior under stimuli, the robots' behavior is therefore not describable through a mathematical model or algorithm. Consequently, there needs to be a set of guidelines, similar to a set of instructions, that explain how the robot works, the parameters it accepts, the range of values for the power supply it is able to endure, etc.

All in all, the production of the robot needs experimentation to choose the optimal design, establish manufacturing parameters, configurations and dimensions and to define its behavior under stimuli. This last part is done for the robot's future user, to ensure its use is safe and to extend its product lifecycle as much as possible and avoid harm or breakage.

These are the objectives that, once accomplished, result in the production of the soft robots and that set focus on the internal development and purely technical process. However, the scope of the project goes beyond just the scientific approach. Some other aspects that are taken into account with this research paper include economic impact and sustainability goals, which will be commented on individually on following sections.

4.3 METHODOLOGY

As with any project, the first step is to learn about the topic and become familiarized with the field of study. This helps researchers get an idea of the existing background on the subject and gather all the information necessary to set the foundation from which they can work upwards and build on. In order to do this several research papers were read and studied for a month to understand the scientific background that allowed for the production of soft robots. The papers read touched upon different aspects of soft robotics in order to gather enough information to build a clear and broad image on the subject.

To further comprehend how soft robots function, the initial steps once in the laboratory consisted on playing with the different type of materials available and subjecting them to external stimulus to see how they respond. As it has already been mentioned, there are many kinds of materials that are used to manufacture soft actuators, the most important element in soft robotics, in charge of translating the stimulus into motion primarily. For this specific investigation and considering the materials available, two different types of dielectric elastomers were tested: VHB tape and platinum cure catalyzed silicones. Both were triggered by an electric supply as their external stimulus. Their configuration for the soft actuator is essentially the same, however, each of them offered different properties and resulted in different behaviors with the applied power. Moreover, the manufacturing processes with each of them varied substantially. The VHB tape from the 3M company comes in different sizes and forms. Both VHB 4910 and VHB 4905 were used for the initial material testing and experimenting. The difference between them is just their thickness, being 1mm and 0.5mm respectively. These are stretchable pieces of soft tape with adherence on both sides, they are easy and fast to work with. They just need to be peeled off their coating and can be directly stretched and taped into any other material or structure. On the other hand, the platinum cure catalyzed silicones from the EcoFlex company require treatment previous to its use in the assembling process. That is, the silicone rubber comes as two separate viscous liquids (A and B) which need to be mixed in equal quantities (1A:1B), then poured into petri dishes with the desired shape and cured during 3 hours at room temperature or less with the use of a centrifuge. For reference, in this specific research an Eppendorf centrifuge 5804 R 15-amp version was used. Like with the VHB tape, two different types of platinum cure silicon rubbers were used: EcoFlex 00-50 and EcoFlex 00-30. The number makes reference to the shore hardness, the pot life and cure time for the 00-50 are less and the material has higher tear and tensile strength and allows for higher deformation before breaking. However, this material does not offer the adherence feature of the VHB tape, and is therefore harder to assemble to the larger robot structure as it needs of regular tape or glue to hold together. As for building the actuator itself, the procedure is the same for both materials, they are pre stretched using a hard structure and carbon grease is painted on both sides forming the electrodes to which the soft wires are connected. The picture below shows the result of the cured silicon rubbers in the petri dish.

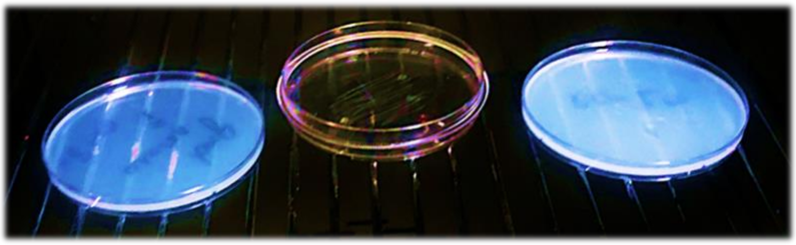


Figure 7 – Smooth-On EcoFlex platinum catalyzed silicon rubbers

As it can be seen, the material is thicker than tape and translucent rather than transparent. Moreover, when trying to build the structure for the actuator, the material turned out to be more fragile and break before the tape under deformation. Together with the fact that the silicon rubber needs of additional tools to stick to the hard structure of the robot's body and all the previous process it requires until its use, the VHB was chosen as more suitable for the final design. However, it must be said that the rubber offers an important advantage over the tape since the mixing and curing process it undergoes allows for it to take many shapes and forms before being pre stretched. Nevertheless, for this specific research and the characteristics desired for the actuator, this feature is not relevant enough to choose the rubber material over the tape.

After choosing the VHB tape as the principal material for the dielectric elastomer actuator, and consequently choosing electric supply as the external stimulus, several models were created coating the tape with carbon grease on both sides creating the electrodes and using different elements to serve as the robot's body, always using acrylic sheets as the direct contact with the tape. As it can be seen in Figure 8 below, different configurations, shapes and sizes were given to the actuator for testing and experimenting, in order to find out how they transform the electric supply into motion given its different structures, and which ones were more effective for several functions. These are just three examples, the first one has the tape, acrylic sheet and carbon grease shaped into a circle. This shape allows for radial deformation in all directions outwards and inwards when turning on and off the power supply respectively. The second one is shaped into a rectangle, allowing for linear deformation along the largest side of it. If this actuator is not fixed into a hard structure as it is shown in the middle picture, the deformation would result in a bending motion, similar to the one achieved in the picture to the right .This third one puts together two pairs of electrodes, that is, two different bent actuators joined together to from a circular shape. In this case, when voltage is applied, both tapes expand flattening the circle to form an oval shape.

Figure 8 – Configurations of dielectric elastomer actuators

There are many other structures and configurations that can be achieved using only the acrylic frame, VHB tape and carbon grease, not to mention all the kinds of robots that can be produced with the use of other smart materials and stimulants.

With the knowledge acquired first through reading other published papers and then experimenting with the soft materials, specifically to manufacture the dielectric elastomer actuator and understand how it responds to the external stimuli, the creative process could begin. This process basically consisted on coming up with possible applications and functions for the soft robots together with a feasible design that would enable them to perform such. Several designs were thought of during weeks and captured in fast sketches as well as three-dimensional computer designs.

The first design that was brought up mimicked a quadruped insect. The robot would consist of four different legs, each made of four bent actuators. All of them would be linked through a small squared platform in the center and each would have attached one spherical wheel at the opposite end, allowing the robot to move in any direction. The three-dimensional sketch can be seen in figure 9 below.

Figure 9 – Quadruped robot design

This initial design triggered many more ideas, possible modifications, further applications and functions, etc. There was a small drawback to this design, the amount of electric connections it needs to stimulate the robot. Since there are four actuators in each of the four legs, there would be up to sixteen pairs of electrodes to connect to the power supply. This does not need to be a problem for this specific research. However, thinking in the long term, if the robot is launched into the market for customer use, there would be less people interested due to the lack of private electric supply. Nevertheless, this idea led to the next, and final one. This idea is more ambitious since besides being able to move in any direction in two dimensions, the robot would be given the ability to climb flat, smooth walls.

To materialize this idea, the major milestone was figuring out how the robots' feet would adhere to the wall allowing it to climb. At this point, the idea of electro adhesion was brought up. Some of the papers read during the initial stage of this investigation introduced this phenomenon in their own personal work. For the design of the robot, the studies carried out by researchers Guoying Gu et al. [7] and was thoroughly analyzed to use as a starting point. Besides the electro adhesive feet, in order to maintain the robot's ability of moving in all directions but reducing the points of contact between the wall and the robot to reduce the number of feet, the whole structure needed to be simplified. To do this, instead of using four legs and four actuators per leg, only two larger actuators were included assembled differently and attached to two feet. One of the original designs that conveyed this idea is included below for an easier understanding.

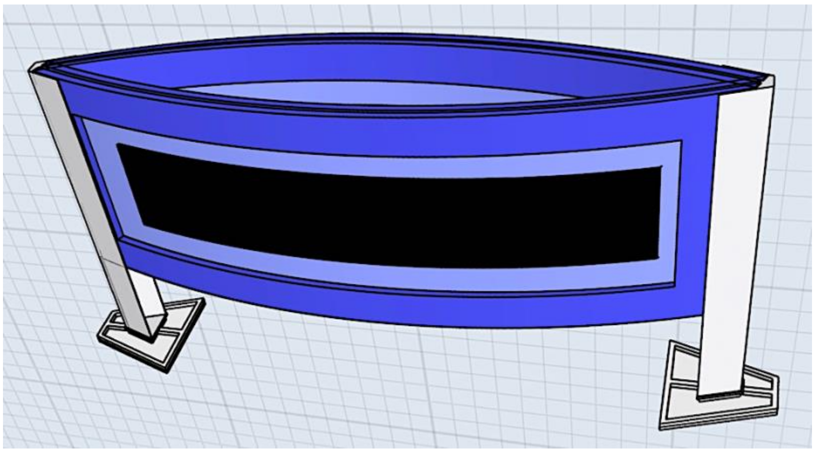


Figure 10 – Original sketch of the soft wall climbing robot

In this case the actuators act as part of the body instead of the legs as opposed to the quadruped robot. All in all, this last design is much simpler in terms of structure, which eases the manufacturing process, and requires less connections to the power supply, as it only has two pairs of electrodes excluding the feet. Moreover, it has the additional feature of climbing through adherence. The shape of the actuators is maintained from the original design. From the different configurations that were tested shown in Figure 8, the bent actuator turned out to be the most efficient for the desired structure and function. In fact, the picture to the right is exactly the same configuration used in the final robot design.

Once the final design is chosen and approved for the robot, the manufacturing process begins. The materials used for the actuator were chosen previous to developing the final design, hence the only materials that have to be determined for the robot are those used as links and those needed for the electro adhesive feet. The actuators are built with the acrylic sheet, VHB tape and carbon grease, and linked together with clear tape. As for the feet, the materials used are graphite layers painted with 2B pencil, the same acrylic frame and VHB tape, and they are linked to the body with the clear tape too. The manufacturing process is easy to perform as an individual, but it could be automatized with a chain process. Nevertheless, in this specific research the robot is manufactured manually.

To obtain optimal results, the different parts of the body are manufactured and experimented with individually and then assembled and tested again. For instance, the actuator is built using different sizes and proportions (length:width:thickness, etc.) and tested with the electric supply to analyze its response. The electro adhesive feet are also built individually with different sole shapes, graphite layer thickness and sizes and tested also with the electric supply to analyze the degree of adherence of each to the wall and to gather the range of electric voltage it can endure. Lastly, when each of the parts is tested individually, the whole robot is assembled to undergo further experiments. The experiments are similar: each of the individual parts (electro adhesive feet and actuators) are submitted to the electric supply, with the voltage values previously defined and the results are focused on the behavior of the whole body as opposed to the prior ones.

The experimenting process, both for the individual parts and the robot itself is very iterative. That is, the results are analyzed, and changes are made to improve the parts and the model, and the tests are repeated until the optimal or desired result is achieved. As it has been mentioned in previous sections, due to the lack of theoretical models and algorithms in the soft robotics fields, this trial and error process is required and the most important one to obtain satisfactory results, as there is not an equation or formula that gives correct values either for dimensions, voltage, etc.

Once the experimenting process is over and all the data needed to define the robot's behavior and the electric supply acceptable range of values, the production process is over. At this point, the robot is ready to operate and be distributed. The possible modifications, further models and future analysis are included in Chapter 7.

To summarize, the methodology process can be clearly broken down to six steps:

1. Study of the soft robotics field
2. Study of soft materials and external stimuli
3. Robot applications
4. Design
5. Manufacturing
6. Experiments

All these steps are essential for the building of any soft robot. However, some researchers might not follow the exact same order.

4.4 ECONOMIC PLAN AND FORECASTING

From an economic perspective, there is two major issues to analyze: costs of production and commercialization. Then, as a result of the strategic combination of these two, the production of the soft robots could be made profitable.

Starting with the costs of production, the first thing to take into account is the cost of the raw materials needed to manufacture the robot. This excludes the tools needed to build and power it, remaining exclusive to those materials that are part of the final product. The table below gathers all these materials and the information relevant to the economic study of the soft wall climbing robot.

Material	Brand	Quantity/Size	Average Cost (€)	Quantity/Size per Unit	Avergage Cost per Unit (€)
Acrylic Sheet	-	300x200mm	3.2	150x150mm	1.2
Carbon Grease	MG Chemical	80g	17	1g	0.21
VHB tape (actuator)	3M	3m	13.5	0.15m	0.68
VHB tape (feet)	3M	25x25mm	0.25	25x50mm	0.5
Soft wire	-	1144m	12.3	0.2m	0.002
2B pencil (graphite)	-	1	0.40	~ 0	~ 0
A4 Paper sheet	-	750	5	0.25	0.001
Clear Duct Tape	-	30m	8	0.2m	0.05

Table 1 – Cost of raw materials

All the materials that form part of the final product are included in Table 1. As it can be seen, the brand is only specified for the carbon grease and VHB tape since the other materials are very common and can be bought from different brands and distributors without causing large and meaningful differences in the final design. The only aspect to take into account when buying these is the size, quantity, type, etc., desired. For instance, the acrylic sheet needs to be 1mm thick, the pencil used for the electro adhesive feet's graphite layer needs to be 2B, etc. As for the A4 paper, clear tape and soft copper wire, these are very standardized products and do not need to be as specified as the rest. In contrast, the carbon grease, acrylic sheet and VHB tape are more expensive given their less common or standard nature and the fact that they need to be bought from a specific brand.

To calculate the cost of each material, different online distributors such as Amazon and RS Online have been analyzed to come up with their average price, taking into account the quantity and size sold. It must be said that, if the production of the robot is ever automatized or made large scale, the price of each raw material would drop due to economies of scale. Nevertheless, since this study considers a small-scale production, the prices included in the table are for a single unit, one-time purchase. As it can be seen, the price per unit for all the materials are extremely low. Specifically, the cost of the graphite layers, paper sheets, duct tape and soft wire used for the production of a single unit are extremely low, tending to null. Nevertheless, they must be considered as part of the costs of production since the inversion has to be made with large- or small-scale production. Moreover, when added together, their sum is not so insignificant.

To find the average price per unit, the quantity used of each raw material for the production of the robot has been measured and estimated to an upper bound and the price is adjusted using ratios with the total quantity bought. If the left column is added together, the total price per unit of the raw materials used intrinsically in the robot is 2.64€ or $2.99. This is a relatively low price if compared to hard robots, and all in all, considering the functions the soft robot is able to perform. However, during the research several models have been created and modified, the materials have been previously studied, etc., meaning that more raw materials have been used during the research process than those included in the last model, incurring some extra costs of production.

Other costs that need to be taken into account include fixed costs of other materials, labor costs and manufacturing process costs. For instance, the power supply needed to stimulate the robot incurs a considerably large initial cost. However, this cost can be redeemed if used repeatedly. That is, if it is used to power robots continuously or to perform other functions, investing on it does not need to be necessarily expensive in the long term. For this specific research the high voltage amplifier used to power the robot (both the feet and actuator) is the Glassman FX20P15 High Voltage DC Power Supply. The market price for high voltage power supplies ranges from 100€ to 500€. The average price rounds from 250€ to 300€. If bought new, the price is large, however, there is a large supply of second-hand voltage amplifiers available. The cables used to connect the power supply to the soft wires and then to the robot are also a fixed cost that might be included with the power supply or might need to be bought separately. Their cost also varies largely but they are usually below the 100€ bound. For these products, in contrast to the raw materials mentioned, the price varies significantly with the brand and product quality. To guarantee a longer product life cycle and to avoid breakage or technical difficulties, it is recommended to invest on more expensive but better brands and products regarding this specific purchase.

Following come the manufacturing costs which also comprehend the labor costs. As for the tools used to manufacture the robot, excluding labor, these are very few. For the initial phase in which the soft materials were studied, some metallic frames were used to pre stretch the dielectric elastomer actuators instead of the acrylic sheets. Other tools used to build the robot include conventional cutters, permanent markers and scissors to cut and give shape to the acrylic frames, VHB tape and paper sheets for the feet and palette knifes to coat the VHB tape with carbon grease. The average prices for these tools are shown below.

Tool	Average Price (€)
Scissors	4
Cutter	8
Palette Knife	2
Marker	1
Total Cost	*15*

Table 2 – Tool average prices

Together with the cost of the power supply and cables, the cost of tools is not accounted the same way as the raw materials, which are considered variable costs as they are directly proportional to the number of robots produced. These incurred costs are usually referred to as initial investments, since their cost are elevated at the beginning, but redeemed as they are used continuously through time.

These last costs together with labor costs add together make the fixed costs. For this specific research, there were a reduced group of people involved in the development and production of the robot. This was done for investigation and scientific purposes and not as a job, hence, there is no labor cost incurred. However, if the production process is ever automatized or done in a large scale with the aim of commercializing the robot, those in charge of the manufacturing process would need to be paid, especially since the process only relies on the workforce. That is, for this research, the robot has completely handmade, without the intervention of any machine for its production. If the future production of the robot continues to rely on human labor exclusively, a large amount of expenditure will be devoted to labor. On the other hand, if the process Is automated and mechanized, a large initial investment will be needed to buy the needed machinery, which will be redeemed with repeated use. Instead, with labor, there would be a repeated payment of wages. Nevertheless, making the process automatic would not replace all labor, and some wages would still need to be paid. This is a mere comment on the economic plan that would need to be analyzed thoroughly if the robot in fact is ever commercialized.

To finish with the costs of production involved in the development of the project, there are some costs that cannot be ascribed directly to the production process, but were incurred for the previous research conducted. During the study of the soft materials and the design processes, other potential materials and tools were used. For instance, the Smooth-On EcoFlex silicon rubbers were considered for the dielectric elastomer actuator instead of the VHB tape. In addition, metallic and 3D printed were used for the pre stretching of the actuators instead of the acrylic frame. The cost of the frames, pressed filaments for 3D printing and the printer itself also incur costs that add up to the total cost of the investigation.

As it was previously mentioned, there are two key parts to an economic plan that combined make a product profitable: costs of production and turnover. In order to generate turnover from the production of soft robots, if this set as an objective, they must be made available to the general public. In the rationale section of this chapter, in the commercialization subsection specifically (4.1.3), the different methods of production and distribution are mentioned. Summarizing, these are:

1. Patent the robot design and sell it
2. Individual customization
3. Batch/bulk production to sell to the general public
4. Batch/bulk production of customized products

The first option is very self-explanatory. The second option would involve slightly modifying the original design of the robot to satisfy other functions or applications as desired by each customer. The third option involves making slightly different versions of the robot to produce in larger or smaller batches to sell to the market. Finally, the fourth option combines the ideas in the second and third option involving customized designs for specific customers who want a large number of units of the same specific robot. A larger explanation can be found under the Commercialization subsection above.

These options refer to the production methods that allow for commercialization. However, there are other factors to take into account in order to make the product profitable. The next step after production is distribution. There needs to be several channels of distribution in order to bring the product to the customers, specifically to make them aware of the existence and availability of the product. The optimal channel of distribution for this product would involve e-commerce. Since it is not an everyday purchase made by regular people, it is not worth selling it at any physical establishment. Instead, the soft wall climbing robot is a product that people are likely to search for online. Therefore, the best channel of distribution would be an online platform. It would be smart to partner with large online wholesalers like Amazon or eBay, which have an infrastructure large enough to distribute the product worldwide at a lower rate than if done without subcontracting. Another smart option would involve using smaller wholesalers that specialize in the distribution of robots and smart machines, to expose the product to an already interested target market. Evidently, for each of the four options of commercialization, the channels of distribution that better adapt to each are different and would have to be studied thoroughly to build an optimal business structure.

The last important thing to consider in order to make the product profitable is the marketing process. The marketing team in businesses are usually in charge of, not only of advertising the product, which is an essential task, but also of setting the price. The chosen price is important given is strong relationship with demand. The law of demand establishes an inverse, not necessarily linear relationship between price and quantity demanded. To set a price for the soft wall climbing robot, besides choosing a value larger than the variable costs of production, the marketing team or those in charge of setting the price would likely undergo a trial and error process. Prices and demand are extremely volatile and change continuously, therefore, in order to find the optimal price for the robot, the assigned value would have to vary and be adjusted temporarily taking into account the initial business success or failure, or, in other words, the quantity demanded with the present price.

In order to analyze the profitability of the product if it is in fact commercialized in the future, the most important data values are those of quantity demanded, price and costs of production. Then, applying the following simple formulas, the turnover and profit or loos are easily calculated:

$$Variable\ Costs = Variable\ Cost\ per\ Unit \cdot Quantity\ Demanded$$

$$Total\ Costs = Fixed\ Costs + Variable\ Costs$$

$$Turnover = Quantity\ Demanded \cdot Price$$

$$Profit(+)/Loss(-) = Turnover - Total\ Costs$$

Even though there is an extremely deeper understanding to building a business or economic model, these formulas provide an overall idea of the results that can be expected from making the soft wall climbing robot available to the market.

4.5 SUSTAINABLE DEVELOPMENT GOALS

The United Nations has been working since its foundation in October of 1945 on improving the wellbeing of society and the protection of wildlife and the planet. One of their most important initiatives has been the development of the Sustainable Development Goals. Its origins date back to 1992 when the Earth Summit was celebrated at Rio de Janeiro, Brazil. They adopted the name of “Millennium Development Goals” during the Millennium Summit at the UN Headquarters in New York City during September 2000 which was then changed to “Sustainable Development Goals” fifteen years later as part of the 2030 Agenda for Sustainable Development, which according to the UN “provides a shared blueprint for peace and prosperity for people and the planet, now and into the future” [19].

There are currently seventeen SDGs listed by the UN, which “are an urgent call for action by all countries - developed and developing - in a global partnership” and “recognize that ending poverty and other deprivations must go hand-in-hand with strategies that improve health and education, reduce inequality, and spur economic growth – all while tackling climate change and working to preserve our oceans and forests” [19]. The goals are shown in the figure below as they are portrayed by the UN.

Figure 11. Sustainable Development Goals by the United Nations [19]

The team working in the development of this project has been committed with the compliance of these goals, and have kept them in mind throughout the planning and manufacturing processes. During this fast growing industrial and technological times, taking care of society and the planet is an essential part of engineers and all the scientific community. For this research, the focus has been set specifically on four of the goals listed in Figure 11, those that were more relevant to the development of the project.

The seventeen goals are all based on five principles, also known as the five Ps: people, planet, partnership, peace and prosperity, which are all based on three large competences: economic, social and environmental.

Regarding the research conducted to produce the soft wall climbing robot, all the principles have been intrinsic during its development, but four of the seventeen goals relate more with the kind of project handled.

4.5.1 AFFORDABLE AND CLEAN ENERGY

The first goal to be considered in the development of the project involves the use of affordable and clean energy. The United Nations set focus on two different aspects with this goal. In the first place, their aim is to increase the global electrification rate, making electricity available in underdeveloped countries. In the second place, their aim is to increase the use of sustainable and renewable energies. For this specific research the focus is set on this second part of the goal.

The soft wall climbing robot requires energy to be powered. This energy is purely electrical, coming from a regular outlet into the high voltage amplifier and directly to the cables, soft wires and lastly, the electrodes in the actuator and feet. The use of electricity as the only source of energy makes operating the robot completely sustainable.

It is true that for future modifications to the robot, the idea of powering it with batteries was introduced in order to make it completely untethered and independent. As opposed to powering it through electric current, which may be considered sustainable, the use of batteries would imply having to change them every now and then. Moreover, the recycling of batteries is not an easy process, and not efficient enough at the moment to result as sustainable as the use of electric power as a source of energy. In addition, the economic impact to the project would also be negative, since the use of batteries would add not only extra costs of production for the purchase of raw materials, but would also require the repeated purchase of batteries to extend the product life cycle of the robot.

The use of clean, sustainable and renewable energy is essential to meet the climate goals set by the UN as part of the 2030 Agenda for Sustainable Development. The use of electricity as a source of energy prevents the release of toxic waste to landfills or the atmosphere. Moreover, the cost of using electric supply is extremely lower in comparison to other energy sources. For instance, the use of batteries would result in continuous disposal, use of chemical (non-renewable) energy and a larger investment overall. The only reason to use them would be to make the robot autonomous, being a counterbalance to all the negative consequences there are to its use.

4.5.2 DECENT WORK AND ECONOMIC GROWTH

The United Nations, with this Sustainable Development Goal aims to "Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all" [19]. Even though their focus is set on reducing unemployment globally and increasing productivity to boost the economic growth of countries which has been hindering over the past years, this research has its own goals to hold compromise with decent work and economic growth.

The use and development of robotics is usually knocked off by those who defend labor amongst everything else. It is true that the introduction of machinery and automatization in companies during the Industrial Revolution caused society to panic as a group due to the large amount of unemployment it generated. The fact that machinery replaces the work of many individuals is undeniable. However, people managed to adapt to this new reality through the creation of new job positions, etc. They learned to take advantage of machinery and automatization for production and other purposes and built their careers around the existence of such instead of mourning their loss. Thanks to this technological revolution, the human race became more intelligent, adaptive and the world evolved to be as it is known today. All this is mentioned to highlight the fact that working in the scientific community, specifically in the robotics field does not have as an objective to replace the value of human labor or else, instead, the goal is to promote the intellectual work of those in our community, having as an ultimate objective to result in a positive impact in the growth of society.

Focusing more specifically in the development of this research and the soft wall climbing robot, there is a different approach to commit with the goal of decent work and economic growth. Almost every aspect regarding the commercialization of the robot and the workforce involved in its production has been commented on previously. Hopefully, making the robot available to potential customers means helping economic growth minimally. Moreover, if the production of the robot continues to be handmade, the amount of labor involved in a large-scale production would be significantly large.

Lastly, it is worth mentioning that the goal of this project in terms of growth, is to have a positive impact in the research field. That is, with the development of the robot the aim is to encourage other future researchers to contribute to the growth of the soft robotics field which will hopefully have a larger impact to society in a close future.

4.5.3 INDUSTRY, INNOVATION AND INFRASTRUCTURE

This might the most relevant sustainable development goal to the elaboration of the project. The UN specifically aims to "Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation" [19]. By now it has already been said that the soft robotics field is part of a relatively new trend in the science community. Not only does it allow for the production of sustainable robots, given the nature of the soft materials used for their making and the renewable sources of energy that power them, but it also offers plenty of room for innovation. All in all, the production of soft robots falls under the promotion of inclusive and sustainable industrialization goal set by the UN.

The scientific community involved in the development of soft robots has been focusing on the production of prothesis and human like body parts, as well as attempting to reproduce organs or pacemakers. Even though they are still working on creating feasible and reliable models for this purpose, their ultimate goal is extremely remarkable.

This project specifically, takes a slightly different path within the soft robotics research field as to the applications it has and the functions it is able to perform. The rationale section (4.1) touches upon the subjects of innovation, applications, commercialization and impact to society in relation to the development of the soft wall climbing robot. The ideas it discusses closely relate to this sustainable development goal. All in all, the whole production process of the soft wall climbing robot, from beginning to end can be described as inclusive, sustainable and innovative.

4.5.4 RESPONSIBLE CONSUMPTION AND PRODUCTION

This sustainable development goal sets focus on reducing the material footprint per capita worldwide, especially in countries like Japan or the United States were capitalism is extended and results proportionately in high levels of consumption. Their aim is to reduce the repeated consumption of products that are disposed of shortly after purchase. In addition, they look up to countries reducing their emissions during the production process and increasing the use of renewable energy as a substitute to the use of limited resources. They specifically call for urgent action “to ensure that current material needs do not lead to the overextraction of resources or to the degradation of environmental resources, and should include policies that improve resource efficiency, reduce waste and mainstream sustainability practices across all sectors of the economy” [19].

The UN calls not only for responsible production but also for responsible consumption. According to a study carried out by engineers at UCLA, people react better to robots that resemble humans physically and psychologically [19]. The development of robots that are soft and feel soft as they are touched has helped engineers produce robots which resemble the human body, especially with the skin. As opposed to hard robotics, the use of soft materials allows for easy mimicking and resemblance, not only aesthetically but also from a functional perspective. For instance, soft materials can perform bending and expanding motions while hard materials are limited to translational and rotational motion, which are also achieved by soft robots. Moreover, the robots designed to interact with humans are safer if made of soft materials. A study run by the BioRobotics Institute in Pisa, Italy, ensures that, as opposed to hard robots, the safety features in soft robots are mostly intrinsic [19].

Besides providing a responsible consumption, the production of soft robots is also liable and sustainably conscious. As it has already been mentioned, the raw materials used in its production, which are mostly hard plastics, are easily recycled in comparison to metallic structures. In addition to the materials used, the manufacturing process also respond positively to sustainability issues. For instance, the soft wall climbing robot was handmade. The lack of an automatized process ensures that no emissions are released from its production.

In conclusion, there has been efforts made throughout the development of the project to commit to the United Nations' Sustainability Development Goals. Even though some of them are totally unaffiliated to this research, those that did relate were present before and during the process.

CHAPTER 5 – MODEL DEVELOPMENT

Chapter 5 describes the development of the project from a technical perspective, describing the scientific background of the functioning of the robot, the design and manufacturing processes and the experiments carried out throughout the process.

5.1 CHARACTERIZATION

This section is used to describe how the dielectric elastomer actuator and electro adhesion forces work through detailed explanations of their technical and engineering background and the scientific phenomena behind their behavior.

5.1.1 DIELECTRIC ELASTOMER ACTUATOR

Actuators are the most important element in soft robots. They are capable of translating the effect of external stimulus into deformation and subsequently, motion in the form of bending, stretching and compressing. In order to manufacture a soft actuator in accordance to the soft robot, there are a limited amount of materials available to do so, vaguely denominated soft smart materials. Some of these are shape memory alloys, fluidic elastomer actuators, shape morphing polymers, pneumatic artificial muscles, etc. Likewise, there are several types of stimulus that have an effect on these materials, and not all of them are compatible with each other. For this specific research, taking into account the type materials and stimulus available, the smart material chosen for the design is dielectric elastomer. As its own name states, this type of elastomer responds to the stimulus of electric supply, specifically to the formation of opposite charged poles to each side of the elastomer.

The elastomer chosen is VHB 4910 and 4905 tape, which is clear and adhesive on both sides. To build the actuator, the tape is pre stretched into using a frame that is able to hold the extended elastomer and then coated with carbon grease on both sides using a knife palette. For an easier understanding of the structure of the DEA, a sketch of its different layers is shown in Figure 12 below.

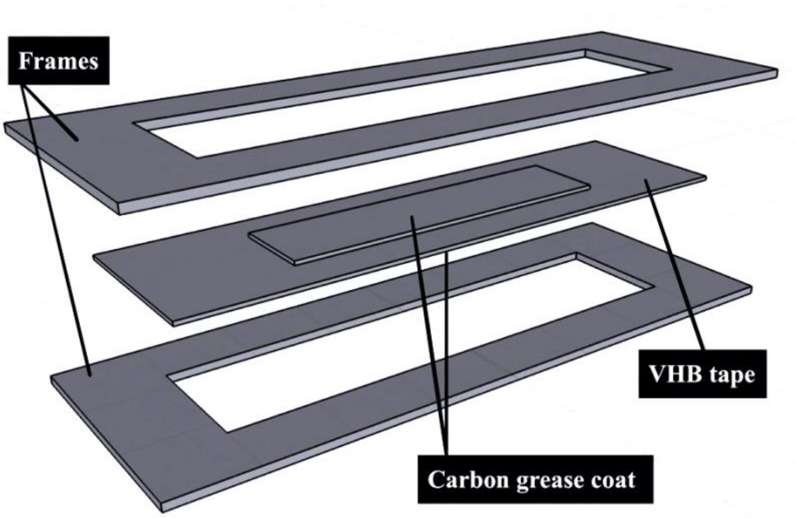


Figure 12 – Layered structure of DEA

The actuator's behavior is based on Maxwell stress. The VHB tape acts as the dielectric material and the carbon grease coated on both sides are the electrodes to which the power supply is connected. Using carbon grease makes connecting the soft copper wire easy as they stick together once the grease dries out. The grease increases the area of electric conductivity, which is proportional to the deformation achieved. Figure 13 below helps understand the functioning of the configuration.

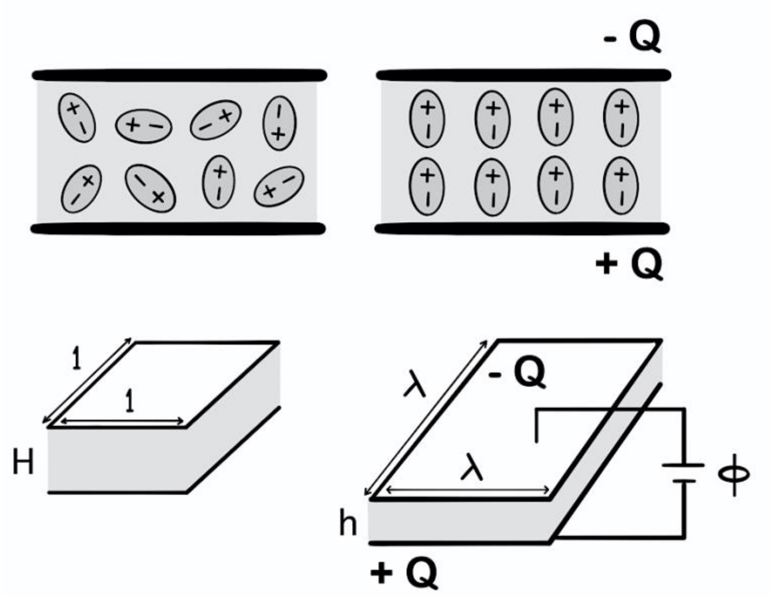


Figure 13 – Distribution of charges in dielectric material with and without power supply

Figure 13 shows the effect of applying voltage to the electrodes. The same amount of opposite charge must be applied to each of the electrodes to create an electric field E. From an electricity and magnetism perspective, the Lorentz force and Gauss Law define the behavior of the material respectively, where F is the resultant force, q is the charge applied to each electrode, v is the velocity at which the dielectric material enters the electric field E and magnetic field B.

$$\boldsymbol{F} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

$$\nabla \cdot \boldsymbol{E} = \frac{\rho}{\varepsilon_0}$$

For the robot design, v takes a null value since the dielectric material does not move relative to the carbon grease (electrodes), and the only force left (qE) is referred to as the electrostatic force. Gauss Law establishes a relationship between the differential dot product of the electric field, the charge function of the dielectric material (VHB tape) and the permittivity of vacuum. The volume resistivity of the VHB 4910 tape is 3.1 x 10^15 Ω-cm. Combining both formulas and the parameters and data applied to the actuators, the resultant Lorentz force can be easily calculated.

Furthermore, to define the deformation of actuation, the formulas involved are the following: Maxwell stress, voltage, and equation of state respectively, where h and H are the thicknesses with and without voltage supply, φ is the voltage applied, E is the electric field, λ is the factor by which the side of a unit square has increased as the dielectric material flattens (shown in figure 13), ε is the permittivity and σ the Maxwell stress.

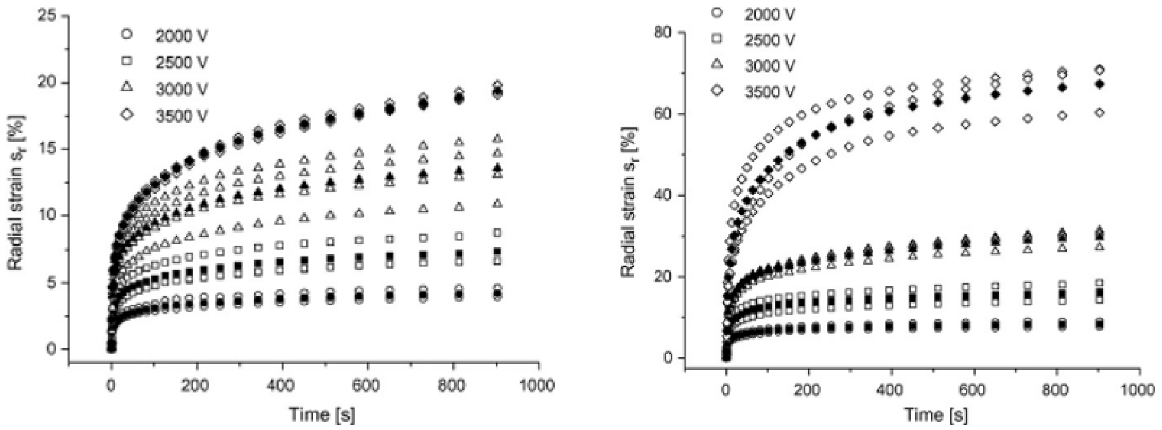
$$\sigma = \varepsilon E^2$$

$$\phi = Eh = EH\lambda^{-2}$$

$$\phi = H\lambda^{-2}\sqrt{\frac{\sigma\lambda}{\varepsilon}}$$

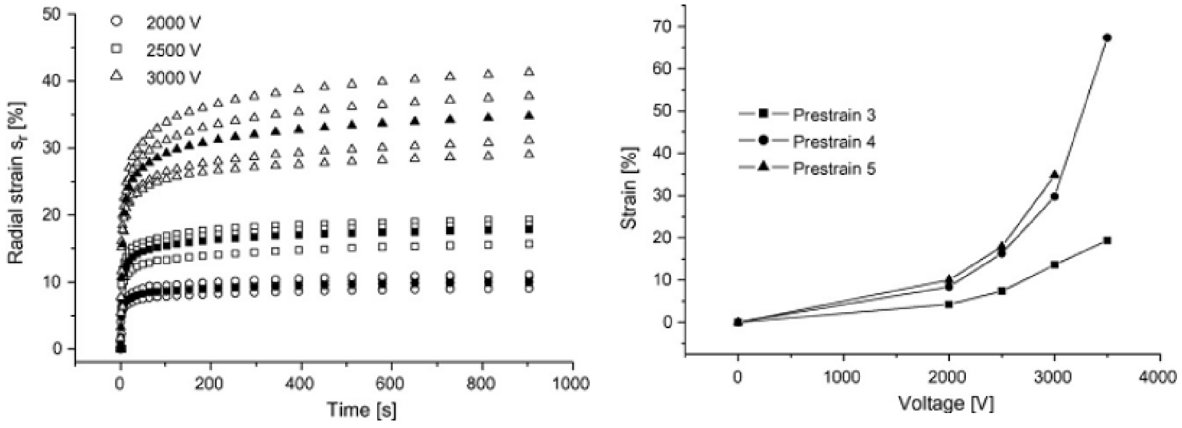
The use of these formulas helps describe the deformation of the actuator as voltage is applied. However, they are not always accurate given the non-linear properties of the dielectric material.

Following, the effect of pre stretching the dielectric material in its future behavior when submitted to the power supply will be analyzed.



Prestretch 3x3

Prestretch 4x4



Prestretch 5x5

(Strain after 900s as function of voltage for different prestrains)

Figure 14 – Effect of pre stretch on the performance of circular DEAs [14]

The frames have two main functions. In the first place, they act as a link that join the actuator and the robot’s body, or it can even be shaped as the body itself. The second, and more important function is that it holds the stretched elastomer. The pre stretching of the membrane is a very significant parameter to the further behavior of the DEA once the external stimulus is applied. As it is stretched, its thickness is reduced proportionally, since the material used is incompressible, as it has a Poisson coefficient of 0.49 ~ 0.5. As it has been previously shown, the size of the Maxwell stress is determined by the electric field generated across the dielectric material. Hence, if the membrane's thickness is reduced through pre stretching, a smaller voltage supply is required to generate the same stress. Not only is this beneficial in terms of requiring less energy supply, but the amount of heat generation also decreases lowering the probability of burning and therefore breaking the membrane. A study conducted in Harvard on the mechanical behavior of DEA gathers the following data describing the relationship between the strain achieved with time at different voltage levels and degree of pre stretching. Figure 14 above shows the results [14]. As it can be seen, the relationship between strain and time is logarithmic. Moreover, the greater the pre strech, the larger the strain achieved applying the same voltage.

Once the functioning and technical background of the individual elements has been described, the dielectric elastomer actuator can be analyzed as a single piece. To examine the behavior of the actuator before having to manufacture it, the ABAQUS commercial finite element software was used. This software simulates the deformation of the DEA under stimulus with a user defined material subroutine (UMAT). The models that define the behavior of each of the materials involved in the making of the DEA must be chosen in accordance to their nature. The linear elastic model defines the acrylic sheets used to pre stretch the elastomer and the neo-Hookean hyperelastic model defines the VHB 4910 tape. For the overlapping part, a static analysis was conducted with the standard 8 node, solid hybrid element (C3D8H) and mesh refinements were added to promote the convergence. The parameters introduced in the software for the dielectric elastomer (VHB tape 4910) were the initial shear modulus (6 x 10^5 Pa), relevant dielectric constant (3.21, 1KHz at room temperature), Poisson's ratio (0.49, close to incompressible) and the bulk modulus [3M VHB 4910 Properties]. The use of a simulation allows for endless modification and combination of values and parameters to understand how these changes affect the behavior of the DEA. Even though it is not completely accurate since it does not take into account externalities, it helps describe the performance of the DEA without having to experiment with it iteratively which is very time consuming and requires excessive use of materials that are likely to be disposed of after running tests with them.

To conclude, it must be said that the dielectric elastomer actuators can be shaped into endless configurations and structures. In fact, the way DEAs are manufactured have a large impact on their behavior under stimulus. Depending on the shape they take: circular, planar, cylindrical, spherical, conical, etc., the amount of fixed restrictions they are subjected to: pre stretching frame, thresholds, limits, etc and the external stimulus applied, the DEAs engage in different behaviors: planar elongation, contraction, radial expansion, bending, etc. The figure below illustrates the phenomena with three different examples: planar expansion in all directions, one dimensional elongation and bending.

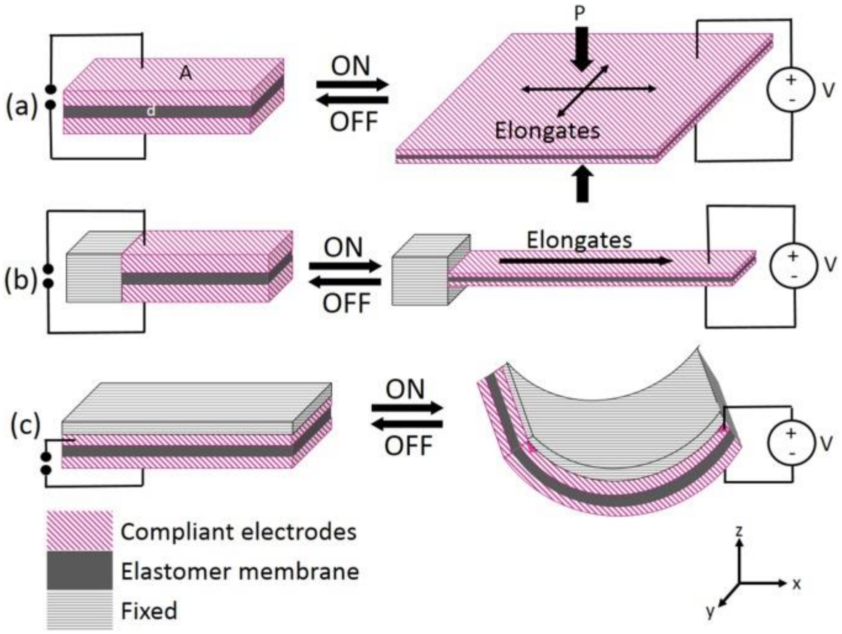


Figure 15 – DEA behavior for different configurations [5]

The nature of the Maxwell stress will always force the membrane to reduce its thickness as a result of the electric field. This together with the restrictions introduced in the design process, results in different outcomes. This will be studied more in depth in the actuator's design section (5.2.1).

5.1.2 ELECTRO ADHESION FORCES

For the soft robot's feet to stay firm to walls or flat surfaces, at most at a 90º angle from the floor, the phenomenon used is that of electro adhesion forces. These feet are controlled using the same high voltage amplifier as the one used for the actuator. Applying voltage to each of the alternatively allows the robot to walk, crawl or climb.

For an easier understanding of how electro adhesion forces work, figure 16 below provides a diagram to accompany the explanation.

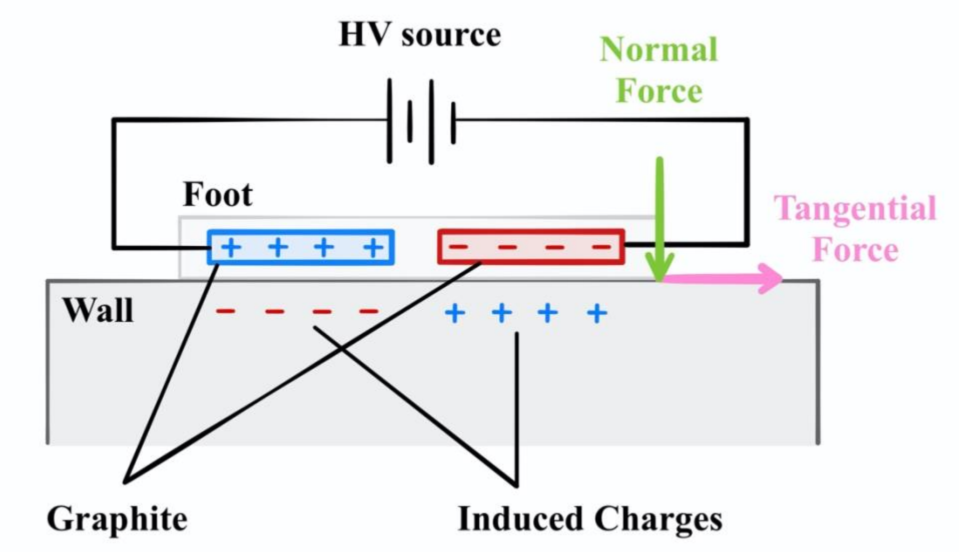


Figure 16 – Electro adhesion forces

When the pair of electrodes generated with the graphite layer of each foot are polarized by applying the same opposite charge, more charge is induced in the surfaces in contact. That is, the wall is polarized through induce charges. This creates an electric field between the wall and the foot that generates what are known as electro adhesion forces and allows the foot to stick to the flat surface. This force can be separated into two vectors to be denominated as tangential and normal forces. The strength of electro adhesion is proportional to the voltage applied and the surface area of the pair of electrodes. That is, the greater the foot and the thicker the graphite layer, the larger the electric field and, subsequently the electro adhesion force it generates. Evidently, the force also depends on the surface in contact with the feet, which is treated as dielectric material. The whole idea and how it is treated is similar to that of the dielectric elastomer actuator. To calculate the normal and tangential force the formulas used are the following, respectively.

$$F_N = kV_F^2$$

$$F_T = \mu_e F_N$$

As it can be derived from the equations, the tangential force depends on the normal force, and both depend on parameters relative to the contact surface and the voltage applied. The parameters needed to define the flat surface are k, a dimensional constant $(\mathrm{N}\cdot(\mathrm{kV})_{-2})$ and μ_e, the effective frictional coefficient of its interface with the foot sole. Finally, V_F stands for the applied voltage. A study conducted at the Robotics Institute of Shanghai Jiao Tong University, characterized different surfaces through experimentation looking to identify the coefficients k and μ_e of several surfaces.

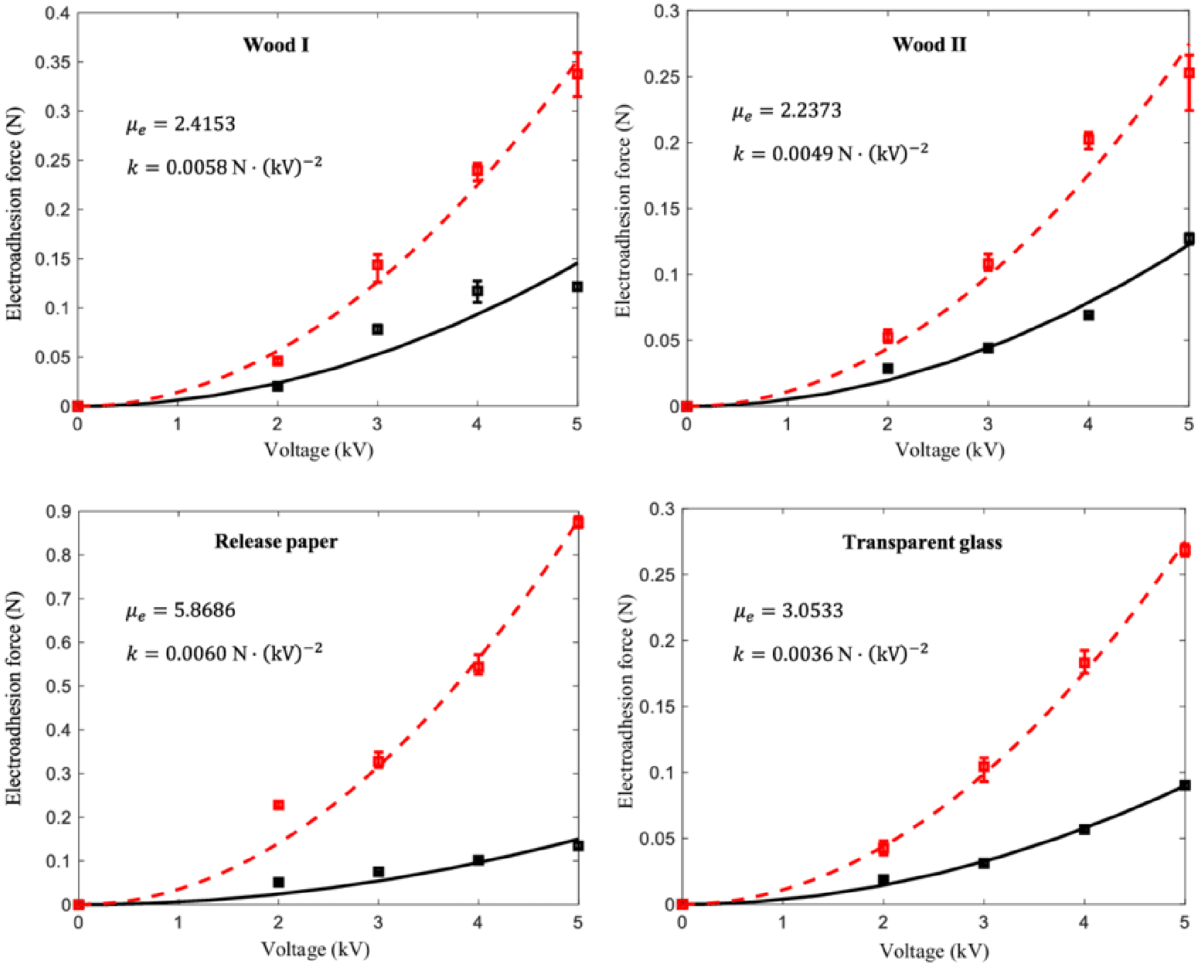


Figure 17 – Characterization of different flat surfaces [7]

To obtain such coefficients, the researchers tried to pull the electro adhesive foot from the flat surface both in tangential (red dotted line) and normal (black continuous line) directions for different voltage values and for each surface. Even though this does not perfectly apply to this specific research given the different foot design and materials used, it gives a clear example of how the robot would perform in different surfaces. The results that can be extracted from the data gathered are that the forces required to pull off the foot grow exponentially with the voltage applied and that the robot would do a better performance climbing through release paper, followed by wood and finally glass. This might be intuitive through touch as the friction levels of each can be defined by rubbing them. However, for accurate results these experiments are required.

To summarize, electro adhesion forces are generated as a result of polarization of surfaces when equal opposite charges are applied to a pair of electrodes and the electric field they create. These forces are proportional to the friction degree of the interface, the size of the contact surface area and the voltage applied. And finally, in order to define the characteristics of the surface and adherence of the foot based on the sole's material and surface area, testing and experimenting is required.

5.2 DESIGN

This section covers the design process for the robot. The two main elements of the soft wall climbing robot's structure are the dielectric elastomer actuator, which also act as its body, and the electro adhesive feet. Their designs were treated individually and then assembled together through two joints. Even though their designs are independent, the whole structure has to be thought of prior to the individual analysis to understand the robot's behavior.

5.2.1 DIELECTRIC ELASTOMER ACTUATOR

As it was mentioned in the characterization section of the DEA, its design is one of the elements that significantly influence its behavior under external stimulus. For the soft wall climbing robot, the desired motion for the DEA was the bending of a flat structure.

Knowing that when voltage is applied, the response of the elastomer membrane is to expand in all directions and reduce its thickness as a result of incompressibility, the actuator needs to be framed to translate this expansion into a bending motion. The acrylic sheet is used to do this. Fixing certain parts of the membrane so that they cannot expand further results in a bending motion.

During the design process, two different models were studied for the DEA to perform the desired bending motion. Even though both of them engage in a bending deformation when voltage is applied, the direction of movement achieved by each one is completely opposite. To help describe their different outcomes figures 18 and 19 illustrate the idea.

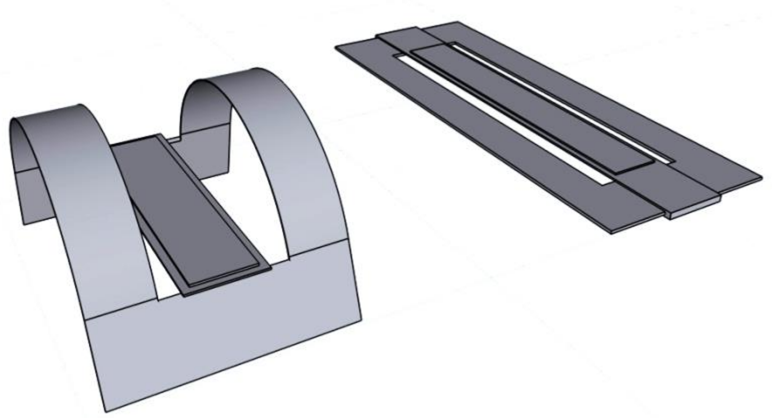


Figure 18 – First design of the DEA

This is the first design that was put to test for the soft wall climbing robot. All three elements that compose it can be seen. The acrylic sheet is shaped into a rectangle with a smaller concentric rectangle cut out. The VHB tape with the carbon grease coated on both sides is then pre stretched and taped into the rectangle so that when it relaxes the acrylic sheet bends to look like element to the left of figure 18. With this design, when voltage is applied to the electrodes and the membrane expands longitudinally, the actuator transforms to look like the element to the right.

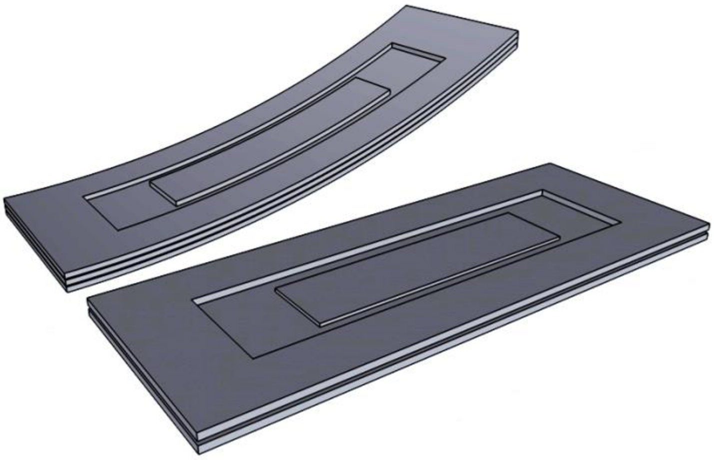


Figure 19 – Second design of the DEA

The second design for the DEA performs exactly the opposite movement when voltage is applied. For this configuration, two layers of acrylic sheets are used. They are cut into the exact same shape as for the first design. However, the VHB tape with the carbon grease layers is now pre stretched in all directions as opposed as only longitudinally and framed in between both layers so that it stays strained. Relaxed or without applying voltage, the configuration looks like the element to the front right of figure 19. When voltage is applied, the acrylic frame restricts the elongation of the membrane and consequently, the deformation generated by the electric field results in the bending of the actuator, which takes the shape of the element to the back left of figure 19.

Once the effects of design on the behavior of the actuator are understood the final configuration can be developed. As it was previously mentioned, the desired motion of for the DEA was that of bending. However, in order to enable the robot to walk, the combination of two different actuators is required. The assembly of such also affects their behavior individually. The whole piece would look like the following.

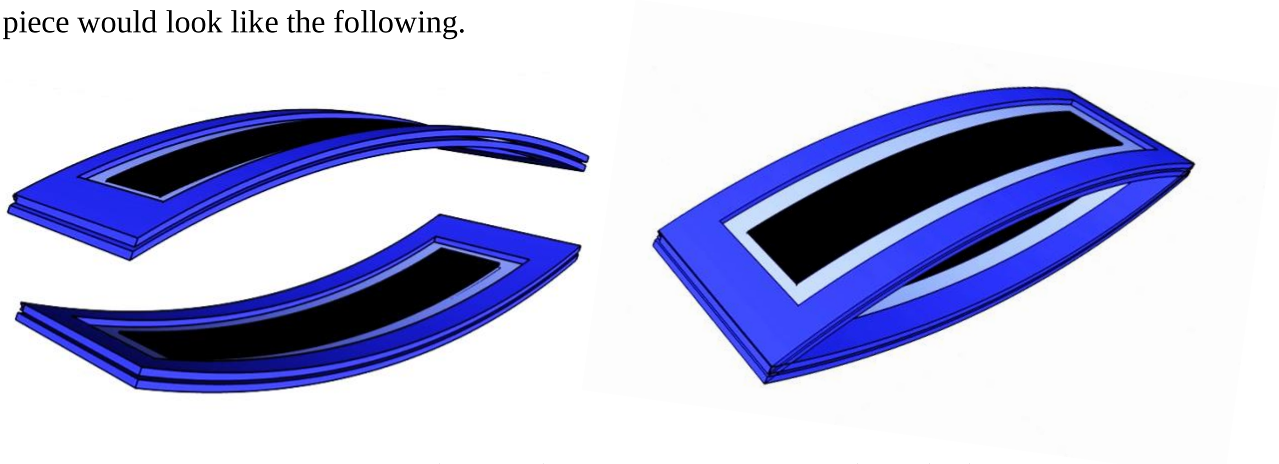


Figure 20 – Dielectric elastomer actuators as robot's body

As it can be seen, the DEA design chosen for the model is the second one. However, in the assembly process they are bent to join each end together so that they maintain the bent shape shown in figure 20 without voltage applied. This drastically changes their behavior when they are stimulated. Now, in order to expand as a result of the deformation caused by the electric supply, both actuators flatten and elongate, as opposed to when they were powered individually. Hence, the final design shown above forms he body of the robot, which achieves movement through expanding when voltage is applied and relaxing to a bent shape when it is taken off. The movement and dimensions of the soft robot will be studied more in depth later on in the manufacturing, experimenting and modeling sections. This is just an adimensional representation of how the DEA is built.

5.2.2 ELECTRO ADHESIVE FEET

The electro adhesive feet consist of four different layers stacked together to achieve the adherence needed for the robot to stabilize while it climbs. Figure 21 depicts a clear image of these. The bottom layer is a cutout from a regular A4 paper, about 0.4mm thick. On the paper, two equal areas are coated with a thick layer of graphite using a 2B pencil. It is essential for these two to be separated enough since they will be the pair of electrodes with which the foot will be connected to power. This helps prevent shorting and subsequently, breakage due to over heating or even burning. If compared to the actuator, the graphite layers are equivalent to the carbon grease in terms of functionality.

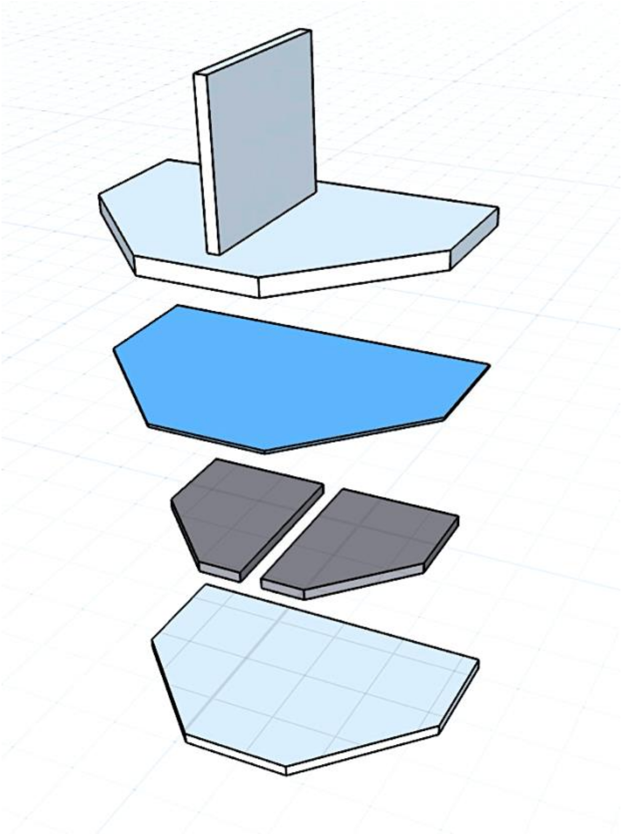


Figure 21 – Electro adhesive foot layered configuration

The third layer consists of VHB 4910 tape cut out to the same shape as the A4 paper. This layer is stuck to the graphite and paper, clipping the soft copper wire in the middle so that each makes contact with the pair of graphite layers that serve as electrodes. In contrast to its function in the actuator, the VHB tape used for the foot only serves as a link between the top and bottom layers. Due to its natural property of adherence, there is no need to use glue or duct tape to join the layers. Moreover, the tape also acts as an insulator to the rest of the robot's body, adding an extra degree of protection against short circuit. In the DEA, the electrodes were placed to each side of the tape, polarizing it to be treated as the dielectric membrane. However, for the feet, the pair of electrodes is placed in the same side of the tape, polarizing the wall or flat surface on the other side of the paper sheet and creating an electric field completely detached from the tape.

The final layer simply acts as the link between the foot and the robot's body. It is also made of an acrylic sheet and sticks to the VHB tape once again taking advantage of its natural properties. The foot takes the following form when all the layers are connected.

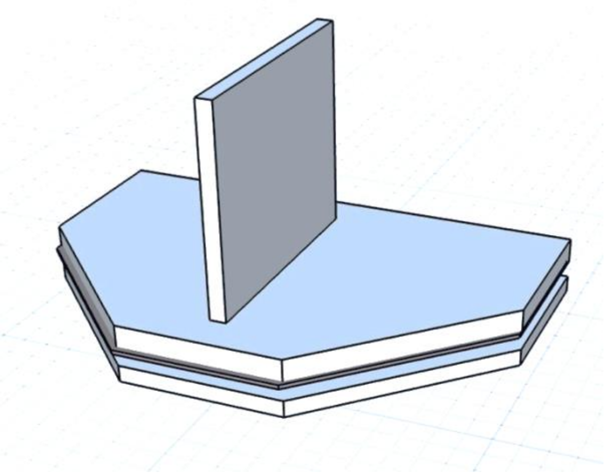


Figure 22 – Electro adhesive foot

The shape chosen for the foot's sole is not arbitrary. As it was mentioned in the characterization section of the electro adhesion forces (5.1.2), the larger the surface area of the graphite layer, the greater the tangential and normal forces generated by the induced charges and the electric field. This idea together with the objective of making the feet mimic the anatomy of living organisms, resulted in the shape shown above. Observing the shape, it can be seen how the tip facing the front resembles the toes of animal or human feet. Beyond the aesthetics, there is a functional reason why this is done. To help explain the utility of shaping the robot's feet like so, figure 23 below depicts the geometric center of the sole.

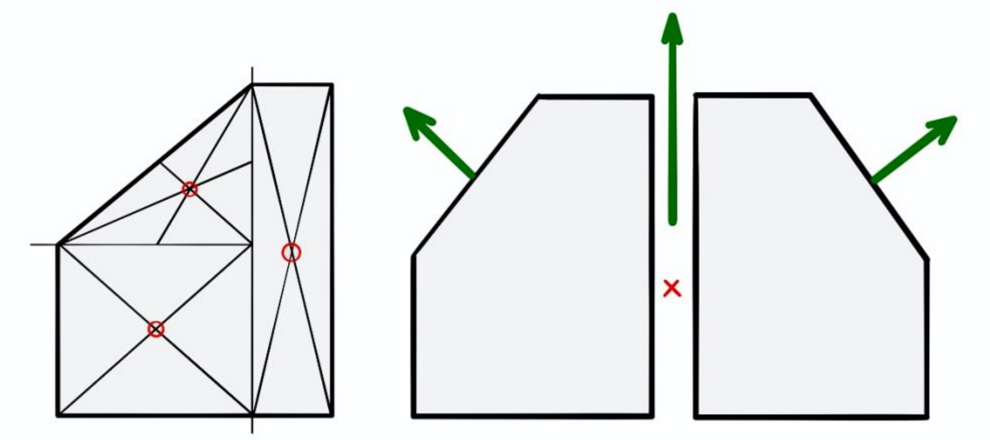


Figure 23 – Geometric distribution of the foot's sole

The electro adhesion forces are directly proportional to the surface area of the sole and the graphite layers. If the sum of forces is represented as a vector, its origin is placed in the center of mass, or geometric center given the two-dimensional configuration. Given its symmetrical shape, the geometric center falls towards the middle back of the feet, a desired outcome. This eases forward movement and hinders recoil. Even though the robot is designed to move in any direction, including backwards, it will engage in forward motion most of the time. The geometric center of the sole is the place where the force experimented by the sole is stronger, meaning that when the voltage is turned off, the front of the sole will detach faster and more easily than the back due to its further distance to the center.

The sole's shape is also designed to reduce frictional forces for forward and lateral movement. Cutting out the top corners to form a tip to the front of the sole, eliminates the frictional restrictions they would infer and makes movement in the direction of the green arrows in figure 23 easier. The aerodynamic properties of the foot also add to this effect, however, due to the size and velocities reached by the robot, it is almost insignificant.

The main reason for shaping the sole like it is shown, is to avoid the robot from falling backwards when it climbs. Like with all living organisms or even automobiles, backward movement is unnatural but necessary sometimes, which is why the robot is designed to be able to perform it whenever its needed, but not continuously. With this, the analysis of the feet's design is completed.

5.2.3 ASSEMBLY

The final step in the design process involves joining all the individual parts. The robot’s body, as it has been already mentioned, is composed of two actuators joined together using duct tape. Hence, the assembly process needs to focus essentially on joining the feet to the body. To do so, the first thing to do involves deciding the relative sizes of each element. This process goes beyond the aesthetic aspect of design. Instead, it focuses on making the robot functional efficiently.

The design of the robot as a whole, needs to concentrate on its main function and purpose: crawling, walking and climbing. That is, the size of the feet and body and their relation needs to be thought of to facilitate the robot’s movement. In the first place, the size of the feet relative to the body, need to be large enough to ensure solid adherence to walls, but not too large as to suppose too much weight for the electro adhesive force to handle. The same applies to the DEAs, they need to be large in order to increase the deformation and subsequently the distance they can cover in a single step, but not too large to add significant weight to the structure. In addition to the relative dimensions of each element, the absolute size of the robot also needs to be defined and adapted to its future functionality and application. All these counterbalances and tradeoffs need to be considered throughout the design process to ensure efficient performance.

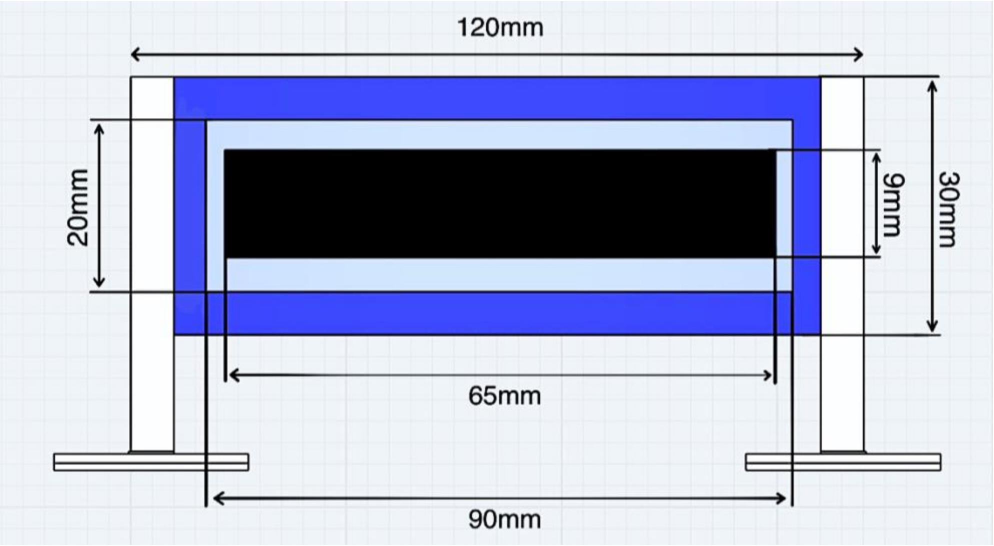


Figure 24 – Dielectric elastomer actuator dimensions

In Figure 24 above, the dimensions of the DEA are depicted. These dimensions are chosen based on previous tests and experiments ran in which voltage was applied and the elastomer's response was analyzed. These will be commented more in depth in section 5.4.1 – Experiments and modeling of the dielectric elastomer actuator. The next figure shows the electro adhesive foot's dimensions.

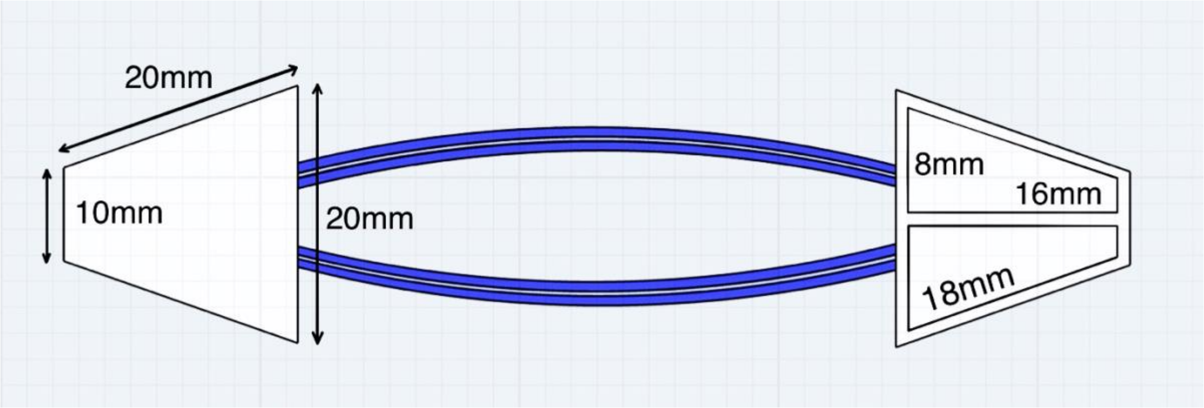


Figure 25 – Electro adhesion foot's dimensions

Like with the DEA, several tests were done with the electro adhesive foot's dimensions, specifically with its shape rather than its size as opposed to the actuator. Once again these will be thoroughly studied in further sections.

After dimensioning each part individually with the aim of building a feasible structure, the missing element is the link between the body and feet. The material used to join both structures is once again the acrylic sheet. This material is firm enough to maintain the structure together and not too heavy in order to ease the robot's movement, since its weight is proportional to the electro adhesion force needed to hold the robot to the wall and subsequently, to the voltage supply needed to generate such force. As it can be seen in figure 26 below, a thick strip of acrylic sheet is bent through the middle to form a semi triangle. At the bottom, a small cut is done also through the middle to create two small flaps. The acrylic sheet used for the top layer of the foot is also cut with the semi triangular shape of the strip in order to fit the two flaps through them. This sheet is then stuck to the VHB tape with its natural adherence, fixing the flaps and forming a solid structure that looks like the three-dimensional sketch shown below. The length of the strip is 50mm and the width of each flap is 10mm.

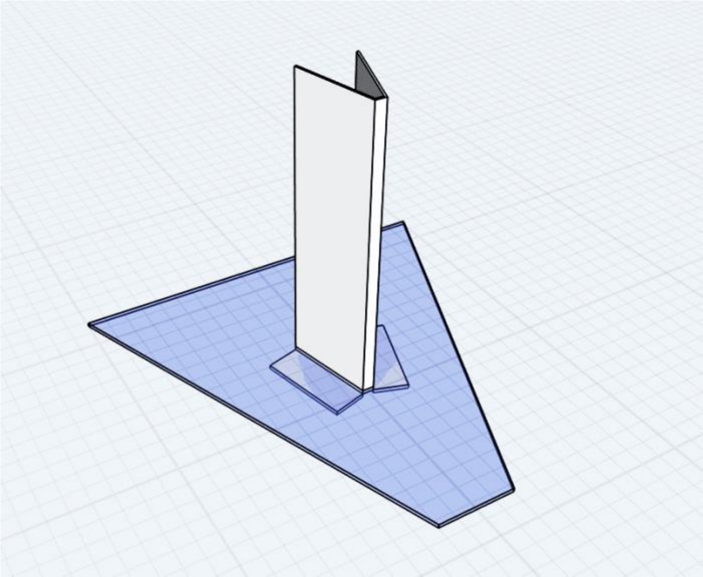


Figure 26 – Design of linking element

The acrylic strips that act as the robot's legs are then taped with clear duct tape to the edges formed by the union of the two actuators. The final result should look like the following illustration.

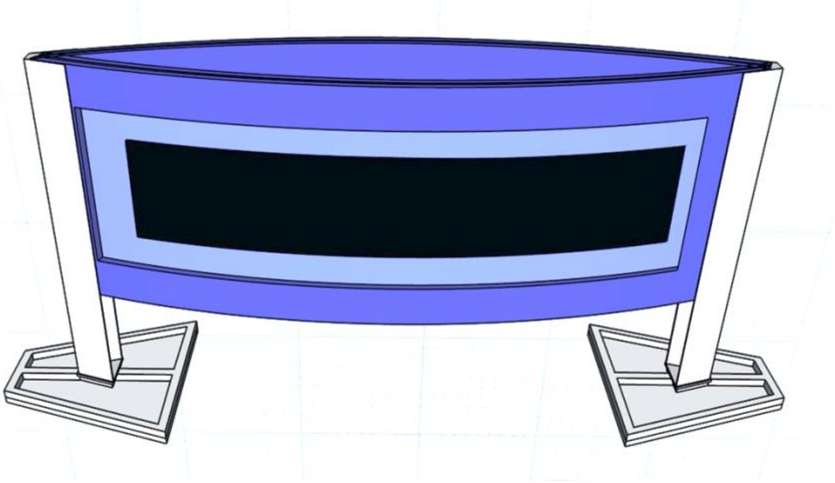


Figure 27 – Final design of the soft wall climbing robot

If compared to Figure 10 in section 4.3 – Methodology, where the original design of the soft wall climbing robot is depicted, the main difference is the relative size of the electro adhesive feet in relation with the rest of the body. The current size is required to provide enough electro adhesive feet to hold the robot's weight firm to walls as it climbs. With the change of this detail, the final render of the robot is ready, and the manufacturing process can begin. Even though the paper is structured to treat the design, manufacturing, experimenting and modeling steps separately for clarity purposes, throughout the research process, all the different stages of production intercalate and overlap, going back and forth in order to repair mistakes and improve the model until the optimal design is produced.

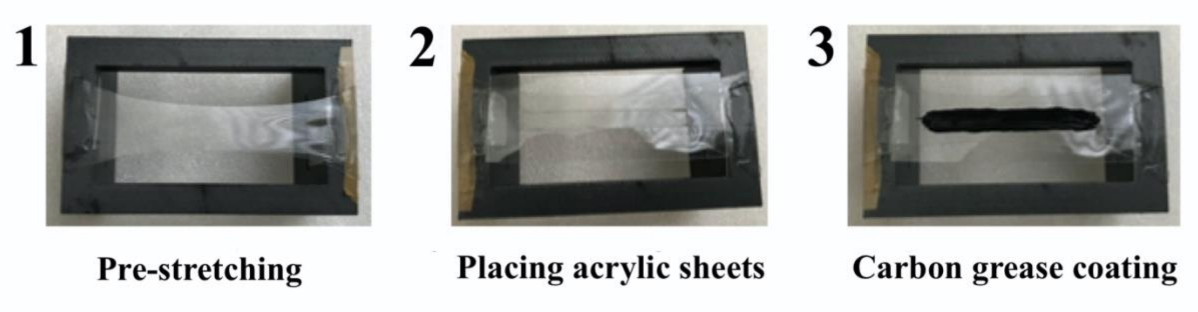
5.3 MANUFACTURING

With the three-dimensional designs and the choice of materials, the manufacturing process is ready to start. Like with the design process, the dielectric elastomer actuator and electro adhesive feet are built individually and then joined together.

5.3.1 DIELECTRIC ELASTOMER ACTUATOR

To manufacture the actuator, the materials needed are acrylic sheets, VHB 4910 tape, duct tape and carbon grease. The tools used will include a knife palette, a metallic rectangular frame to pre stretch the elastomer membrane, scissors, a ruler, a permanent marker and a cutter.

In the first place, the permanent marker is used to outline two concentric rectangles of dimensions 120x30mm and 90x20mm in an acrylic sheet with the help of a ruler, scissors and a cutter. To produce two actuators, four of these cut outs are required. Once these are ready, 45mm of the VHB 4910 tape is cut and pre stretched in all directions and set in the metallic frame. Then two of the acrylic sheet cut outs are place on the top and bottom of the pre stretched tape, one exactly on top of the other, and the excess tape is cut with scissors or a cutter. Even though the natural adherence of the tape should hold the acrylic sheets together, duct tape is placed on all four edges to stick the outer sides of the acrylic frame. This prevents the VHB tape from relaxing to its normal shape and breaking the configuration. Once the tape and acrylic sheet are all set, a thin carbon grease layer of dimensions 65x9mm is coated over both sides of the VHB tape using a knife palette. As for the dimensions of these step, the carbon grease does not need to be perfectly placed on the rectangle defined, but it is important that it does not touch the acrylic sheet at all, and that there is a small region of tape without carbon grease. This is done to avoid short circuit. If the carbon grease from the top and bottom of the tape make contact, shorting is likely to occur, and the excess heat generated will burn the tape breaking the actuator. A visual representation of the steps to follow is shown in figure 28 below.



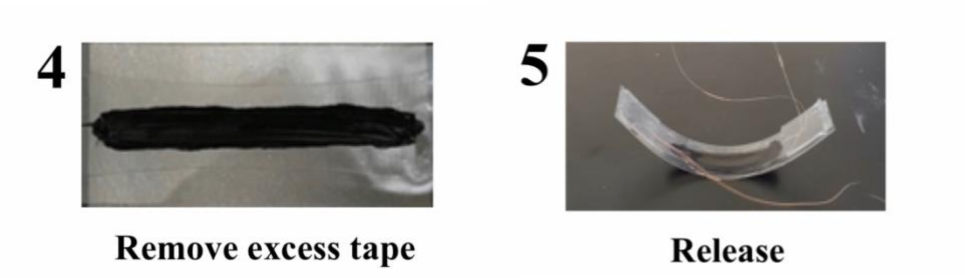


Figure 28. Manufacturing of the dielectric elastomer actuator

As it can be appreciated in the last step, when the actuator is released from the pre stretching frame, as the membrane tries to relax and return to its original size, the actuator bends. Then, when voltage is applied, the actuator will flatten in all directions as it reduces its thickness as a result of the deformation caused by the electric field. The assembly of the two actuators required to build the robot's body will be analyzed in following sections.

5.3.2 ELECTRO ADHESIVE FEET

For the production of the electro adhesive feet the materials required are a regular A4 sheet of paper, a 2B pencil, some more acrylic sheets and VHB 4910 square tape. The tools used to manipulate the materials will be a permanent market, a ruler, scissors and a cutter. The first thing to do is to define the sole's shape, which has already been done during the design process. This shape needs to be lined using the marker on the A4 paper and the acrylic sheet. A thin rectangle also needs to be lined in the acrylic sheet to build the leg of the robot. Even though this section focuses on the feet exclusively, the legs are needed to be manufactured with the feet. Once all the lining is done, the shapes are cut using a cutter for the acrylic sheet and scissors for the paper. Then, the 2B pencil and the ruler are used to line and fill the graphite layers on the A4 paper. In this step it is essential to press the pencil hard against the paper and fill in all the blank spots to create a thick layer of graphite, since it will serve as the feet's electrode and will have a direct effect on the electro adhesion force. For the acrylic sheet, once the sole shape is cut out, using the cutter, two small stripes forming a semi triangle must be cut on the center of the sheet to fit the leg's flaps through them. The thin acrylic rectangle must be cut and bent through the middle. Then, using the scissors, a small cut is done through the bending at the bottom of one of its ends, creating the flaps that will fit through the holes of the other acrylic sheet. These first steps to follow are illustrated in figure 29 below.

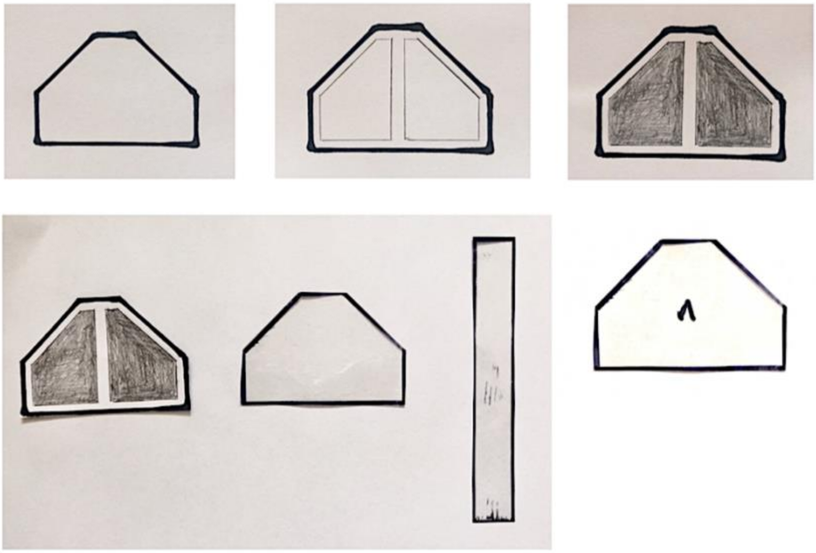


Figure 29 – Manufacturing of the electro adhesive feet I

At this point all of the layers are ready to be assembled. The A4 paper is laid down and on top off it, without the need of pre stretching it, the whole VHB square tape is placed on top. Before doing this, it is important to place the soft wires, each touching one graphite layer underneath the tape so that they hold together. Next, the flaps are introduced through the holes of the acrylic sheet and flattened, and the sheet is stuck to the other side of the VHB tape. To finish, the excess material of the tape is removed using the cutter so that it has the same sole shape. For an easier understanding, figure 30 below shows the final steps followed in the manufacturing process.

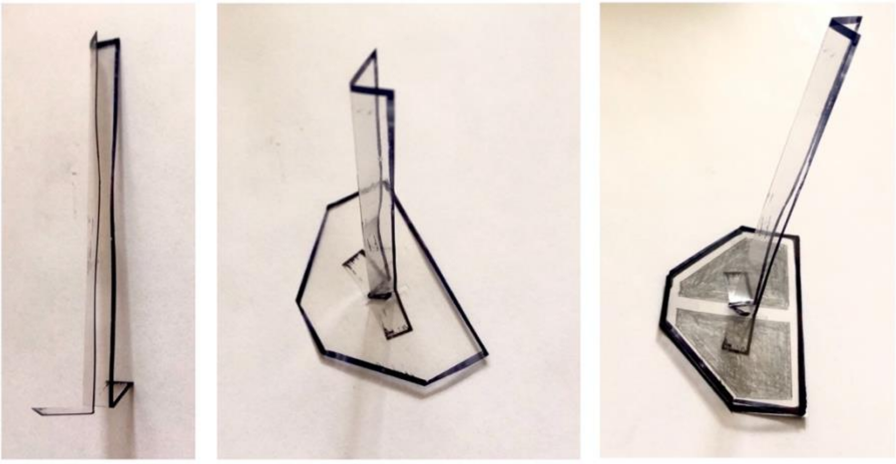


Figure 30 – Manufacturing of electro adhesive feet II

The feet are now ready to be assembled with the robot's body, which will be analyzed on the following section.

5.3.3 ASSEMBLY

The assembly process consists on joining the two actuators to form the robot's body and then join the legs to the body to achieve the final result. For, these, the only things needed are the two actuators and pair of feet previously manufactured and some clear duct tape.

Figure 31 – Manufacturing of robot's body

In the first place, the actuators are placed facing each other through their concave side so that they form an oval shape as it is shown in figure 31. Using some duct tape for each end, these are joint taping the inside and outside of the edges to build a solid link. Using duct tape instead of a harder material for the link has its explanation. The tape, as opposed to a harder plastic, allows to join the DEAs firmly, still allowing them to move as individual elements and perform relative movements to one another.

Once the body is assembled, the legs must be placed on each of the edges where the dielectric elastomer actuators join. Each foot is placed facing outwards and each leg is taped to the edge. The final result should resemble the robot shown in figure 32 below, a fast prototype of the robot.

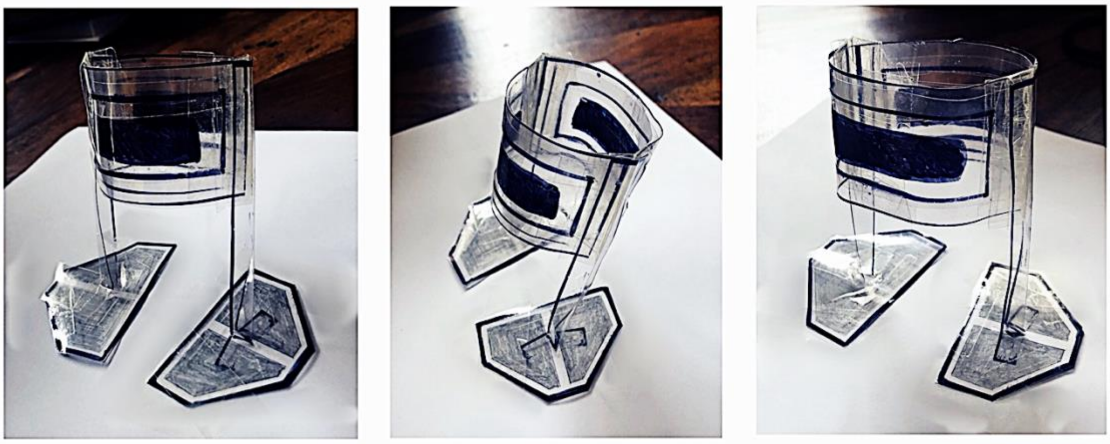


Figure 32 – Soft wall climbing robot prototype

To conclude, it must be said the manufacturing process is not extremely challenging. However, the details need to be taken care of in order to create a model with the dimensions required in order for the robot to perform its functions optimally. The manufacturing process for this research was hand based, however, it could be automatized for larger scale production using a chain process. Nevertheless, these details should be part of a future analysis of the robot's potential.

5.4 MODELING AND EXPERIMENTATION

This section will explain the experiments and tests ran with each individual element of the soft robot, as well as the whole configuration. It will also explain the robot's behavior under the effect of the external stimulus and how it can be controlled to perform the desired behavior at all times.

5.4.1 DIELECTRIC ELASTOMER ACTUATOR

Actuators are the most important part of soft robots given their function of translating the external stimulus into the desired motion. Since the beginning of the research process, before having as an objective the production of the soft wall climbing robot, the central focus was set on the DEA. Hence, most of the experimentation processes involve studying and analyzing the dielectric elastomer actuators.

The firsts experiments were carried out during the initial stage of research when the type of material was being chosen as the elastomer membrane of the actuator. For these experiments, as it has been mentioned on previous sections, the materials tested were: 3M VHB 4910 tape, 3M VHB 4905 tape, Smooth-On EcoFlex 00-30 and Smooth-On EcoFlex 00-50. The last two needed to be created out of two different solutions and were then cured using an oven, the tape is ready for use as it is purchased. The first decision taken was to remove both silicon rubbers membranes given all the previous work it needed to use it later as well as the texture achieved as an outcome. The layers were too thick and broke with deformation way before the VHB tape. Therefore, the decision had to be made between choosing the VHB tape 4910 or 4905. As a reminder, the difference between these two is only their thickness (1mm and 0.5mm respectively). The main function of the elastomer membrane in the DEA was to stretch and deform without breaking, and being able to recover to its original shape after the external stimulus is released. Due to its thickness, the 4910 tape was chosen as its response to deformation was better than that of the 4905 tape. This was the result of the first experiment, which had as an objective to choose the membrane material.

The next step in the for the design of the robot, specifically the DEA, consisted on choosing the shape and form this one would take. Some of the shapes that were experimented with were the planar rectangular shape, planar circular shape and convex rectangular shape, which are depicted on figure 8 in the methodology section. To test these different configurations, the procedure consisted on building the DEA with the pre stretching membrane, acrylic sheet, VHB tape and the carbon grease, and applying a wide range of voltage values to the electrodes to analyze their response in terms of behavior and resistance. In other words, the observation focused on both the level of motion achieved by the actuator and the voltage values it endured.

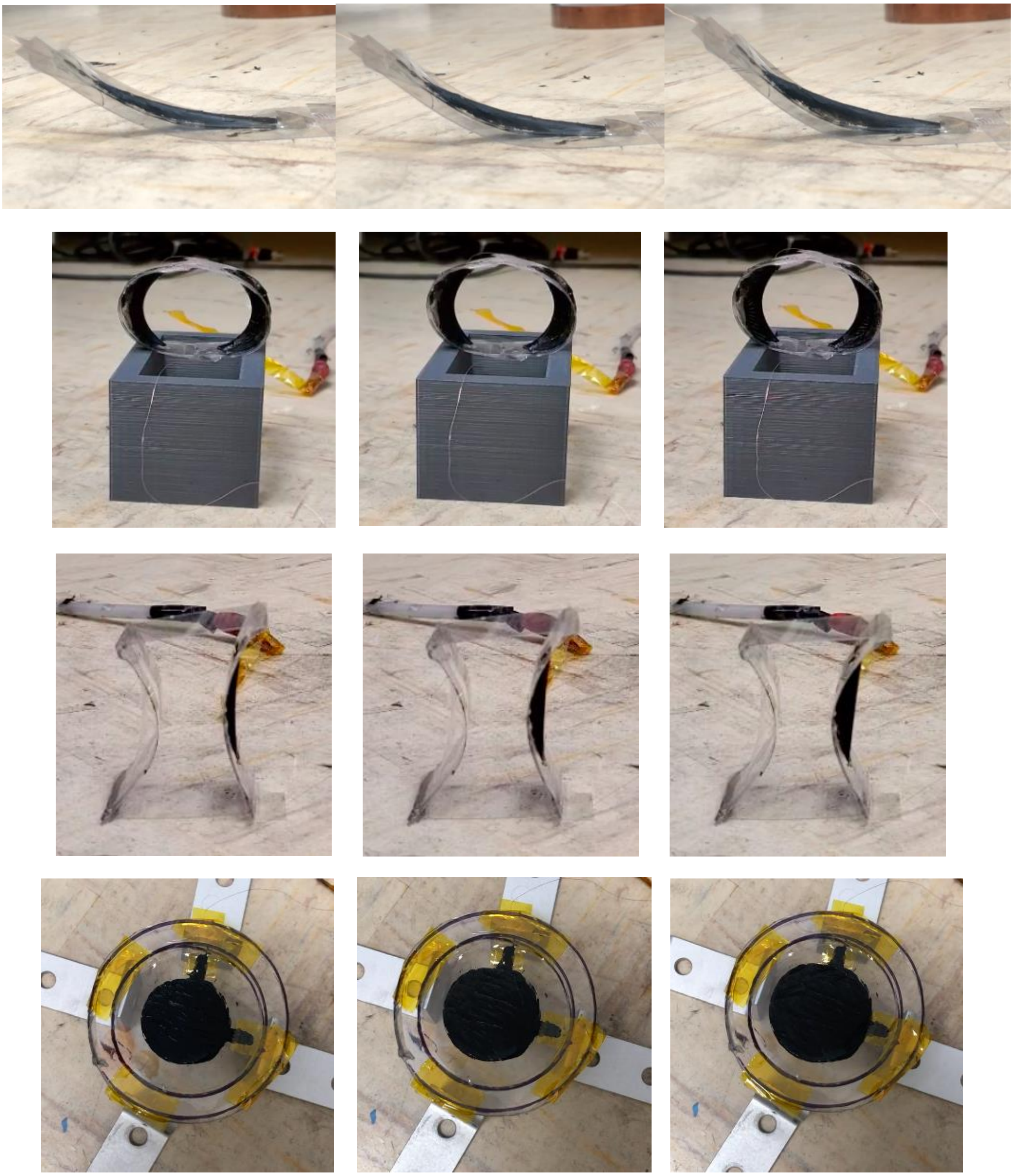


Figure 33 – DEA shape experiments

The pictures shown above are screenshots taken of several videos were differently shaped actuators are subjected to an increasing voltage supply. To the left, the actuator is shown without external stimulus. The following pictures show how as voltage is increased, the black carbon grease coated area expands. The effect is not very explicit or large, but if examined closely, it can be appreciated. While carrying out these experiments, the range of values of voltage supply they could endure at different frequencies was noted to avoid the breaking of the elastomer membranes, which are likely to burn if too much voltage is applied, or if increases too quickly.

Knowing how each shape affects the actuator's behavior, and once the application and function of the robot was defined, the next step was to choose the type of actuator to be used. For the soft wall climbing robot the actuator would consists, as it has been shown throughout the design process of a flat rectangular actuator which is then bent to form a convex shape during the pre-stretching process. Then two of these actuators are joined to form an oval shape. Hence, out of all the shapes shown in figure 33, the first and second rows are perfect examples of the real manufacturing process.

Having decided the materials and the shape for the actuator, the only thing left to do involves dimensioning the structure, which also needed an experiment. This one consisted on creating differently sized acrylic sheet frames and cutting different lengths of the VHB tape.

	Acrylic sheet		***VHB tape***
	Length (mm)	**Width (mm)**	**Length (mm)**
Test 1	65	5	16
Test 2	65	7	16
Test 3	65	9	16
Test 4	65	5	30
Test 5	65	7	30
Test 6	65	9	30
Test 7	65	5	45
Test 8	65	7	45
Test 9	65	9	45

Table 3 – DEA experiment III

The values for the experiment are gathered in table 3 above. Since there are three different parameters with three different possible values to choose, the were a total of nine tests to run. For each of the nine actuators, voltage was applied from null value to the point where the elastomer membrane burnt, in order to establish the range of values that each could endure. In addition to the range of values for the electric supply, the deformation achieved by each actuator for several voltage values was measured too. With the experiment's results, the final dimensions chosen for the actuator, as it is shown in the design section of the DEA, were 65x9mm for the acrylic sheet frame and 45mm for the VHB tape's original length before pre-stretch.

With experiment 3, all the data needed for the production of the optimal DEA is gathered. Further experiments in which the body of the robot, formed by the two actuators, will be analyzed in section 5.4.3.

5.4.2 ELECTRO ADHESIVE FEET

The experiments needed to define the production of the electro adhesive feet were fewer than for the DEA. The materials and structure for the feet were chosen since the beginning of the process. Hence, the only decision to be made involved the kind of shape the sole of the feet had to take. Based on the fact that the surface area of the graphite layer is proportional to the electro adhesion forces generated by the electric field, two different models were designed to try out. The first configuration had as a base a circular shape with two semi circles for the graphite layers. This allows for a good weight – surface area relationship. The second shape is a combination of a triangle and a rectangle, like the one shown throughout the design process. This worsens the surface area – weight counterbalance but gives the feet a pointed shape that reduces the friction forces and eases forward movement. The experiment carried out with these configurations involved sticking them to the wall and powering them with the electric supply with a wide range of voltage values and observing how they hold to the wall at these values and after removing the supply. To test their adherence strength, the two feet were also placed on the floor and pulled from with the same force at different voltage levels. Both tests, placing them in the wall and the floor were repeated for each shape using light and thick graphite layers. Even though the result of this last test was foreseeable, its effect was more significant than expected. Figure 34 below shows screenshots from the videos taken of the wall test for both configurations.

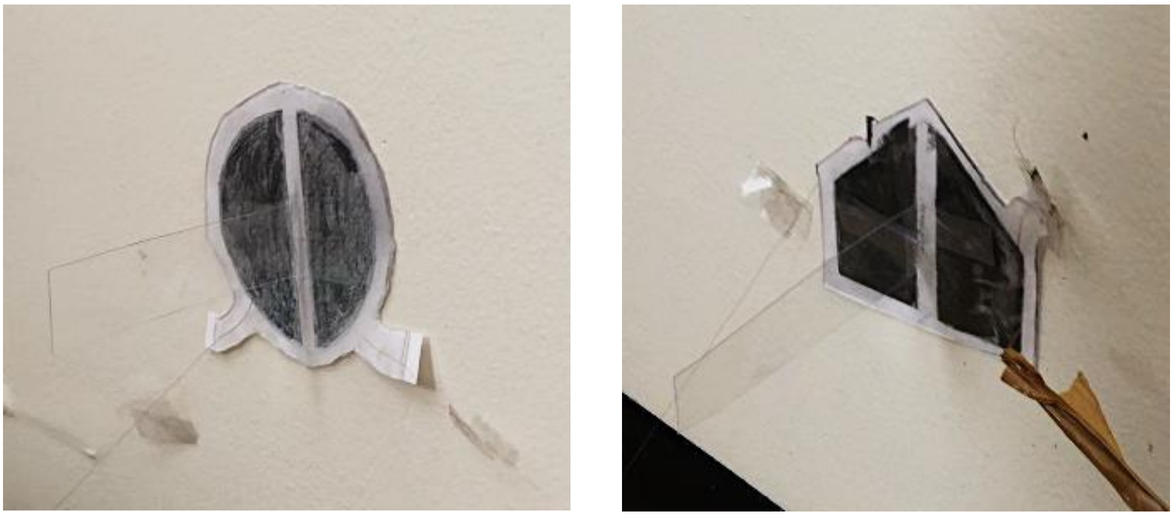


Figure 34 – Electro adhesive feet experiment

The picture to the left is part of the circular shaped, thin graphite layer experiment, while the picture to the right shows the other shape with a thick graphite layer. The difference is very explicit and is easily appreciated.

After running all the experiments required, the chosen shape was the combination of the triangle and rectangle. Even though the surface area – weight ratio is better for the other configuration, its shape significantly reduces friction levels for a forward movement that counterbalances for the extra weight.

5.4.3 SOFT WALL CLIMBING ROBOT

There are several experiments designed to test the efficiency of the robot design as a whole. However, most of these experiments are designed to gather data on the robot's behavior rather than on improving its design. As it has been mentioned on repeated occasions, there is no theoretical model or algorithm that defines the behavior of soft materials due to their nonlinearity. Hence, experiments need to be done with the robots simply to define their response to external stimuli to build a guide in which all this data is gathered to enable future users to control it efficiently.

Therefore, the experiments for the final result of the soft wall climbing robot are design to measure its ability to crawl, climb, turn, etc. The experiments consist on making the robot perform all these different actions and measuring its turning angle range, its range of velocities, etc. The following list includes all the measurements that need to be defined to build a model on the behavior of the soft robot.

- Turning angles for the range of values of voltage supply on a flat surface
- Turning angles for the range of values of voltage supply on a flat wall
- Turning angles for the range of values of voltage supply on a 45º ramp
- Speed at different voltage supplies on a flat surface
- Speed at different voltage supplies on a flat wall
- Speed at different voltage supplies on a 45º ramp
- Electro adherence force at different voltage supplies on a flat surface
- Electro adherence force at different voltage supplies on a flat wall
- Electro adherence force at different voltage supplies on a 45º ramp
- Body extension at different voltage supplies

With a spread sheet that gathers all this data and the following explanation, any new user should be able to operate the robot. The steps to follow to operate the robot are very simple and intuitive. There are four different connections from the power supply to the robot, two connecting each actuator and two connecting the feet. For the robot to move forward, the foot to the front needs to be free to move with no voltage supply as opposed to the back foot which needs to hold on to the floor with electric supply. Once this is done, both DEAs need the same amount of voltage supply to perform a forward movement. When the distance desired is covered, the front foot needs to hold on to the floor by supplying voltage and the back foot needs to be released. With this done, the voltage supply for both DEAs is cut off so that the body and back foot move forward as the elastomer membranes relax and bend back to its original shape. These steps must be repeated for the robot to continue moving. To achieve backward motion, the same procedure needs to be followed changing the voltage supply for the feet.

If the desired action is lateral movement, the front foot needs to be released of electric supply while the back foot holds to the floor with the voltage supply on, just as for forward movement.

The change comes with the voltage supply for the DEAs. To turn to the right, the left actuator must be turned on while the right one is turned off. The expansion of just the left DEA will cause the front foot to slightly move to the right. Once the left DEA reaches full expansion, the front foot is fixed to the floor through electric supply, and the left DEA and back foot are released to complete the movement. To turn to the left, the exact same procedure needs to be followed changing the voltage supply of the actuators.

Having defined lateral, forward and backward motion, the only thing left to control is the robot's speed. The speed of a single movement depends proportionately on how fast the voltage supply is increased as well as the voltage supply itself. There is the risk of burning the DEA is this step is done too fast or if too much voltage is applied, which much be taken care off. Then, the speed at which the user is able to repeat the steps for a single movement determines the overall velocity of the robot.

This explanation concludes the modeling of the robot, which would now be ready for use.

CHAPTER 6 – CONCLUSIONS

This investigation started as an attempt to join the scientist community that studies the soft robotics field. This area of study has a lot of room for innovation, as it has only recently started to develop. As with any investigation the initial process was limited to acquiring knowledge on the subject from previous published papers from other researchers. The best way to learn about the topic is understanding how others have worked with it using the existing current technologies. However, this is not enough to produce a robot. Hence, the next thing to do involved getting to know the soft materials needed to produce the actuator, being this the most important piece of any soft robot. After several tests and experiments and taking into account the technologies available, the decision was made to use a dielectric elastomer membrane to manufacture the actuator and, subsequently, to use electric supply as the source of external stimulus.

Having chosen the materials, the next step is finding an application or function for the soft robot to perform. It is essential to give a sense of purpose to the robot in order to obtain a useful outcome and to attract its users. The creative process is one of the hardest steps in the investigation, especially if the goal is to produce an ambitious and purposeful soft robot. Searching for inspiration in the anatomy of living organisms such as plants, animals and humans is key in the soft robotics field, since these robots aim to perform functions that hard robots are not capable of. After considering several designs, the soft wall climbing robot was chosen as the best potential product. The idea of electro adhesion forces was introduced to the research at this point as a necessity in order for the robot to be able to perform its principal function.

Once the robot’s function is clear, the rest of materials need to be chosen and different designs need to be brought up to test. As it has been mentioned, the choice of materials, design, manufacturing, experimentation and modeling process were complementary and overlapped with one another. Going back and forth is common in the soft robotics field due to its relative newness. The lack of mathematical models makes trial and error an essential requirement in the production process. The combination of all these steps finally resulted on the final prototype of the wall soft climbing robot. Finally, after making some modifications and improvements to this prototype, the final model was created.

Looking back to the set of objectives proposed at the beginning of the process, it is rewarding to see how all of them have been fulfilled to a greater or smaller degree throughout the totality of the creative and production processes. It is true that some aspects could have been treated paying more attention to the small details, but the overall result was satisfying. The parts of the process which could be improved are the experimenting and modelling steps. Working more in depth on these two parts would have allowed to gather a more complete set of data. This would be an advantage in the sense that more modifications could have been made to the robot's model in order to improve its performance. Inevitably, the more tests and experiments the robot undergoes, the more accurate their results. In addition to the possible improvements made to the robot, the data gathered when running the tests would also result in a more complete user guide to control the robot. Even though this control is intuitive and can be done by almost everyone when the process is explained, excelling at it goes far beyond merely knowing how to use it. Having a clear set of data that informs about the robot's behavior in terms of bending angle, velocity, climbing, etc., is always beneficial towards making it attractive and useful. If further work is put into this research project, this would be one of the areas were more work needs to be done. Nevertheless, the current results are satisfactory enough.

One of the most important achieved objectives has been carrying out the research project always taking care of making it sustainable and socially responsible. The soft robotics field has much potential in the scientific community not only for performing functions and applications hard robots are not capable of, but also for its degree of intrinsic sustainability. That is, the development of soft robots is naturally environmentally and socially responsible given the materials used as well as the sources of energy. For instance, in this specific research, most materials used can be easily recycled. Moreover, the use of electric supply as the external stimulus, that is, a renewable source of energy, also complies with the sustainable objectives set for the project.

To finish, it must be said that carrying out this research project and being able to see the effort put into it with the final result is very gratifying. All in all, the whole process has been very enlightening in terms of learning about the scientific background required, and about how a research project needs to be carried out. The results are beyond satisfactory. There is much potential for the soft wall climbing robot, which will be commented on the following section as part of the future analysis.

CHAPTER 7 – FUTURE ANALYSIS

This chapter studies the possibilities in terms of further investigation of the project. Throughout the development of this one, some of the potential of future modifications and works on the soft wall climbing robot have already been mentioned. Since the model created for the robot in this specific research is an original version, there is plenty of room for improvement and adjustments.

The first thing that would need to be done is further experimentation and tests with the existing model. As it has been commented on the previous chapter, this has been the weakest part of the project, and needs reinforcing. Besides, in order to improve, the faults and flaws need to be identified first. The best way to do this is putting the original model to the test and observing its limitations and weaknesses. Once these are identified, the necessary measures and modifications to improve the robot can be conducted. This will allow to improve some parts of the design and manufacturing processes.

Another aspect that can be altered in future versions of the robot is the types of materials chosen and technologies used to create the robot. The amount of resources available is a big indicator as to what can and cannot be done during the production process. For this specific research, the resource availability is the main reason why the dielectric elastomer actuators and electric supply as the source of energy and external stimuli were chosen to produce the robot. However, for future development of the robot, other types of soft materials and sources of external stimuli can be used for the actuator. Nevertheless, as it has been already said, this highly depends on the infrastructure and resources of each research team. With this being said, the raw materials and tools needed to produce soft robots are not the hardest to find nor the most expensive. In fact, they are relatively cheap compared, for instance, to hard robots and other mechanized parts.

Tying in with the infrastructure and technologies available, another modification that could improve the production of soft robots as well as the result itself would involve automatizing the process. Hand making soft robots is no challenge. However, it is important to take note of the small details and be very precise during the manufacturing process. The hardest part of producing this type of robots might be their size and hence, the accuracy and delicacy with which they have to be treated. Hence, automatizing the process through the use of chain production would speed up the process and probably obtain better results than the handmade versions. Human error is inevitable, and it could be completely removed if the production process relies on mechanized activity.

The last two aspects to comment on relative to the further analysis of the production of the soft wall climbing robot have already been picked up on previously during the project. These include the development of further versions of the model and the commercialization and distribution of the product.

As it was explained in the applications section of chapter 4 as part of the rationale of the project (4.1.2), with certain improvements and modifications made to the original model, it would be possible to create different versions of the soft wall climbing robot to perform different functions as they are called for when demand builds up. With the use of additional features or simple modifications, the original robot could turn to a versatile model that transforms into different versions of itself, enabling it to perform different functions and be used for multiple applications. This is not hard to do with the previous steps of further experimentation and automatization of the production process. Once the original version is exploited to its optimal form, altering its design is relatively fast and easy, and then the only thing left to do is to program the machines to manufacture it. Being able to do this would allow the research team to satisfy the surging demand of third parties, including the market for the general public, hopefully providing them a useful product.

The next step, as it has already been introduced as a result of versioning the original model, is commercializing the product. The rationale and economic plan and forecast sections of the research already touch upon this plan. To summarize, the best distribution channels for the soft wall climbing robot would be large wholesalers' online platforms, that is, e-commerce. Lastly, the different ways of making the robot profitable based on the diverse types of demand would be patenting the design and selling it, doing individual customization, doing batch/bulk production to sell to the general public and/or doing batch/bulk production of customized products.

Hopefully all these potential future works that could be made with the original soft robot model would still comply with the ethical and sustainable objectives set for the development of the project.

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