COMILLAS
UNIVERSIDAD PONTIFICIA
ICAI

GRADO EN INGENIERÍA EN TECNOLOGÍAS INDUSTRIALES

TRABAJO DE FIN DE GRADO

# DESIGN AND IMPLEMENTATION OF A SOFT ROBOT USING DIELECTRIC ELASTOMER ACTUATORS (DEAs) AND DIGITAL MODELING FOR 3D PRINTING

Author: Jacobo Azpeitia de la Torre

Supervisor: Yong Huang

Co-Supervisor: Kaidong Song

Madrid

Julio 2020

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

**Design and implementation of a soft robot using Dielectric Elastomer Actuators (DEAs) and digital modeling for 3D Printing**

en la ETS de Ingeniería - ICAI de la Universidad Pontificia Comillas en el

curso académico 2019/20 es de mi autoría, original e inédito y

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El Proyecto no es plagio de otro, ni total ni parcialmente y la información que ha sido

tomada de otros documentos está debidamente referenciada.

Fdo.: Jacobo Azpeitia de la Torre Fecha: 14/07/2020

Autorizada la entrega del proyecto

EL DIRECTOR DEL PROYECTO

Fdo.: Yong Huang Fecha: 14/07/2020

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# Acknowledgements

The following project has a large technological and research component, which is not available to everyone due to its innovative nature and experimental status.

Therefore, I would like to thank in this section the University of Florida, the possibility of carrying out this research, being able to have its resources, such as the 3D printers, the machine that supplies high voltage, and other laboratory tools.

In particular, I would like to thank Yong Huang, director of the laboratory, and Kaidong Song, supervisor of the laboratory in the daily experiments, and guide of the project, for the opportunity to be part of the research group, making this work possible.

# DISEÑO E IMPLEMENTACIÓN DE UN ROBOT BLANDO UTILIZANDO ACTUADORES ELASTÓMEROS DIELÉCTRICOS, MODELADO DIGITAL E IMPRESIÓN EN 3D

**Autor: Azpeitia de la Torre, Jacobo**
Director: Huang, Yong
Co-Director: Song, Kaidong
Entidad Colaboradora: University of Florida

## RESUMEN DEL PROYECTO

### Introducción

La robótica tradicional es un pilar fundamental e irremplazable en la industria moderna, ya que los robots pueden realizar tareas complejas y repetitivas con gran precisión, eficiencia y rapidez. En ella se emplean estructuras rígidas, hechas de materiales resistentes y duros, como los aceros u otros metales comunes. No obstante, su elevado peso y rigidez reduce su movilidad y adaptabilidad, restringiendo su uso a determinados lugares y condiciones de trabajo.

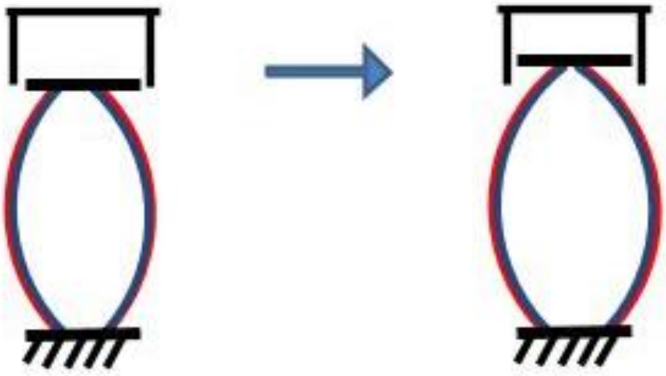
Como complemento de los robots convencionales, se ha producido en las dos últimas décadas un incipiente desarrollo de la robótica blanda, una tecnología innovadora cuyas principales ventajas son la deformabilidad, ligereza y adaptabilidad de sus componentes. Esta ciencia está basada en el uso de actuadores blandos, que reaccionan a un estímulo exterior deformándose y generando un movimiento similar al de un vegetal o un músculo animal. Existen muchos tipos de actuadores en función del estímulo al que responden, pero en este trabajo solo hablaremos de los elastómeros dieléctricos (DEAs), que responden a estímulos eléctricos. Estos actuadores están constituidos por una lámina de material dieléctrico, situada entre dos electrodos flexibles, que conforman un condensador. Al aplicar un voltaje alto (Kilovoltios) entre los electrodos, aparece una fuerza de atracción en el interior del dieléctrico que provoca que el sistema se comprima en grosor y aumente en superficie. A lo largo de los últimos años, se han desarrollado numerosas configuraciones originales, con distintas formas y aplicaciones muy diversas, existiendo diseños para aplicaciones terrestres, acuáticas, aéreas, y en el campo de la robótica humanoide.

Sin embargo, los robots blandos se encuentran aún en un estado inicial de su desarrollo, no existiendo en la actualidad aplicaciones comerciales. Por ello, la naturaleza del trabajo que se expone en este documento tiene un carácter experimental y de investigación. En este proyecto se expone el proceso seguido para el diseño y la implementación de un robot blando aplicado al control de flujo de gases medicinales.

## Metodología

Previamente a la elaboración de los primeros diseños, como en cualquier disciplina, es imprescindible conocer a fondo la técnica a aplicar. Por ello, se llevó a cabo una profunda investigación de las aplicaciones existentes, seguida de algunas demostraciones y pruebas en el laboratorio. A continuación, con ayuda de la herramienta SolidWorks se concibieron y fueron presentados tres prototipos: una rueda discontinua de diámetro variable, un caudalímetro en forma de tobera de sección transversal variable, y un caudalímetro de sección rectangular con base móvil.

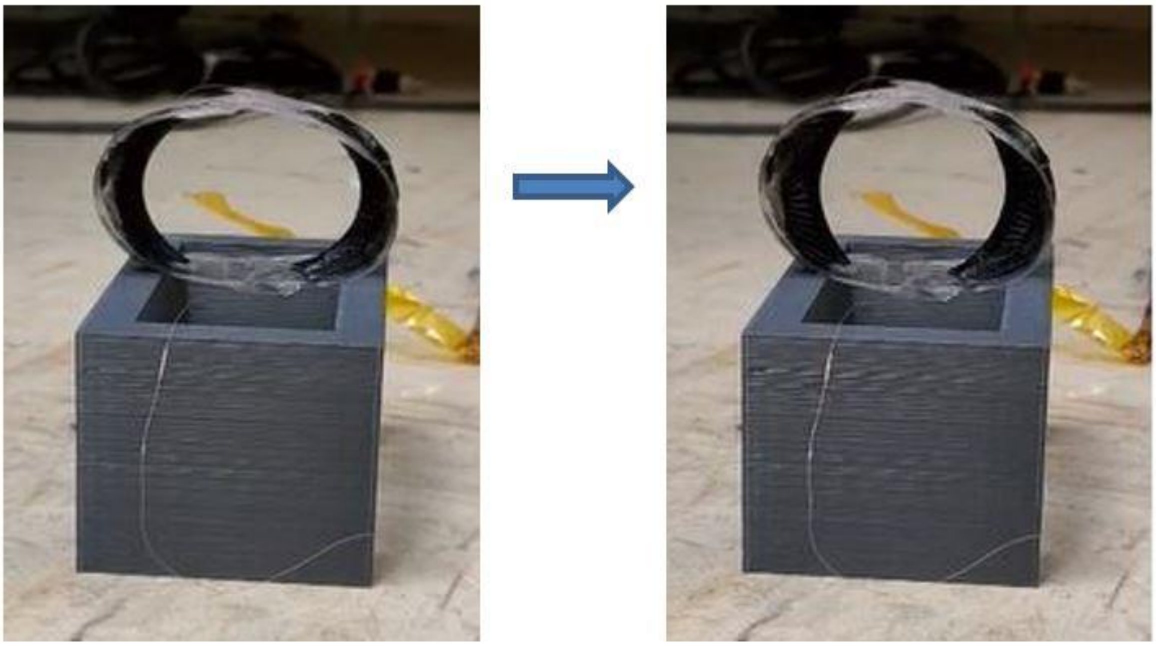
Tras perfeccionar ciertos aspectos en cuanto al funcionamiento y montaje, se procedió a la fabricación de los tres prototipos. Para la elaboración de los marcos necesarios, se empleó como herramienta una impresora 3D de Modelado por Deposición Fundida (FDM), extruyendo Acrilonitrilo Butadieno Estireno (ABS) como material. Con los sistemas fabricados, se llevaron a cabo una serie de experimentos para determinar cuál tenía mayor potencial, escogiendo finalmente el caudalímetro rectangular, que se muestra en la siguiente imagen:



El mecanismo está basado en dos actuadores curvos, que impulsan la base de un tubo de sección rectangular cuando se les aplica voltaje alto. La aplicación propuesta para el sistema, es la de regular el flujo respiratorio de un paciente, integrándose en un complejo equipo de electromedicina. Para optimizar el rendimiento de los actuadores, se probaron diferentes elastómeros, varias dimensiones interiores de los marcos, y distintos grados de estiramiento del dieléctrico. Finalmente, se escogió como DEA, el VHB 4910 de la marca 3M, un marco de 65 x 7 mm, y una longitud de la cinta de VHB sin estirar de 30 mm. Para los electrodos, se empleó grasa de carbono 846-80G, y la máquina utilizada para aplicar el voltaje fue la Glassman FX20P15. El sistema de electromedicina para el que se particulariza la solución es la máquina NOXTec de la Compañía española ITC.

**Resultados**

El primer prototipo dio como resultado un mecanismo que funcionaba de la manera esperada, expandiéndose y aumentando su diámetro, pero sin estabilidad ni homogeneidad. El segundo, por su parte, no mostró el movimiento deseado, por lo que fue directamente descartado. Por último, el diseño basado en los actuadores curvos mostró los resultados más prometedores, al ser capaz de aumentar su altura aproximadamente en un 10% respecto del total, unos 5mm. Admitía además una buena capacidad de modulación del movimiento.



## Conclusiones

De este trabajo se pueden obtener principalmente dos conclusiones. La primera, es que se trata de una tecnología complicada y sobre la cual se dispone aún de experiencia y estándares muy limitados. Adicionalmente, los materiales no se comportan de manera lineal y su funcionamiento depende de muchos factores poco parametrizados hasta el momento. Por ello, es complicado que puedan existir pronto aplicaciones comerciales a gran escala.

No obstante, la segunda conclusión obtenida es que la tecnología es muy versátil y tiene un gran potencial de desarrollo. Si se consiguen minimizar sus desventajas y potenciar sus propiedades, los robots blandos tendrán seguro muchos campos de aplicación en el futuro.

## Referencias

[1] Ujjaval Gupta, Lei Qin, Yuzhe Wang, Hareesh Godaba, and Jian Zhu (2019). Soft robots based on dielectric elastomer actuators: a review. *Smart Mater. Struct.* **28** 103002

**Palabras clave:** Actuador Elastómero Dieléctrico, robótica blanda, caudalímetro.

# DESIGN AND IMPLEMENTATION OF A SOFT ROBOT USING DIELECTRIC ELASTOMER ACTUATORS (DEAS) AND DIGITAL MODELING FOR 3D PRINTING

**Author: Azpeitia de la Torre, Jacobo**
Supervisor: Huang, Yong
Co-Supervisor: Song, Kaidong
Collaborating Entity: University of Florida

## ABSTRACT

### Introduction

Traditional robotics is a fundamental and irreplaceable pillar in modern industry, since robots can perform complex and repetitive tasks with great precision, efficiency and speed. It uses rigid structures, made of tough, hard materials such as steel or other base metals. However, their high weight and rigidity reduce their mobility and adaptability, restricting their use to certain locations and working conditions.

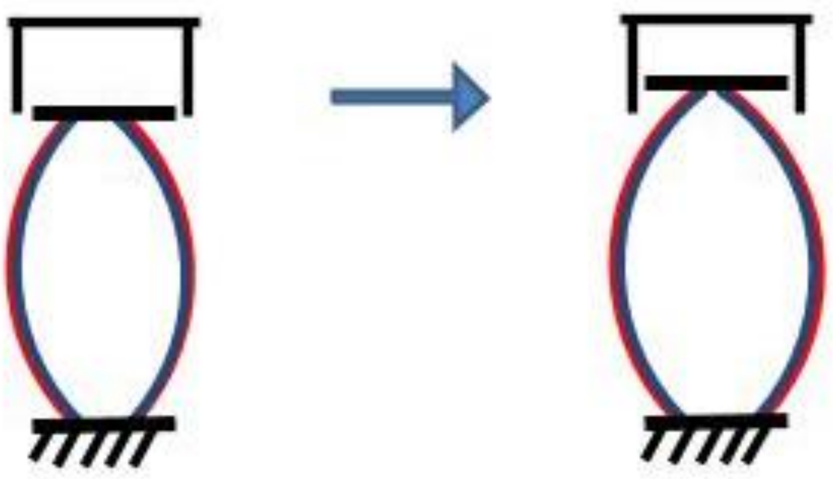
As a complement to conventional robots, there has been an incipient development of soft robotics in the last two decades, an innovative technology whose main advantages are the deformability, lightness and adaptability of its components. This science is based on the use of soft actuators, which react to an external stimulus by deforming themselves and generating a movement similar to that of a vegetable or animal muscle. There are many types of actuators depending on the stimulus to which they respond, but in this work, we will only talk about dielectric elastomers (DEAs), which respond to electrical stimuli. These actuators are constituted by a sheet of dielectric material, located between two compliant electrodes, which form a capacitor. When a high voltage (Kilovolts) is applied between the electrodes, an attraction force appears inside the dielectric, which causes the system to compress in thickness and increase in surface. Throughout the last years, numerous original configurations have been developed, with different forms and very diverse applications, existing designs for terrestrial, aquatic, aerial applications, and in the field of humanoid robotics.

However, soft robots are still at an early stage of development, and there are no commercial applications at present. For this reason, the nature of the work presented in this document is experimental and investigative in nature. In this project, the process followed for the design and implementation of a soft robot applied to the flow control of medical gases is presented.

## Methodology

Prior to the elaboration of the first designs, as in any discipline, it is essential to know in depth the technique to be applied. Therefore, a thorough investigation of the existing applications was carried out, followed by some demonstrations and tests in the laboratory. Three prototypes were then designed and presented using the SolidWorks tool: a variable diameter discontinuous wheel, a variable cross-section nozzle flowmeter and a rectangular flowmeter with a movable base.

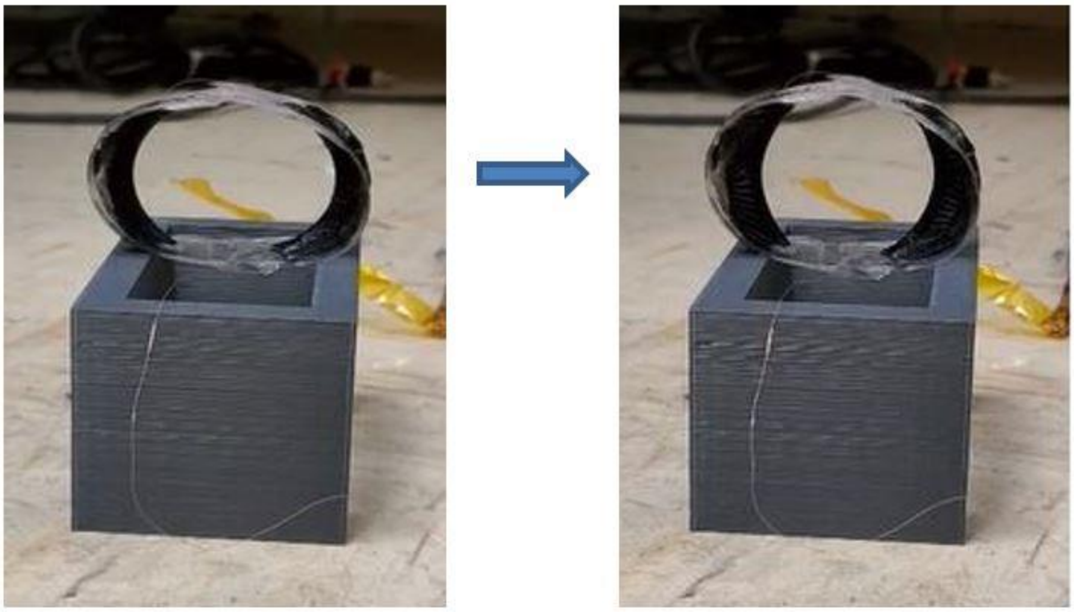
The three prototypes were then manufactured after some operational and assembly improvements had been made. To produce the necessary frames, a 3D Fused Deposition Modeling (FDM) printer was used as a tool, extruding Acrylonitrile Butadiene Styrene (ABS) as the material. With the systems manufactured, a series of experiments were carried out to determine which had the greatest potential, finally choosing the rectangular flowmeter, which is shown in the following image:



The mechanism is based on two curved actuators, which drive the base of a rectangular section tube when high voltage is applied to them. The proposed application for the system is to regulate the respiratory flow of a patient, being integrated into a complex electromedical equipment. To optimize the performance of the actuators, different elastomers, various internal dimensions of the frames, and different degrees of dielectric stretching were tested. Finally, the VHB 4910 from 3M was selected as DEA, with an unstretched 30 mm tape, and a frame of 65 x 7 mm. For the electrodes, carbon grease 846-80G was used, and the machine used to apply the voltage was the Glassman FX20P15. The electromedical system for which the solution is specified is the NOXtec machine from the Spanish company ITC.

## Results

The first prototype resulted in a mechanism that worked as expected, expanding and increasing its diameter, but without stability or homogeneity. The second one, on the other hand, did not show the desired movement, so it was directly discarded. Finally, the design based on the curved actuators showed the most promising results, being able to increase its height by approximately 10% of the total, about 5mm. It also admitted a good capacity of movement modulation.



## Conclusions

Two main conclusions can be drawn from this work. The first is that it is a complicated technology and one for which there is still very limited experience and standards. In addition, the materials do not behave in a linear manner and their functioning depends on many factors that have not been parameterized so far. Therefore, it is difficult that large scale commercial applications can exist soon.

However, the second conclusion is that the technology is very versatile and has great potential for development. If their disadvantages can be minimized and their properties enhanced, soft robots will certainly have many fields of application in the future.

## References

[1] Ujjaval Gupta, Lei Qin, Yuzhe Wang, Hareesh Godaba, and Jian Zhu (2019). Soft robots based on dielectric elastomer actuators: a review. *Smart Mater. Struct.* **28** 103002

**Keywords**: Dielectric Elastomer Actuators, soft robotics, flowmeter.

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# 1 INTRODUCTION

Conventional robots are very useful for carrying out many tasks that can be difficult, exhausting, or simply impossible for humans, such as picking, assembling, and placing heavy components of a structure. These robots are usually made by hard, rigid materials, mainly metals, such as aluminum or steel. Their strength, endurance, and accuracy make them capable of repeating processes with high efficiency. Therefore, they are currently very valuable and irreplaceable in many industries such as vehicles manufacturing or money printing.

However, this technology has several disadvantages linked to the same properties that make it so useful. First, their limited adaptability does not allow them to work in different environments, since they need a big and specific infrastructure around them to work correctly. Secondly, their mobility and speed are limited by the materials they are made of, reducing considerably their applications. Finally, their size and complexity make them expensive to produce and maintain.

To complement the traditional robots, there has been a big development in the past two decades in soft robotics. This new technology consists on the use of very light, flexible materials to create artificial structures that mimic animal muscles or vegetal movements. Unlike their rigid relatives, soft robots have shown an amazing potential for different environments and applications.

Soft robots use an actuator, which responds to an external stimulus creating a muscle-like movement. They are much simpler, smaller, and more deformable structures than rigid robots, what makes them suitable for jobs that cannot be done currently. In addition, the possibility of working as untethered units, allows a bigger mobility and adaptability.

This project presents a review of soft robotics, how they work, the types we have and their current applications. Afterwards, the full process of designing, experimenting, and implementing a soft robot will be presented.

This robot is an electric flow meter, designed to change the flow of oxygen delivered to a patient by changing the airflow area. We will see the different designs proposed, and how they vary their shape to achieve its purpose, reacting to the external stimulus applied, which is high voltage.

# 2 DESCRIPTION OF TECHNOLOGIES

A soft robot is generally made up of two separate parts: the actuator and the housing. This chapter describes the technologies available for manufacturing each of these parts. Subsequently, the operation and characteristics of the technologies chosen to develop the robot presented later in this project will be detailed.

## 2.1 SOFT ROBOTICS

### 2.1.1 TYPES OF ACTUATORS

There are many technologies to develop a soft robot, regarding the stimuli to which they respond. Some of the main types of actuators are: Shape Memory Alloys (SMAs) and Shape Memory Polymers (SMPs) -which respond to temperature changes-, Electroactive Polymers (EAPs) -reacting to an electric field-, Fluidic Elastomer Actuators (FEAs) -operated by pressure-, Ionic Polymer Metal Composites (IPMCs) -based on the ion migration effect-, or Pneumatic Artificial Muscles (PAMs). We will focus on Dielectric Elastomer Actuators (DEAs), which respond to electric voltage as external stimuli because they have shown to have the highest potential for soft robotic applications due to their fast response, large deformation, and efficiency.

### 2.1.2 OPERATING PRINCIPLES

DEAs consist basically on a capacitor formed by two stretchable electrodes that sandwich a thin dielectric elastomer layer. When high voltage is applied to the electrodes, an electric field $E_0$ is born between them.

When the elastomer is introduced into a capacitor charged with a certain Q, the molecular dipoles of the dielectric are oriented against the electric field generated inside. That is, the material is polarized in the opposite direction to this field, accumulating negative charges next to the positive plate of the capacitor, and positive charges next to the negative plate.

Therefore, an electric field $E_P$ appears in the opposite direction of $E_0$, consequently reducing the magnitude of the final electric field inside the dielectric, according to the relative permittivity constant of the material, which is designated as $\varepsilon_r$.

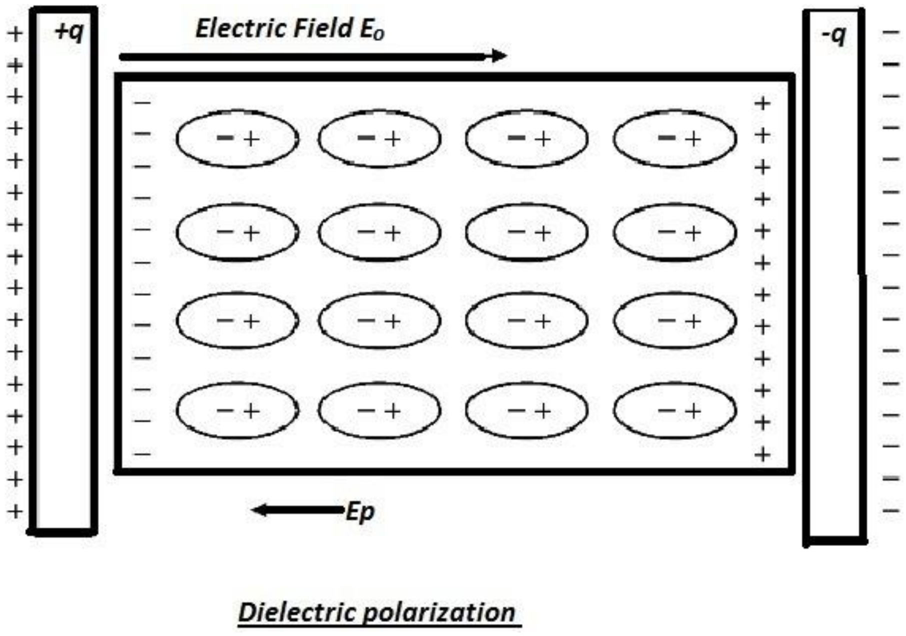


*Figure 1.Dielectric effect [1]*

A consequence of this effect is, that to reach a certain voltage, a load $\varepsilon_r$ times greater on each plate is required. Bearing in mind that the force of attraction between two flat plates, that are much greater on surface than the distance separating them, has the form:

$$F = q\,E$$

We can deduct that, if the voltage is fixed, then E is fixed, so the dielectric effect produces an increase in the force of attraction by raising q by a factor of $\varepsilon_r$. We usually define this force in relative terms to the surface, as Maxwell stress.

It is represented with the symbol $\sigma$, and it can be expressed as a function of the voltage (V), the thickness of the elastomer (d), the free-space permittivity ($\varepsilon_0$) and the relative permittivity of the material ($\varepsilon_r$).

$$\sigma = \varepsilon_r \, \varepsilon_0 \frac{V^2}{d}$$

This Maxwell stress compresses the dielectric, causing it to expand outward and reduce its thickness, according to the law of conservation of mass. For this reason, stretchable electrodes are needed, so that they can adapt their shape with the elastomer.

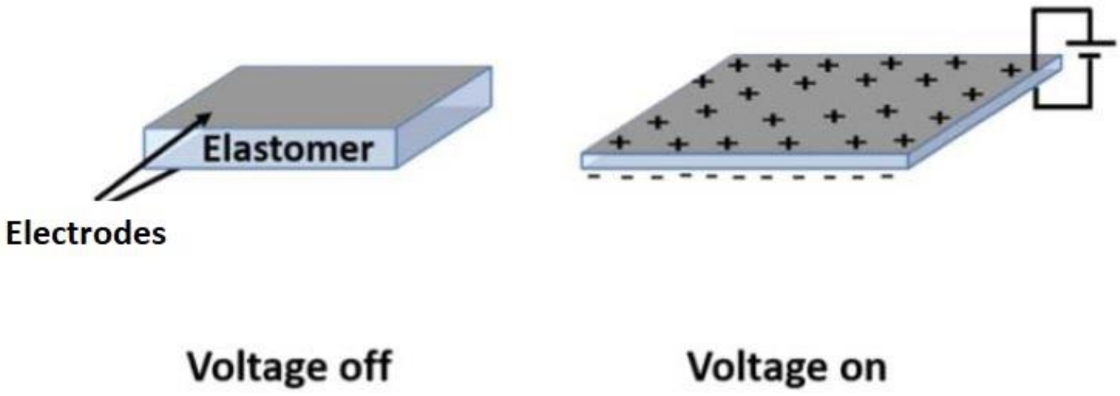


*Figure 2. DEA expansión [2]*

### 2.1.3 ADVANTAGES AND DISADVANTAGES

As we have already seen, DEAs have proved to be a very promising material within the field of soft robotics, thanks to the fast response exhibited, the large deformation they can achieve and the versatility they offer in terms of configurations and environments in which they can work.

One feature that makes this technology so appealing is that it is safe to be implemented in units that will interact with humans. Another point in favor of DEAs is that they offer the opportunity to use different materials as dielectric, allowing us to choose it according to parameters such as the shear modulus, or the dielectric breakdown constant.

Finally, another great advantage offered by this type of material is their ability to generate complex movements from simple structures. In the following sections we will show examples of structures with multiple degrees of freedom, while maintaining a light weight and simple shape.

However, there are also some disadvantages for this technology. First, to obtain a large deformation, DEAs generally require high voltage (~kV). Circuits operating at high voltages are more complicated than the ones operating at low voltage, and they dissipate more energy as heat, causing a bigger material fatigue and reducing its lifetime. If an untethered unit is pursued, accessory amplifiers are required. This makes the system heavier, more expensive, and since portable amplifiers typically have low bandwidth, slower too.

Another thing that affects the lifetime and reliability of DEAs is pre-stretching the material that also limits the adaptability and flexibility of the actuators. Despite its negative consequences, omitting this is hard because it has some advantages such as larger deformation achieved and the suppression of electromechanical instability. These examples show the big challenges that still need to be solved by the industry of soft robotics [2].

## 2.2 3D PRINTING

Also known as additive manufacturing, this technology has undergone an enormous advance in recent decades, thanks to its virtues such as low cost, the ease with which parts can be designed and the speed and precision with which they are manufactured.

In the soft robotics industry, 3D Printing is a key component, as it allows developers to design lightweight and strong housings or frames, with the desired shape and without compromising their qualities. Thanks to this fast and inexpensive technology, several custom-made models can be designed and tested for a given prototype.

Nowadays, there is a wide variety of methods and materials for 3D printing. However, the process prior to manufacturing the part is very similar for all types. At the beginning, a three-dimensional design of the object must be elaborated, with a digital design tool. The design must be made in a format compatible with the 3D printer's processor, which reads it and proceeds to reproduce it. Below, we present the different modes of 3D printing that exist today. Even though there are many different types, we will only speak about the most commonly used.

First of all, we find Stereolithography, patented in 1984, together with the design of the STL file format (STereoLithography), widely accepted today by 3D printing software. This method cures a liquid material thanks to photopolymerization, where every layer is cured with UV light after it is jetted. One of its advantages, is that models produced by Stereolithography can be handled right after being produced.

The following image shows a schematic representation of Stereolithography, where a light-emitting device a) (laser or DLP) selectively illuminate the transparent bottom c) of a tank b) filled with a liquid photo-polymerizing resin; the solidified resin d) is progressively dragged up by a lifting platform e) [3].

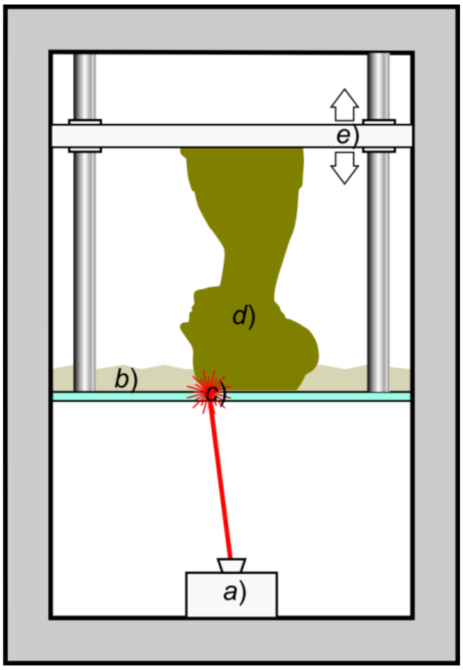


*Figure 3. Stereolithography [3]*

Another type of 3D printing is the Selective Laser Sintering (SLS), which has some similarities with STL. This method uses a laser, precisely guided by a mirror to heat and sinter the powder layered by a roller, when the last layer has solidified.

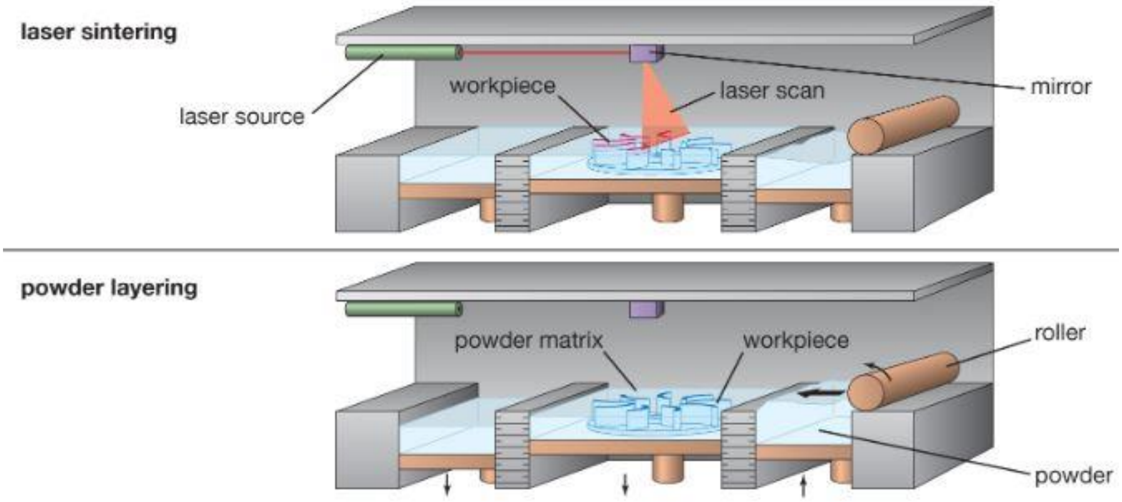


*Figure 4. Selective Laser Sintering [4]*

Finally, the most commonly used method to print three-dimensional plastic parts is called Fused Deposition Modeling (FDM), which is also the type of additive manufacturing used in the research presented in this project. This is mainly because it is the cheapest and most accessible method. Although the results are not as good as those of stereolithography, high level finishes are obtained.

The figure presented below is a schematic representation of the 3D printing technique known as Fused Deposition Modeling, in which a filament a) of plastic material is fed through a heated moving head b) that melts and extrudes it depositing it, layer after layer, in the desired shape c). A moving platform e) lowers after each layer is deposited. For this kind of technology additional vertical support structures d) are needed to sustain overhanging parts [3].

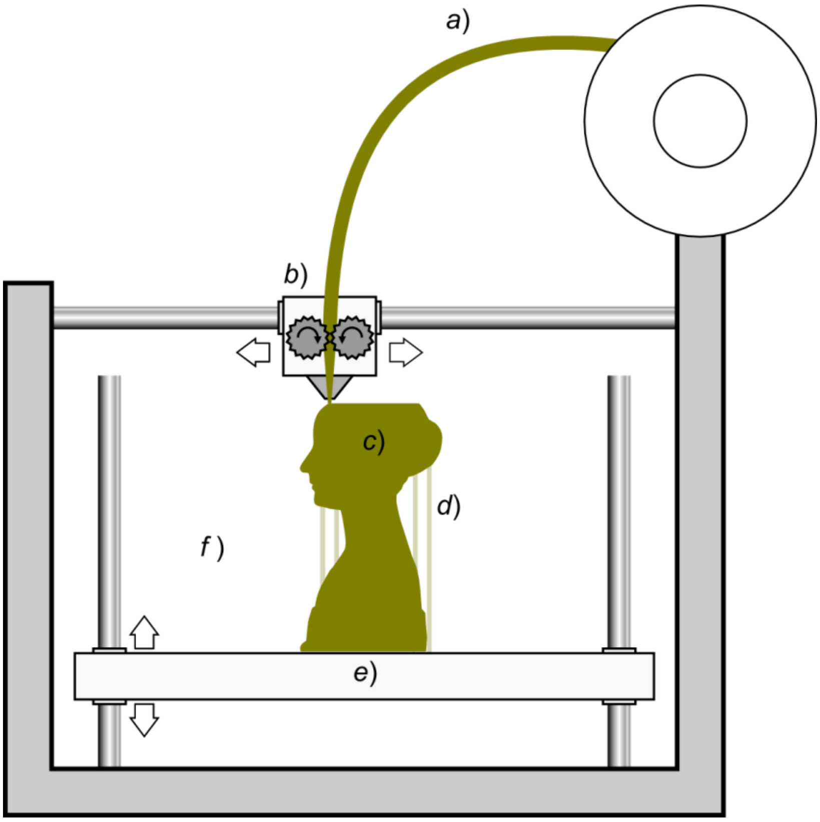


*Figure 5. Fused Deposition Modeling [3]*

# 3 STATE OF THE ART

Despite the many advantages of soft robotics, we have seen that it is a very recent technology with a lot of work and improvements to be done. Therefore, either a sufficiently large market or sufficiently developed products have not yet been found for soft robots to be marketed.

An example of this is the company Empire Robotics, who tried in 2012 to commercialize a jamming-based robotic griper called Versaball, but they were forced to close their doors in 2016 because it was not profitable. In other words, a higher level of product development is still required, for potential customers to be satisfied with the usefulness of the products [10].

However, this technology offers a very wide range of possibilities, both in the way the actuators are connected, and in the application fields. These possibilities will be better explained in the following sections.

## 3.1 SHAPES AND CONFIGURATIONS

An important role in the development of this technology is played by the creativity with which the structures have been configured. In this section we will review some of the most common configurations and an application of each to illustrate the working principle.

For example, numerous applications have been developed thanks to a curved implementation of DEAs. These curved structures are manufactured by pre-stretching the material in a flat, lightweight plastic frame. As a result, a compressive force appears at the ends of the frame, causing the structure to bend.

Then, when voltage is applied to the actuator, the resulting expansion force stretches the material, reducing the curvature. The following pictures illustrate the operating principle.

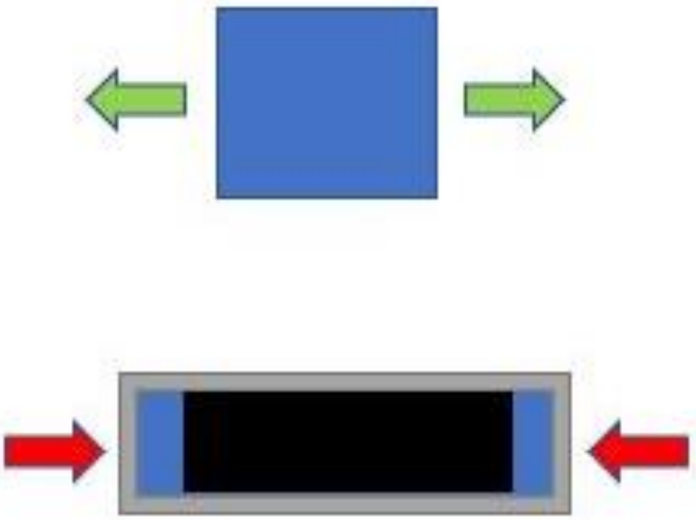


*Figure 6. Pre-stretching of the elastomer*

*Figure 7. Resulting forces upon high voltage*

The most common application for this configuration is using them as **grippers**. Thanks to their actuation they can pick up and place light objects. An example of a soft robotic gripper implemented using this mechanism is the system developed by Jun Shintake *et al* [5]. The robot incorporates an electro-adhesion system at the ends of the curved actuator, which makes it easier for the object to be picked up to adhere to the actuator, reducing the pressure at the contact points.

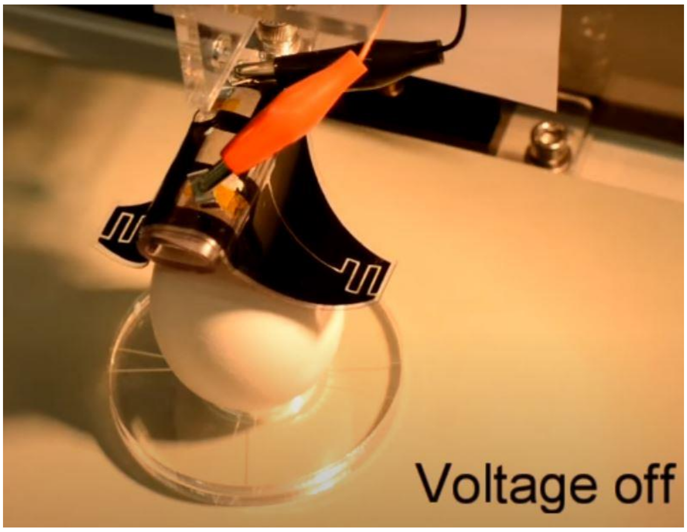


*Figure 8. Gripping egg voltage off [5]*

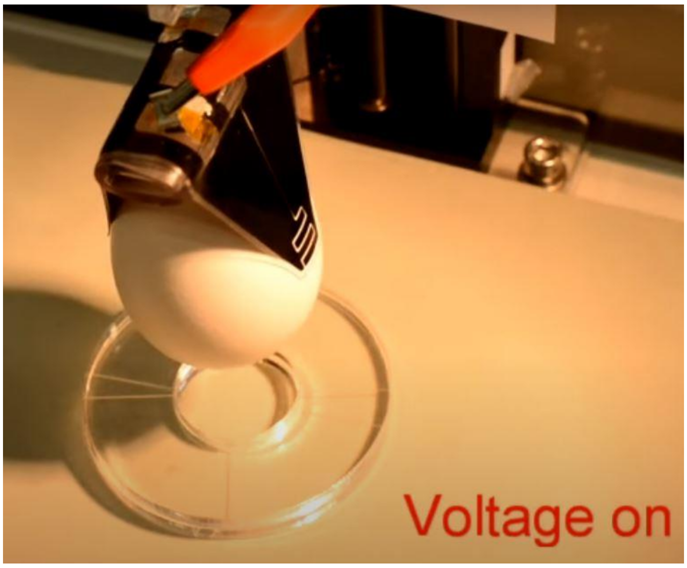


*Figure 9. Gripping egg voltage on [5]*

Thanks to the electro-adhesion system, the robot proved it can lift not only fragile objects, like the raw egg shown in the picture above, but also flat elements very hard to grip. The figures below illustrate the power of this adhesion system, capable of lifting a completely flat, light, and thin piece of paper.

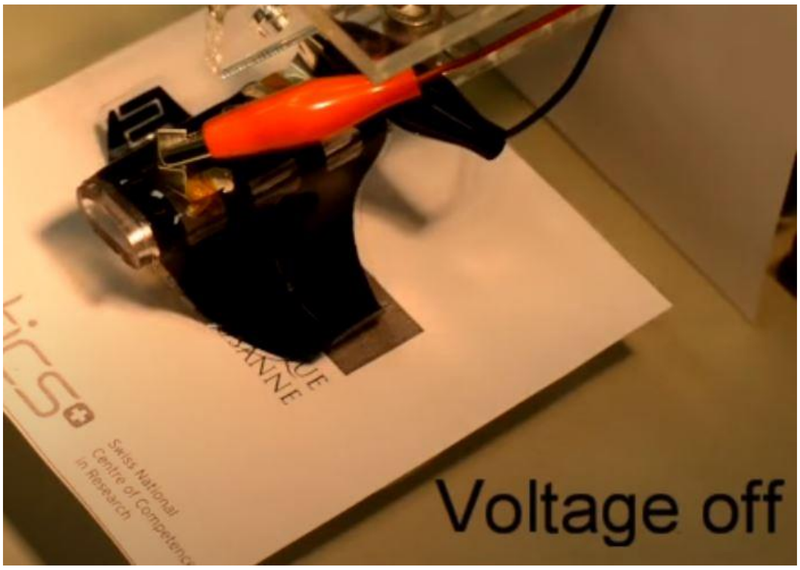


*Figure 10. Gripping paper voltage off [5]*

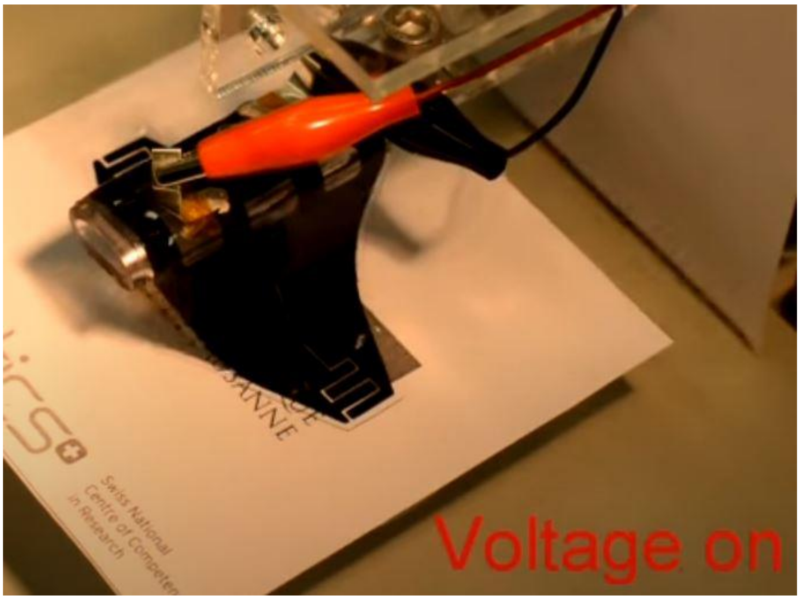


*Figure 11. Gripping paper voltage on [5]*

The gripper consists of a pre-stretched elastomer membrane with patterned compliant electrodes laminated between two passive silicone layers. Different colours of the electrodes represent their polarity (red is positive, and black is negative).

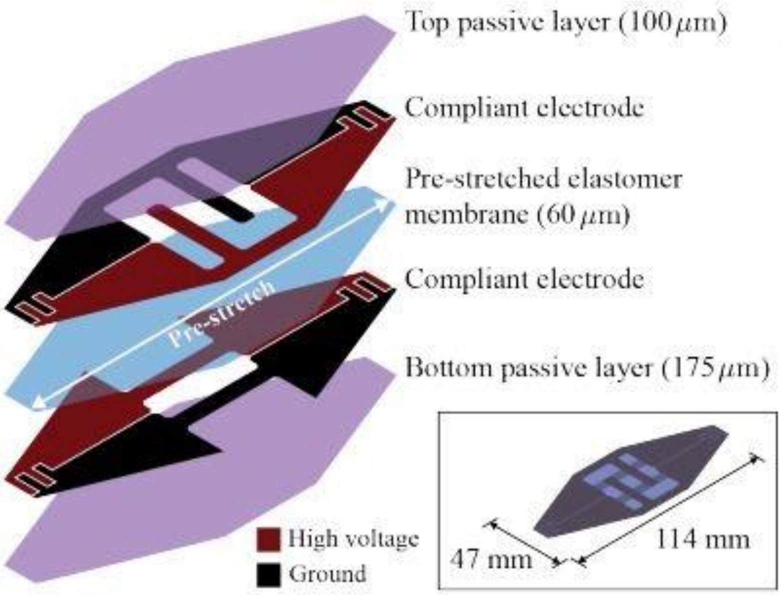


*Figure 12. Gripper's inner structure [5]*

The reason for the gripper pattern is found in the explanation of the electro-adhesion effect. If the poles are interspersed, a circular electromagnetic field is induced that affects the materials it comes into contact with, generating attraction forces between the gripper and the object to be gripped.

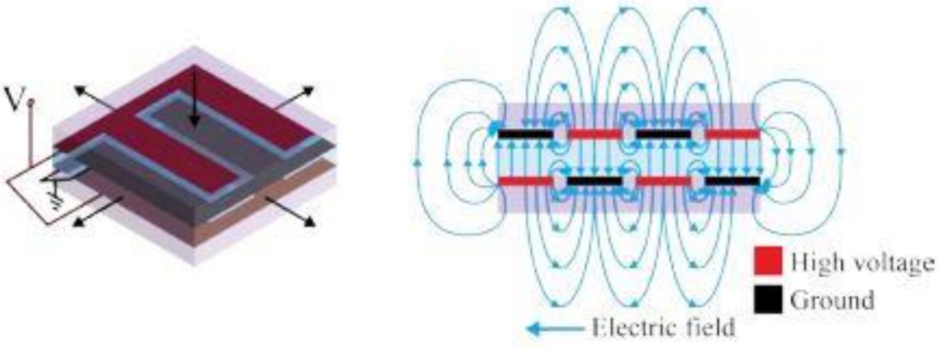


*Figure 13. Electro adhesion physics [5]*

Other creative design is **multilayered** flat DEAs, which can reach a much higher reduction in height by stacking many actuators one on top of another. This configuration also allows a reduction in the voltage to be applied per layer, thus reducing material fatigue and heat dissipation.

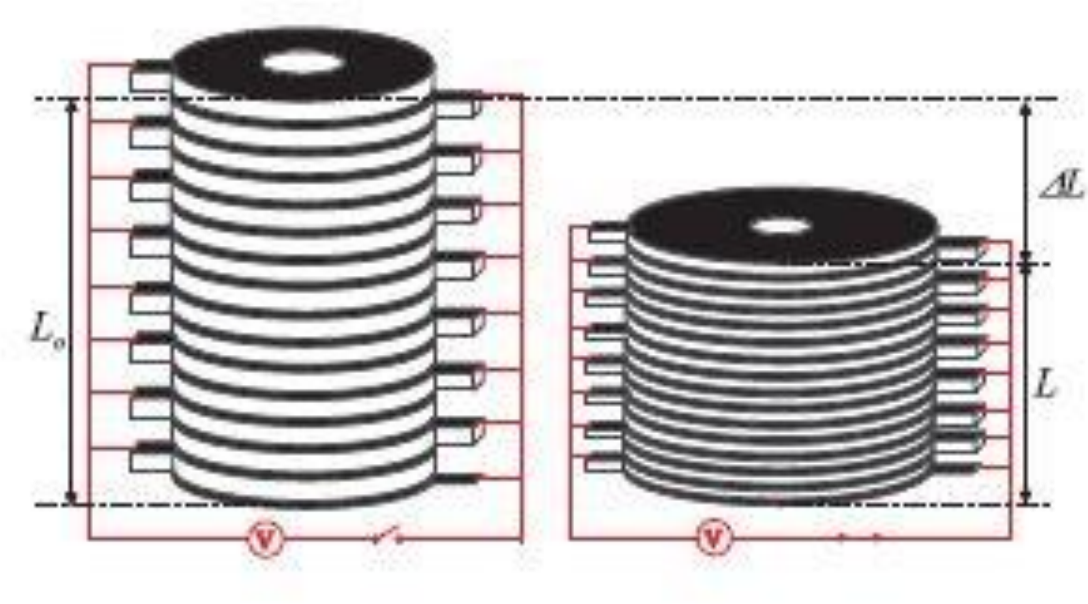


*Figure 14. Multi staked actuators operating principle [6]*

The operating principle is as simple as superposition. If you can obtain a deformation in height *x* with one actuator, you can achieve an effect of *100x* by using 100 actuators. Unlike the most part of soft robotic implementations that take advantage of the expansion effect upon voltage, this one uses the reduction in thickness to create movement. It has been used by many researchers in various applications.

An example of this configuration would be the work presented by Canh Toan Nguyen *et al* [6], who reports the use of this system to implement a biomimetic legged quadruped robot capable of linear motion. It uses multistacked actuators for propulsion, and the help of two joints and a hard, rigid frame.

The following picture shows in deeper detail the components of each of the four legs that form the structure: (1) the stacked actuators, (2) the femur, (3) the tibia, (4) the foot, and (5) the frame, naming every element analogous to its equivalent in a human leg.

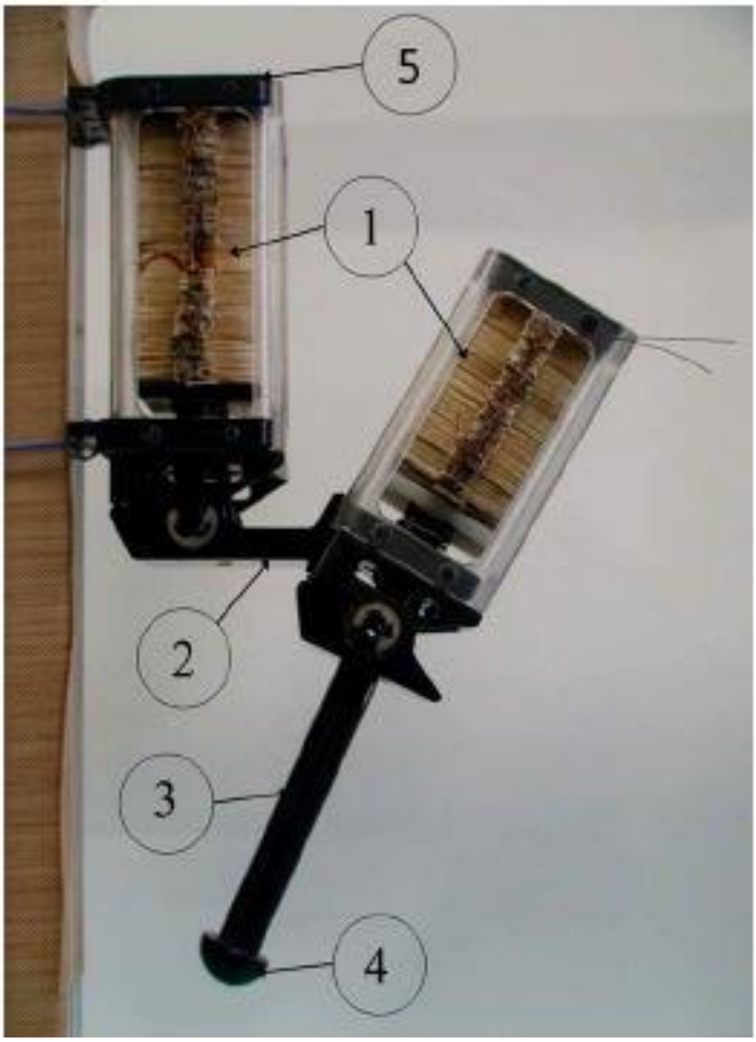


*Figure 15. Assembly of each leg [6]*

The walking motion of this soft robot is composed by four steps. The first stage is the femur rise. Upon high voltage through the actuator in the hip joint, the multistacked actuator is compressed. Therefore, the elastic force of the spring will lift up the femur. The maximum angle the femur can reach is approximately 25º.

Then we have the tibia rise. After the femur has reached the maximum angle, the driving voltage of the actuator at the knee joint is increased. Likewise, the actuator is contracted and the tibia is lifted up. The maximum angle the tibia can reach is around 30º.

The third phase would be the femur descent. The voltage of the actuator at the hip joint is decreased until the foot touches the ground. In a flat terrain, the foot has to descend 34 mm from the initial position.

Finally, the cycle is completed with the tibia descent. In this stage, the voltage applied at the knee joint is turned off and the actuator expands to its initial state, getting ready to start over. The picture below illustrates the movements in each phase.

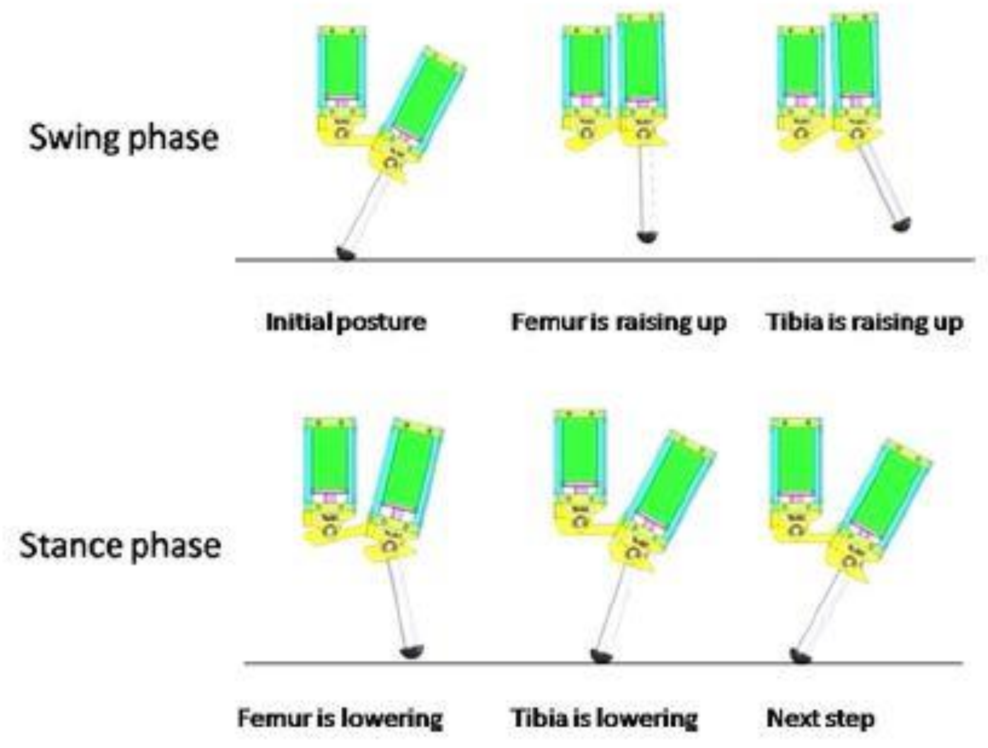


*Figure 16. Walking motion of the quadruped robot [6]*

**Circular** shaped DEAs have been also used in the industry for several applications. One example of this configuration is the mechanism developed by Luc Maffli *et al* [7]. They used a round actuator to modify the radius of curvature of a lens, allowing it to focus at varying distances.

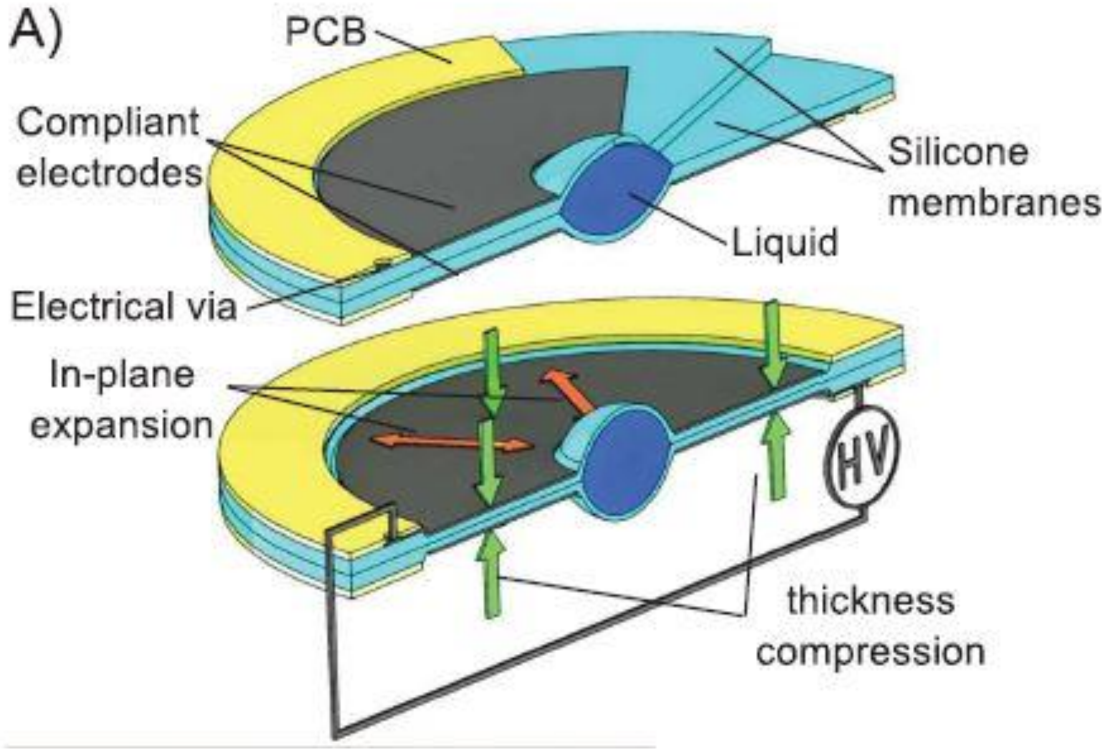


*Figure 17. Tunable lens operating principle [7]*

The diameter of the optical lens at the center is 5 mm, and the outer diameter of the annular electrode is 19 mm. When a voltage is applied between the electrodes, their in-plane expansion compresses the lens. Because the volume of the encapsulated liquid remains constant, this causes a decrease of the radius of curvature of the lens, and hence a decrease of its focal length.

The tunable lens is placed in front of a 5-megapixel CCD sensor with no other optical elements, and used to picture objects at different distances. At the top of the figure, it is shown a schematic representation of the setup, with a 10 × 3 mm EPFL logo positioned at a distance of 120 mm from the lens, as well as trees and buildings approximately 70 m away. At the bottom, the resulting images captured by the sensor for 2 different driving voltages (2.8 kV, and 0V), showing the focal plane can be placed on the logo and the background [7]. The experiments exhibited a settling time for the focal variation shorter than 175 μs.

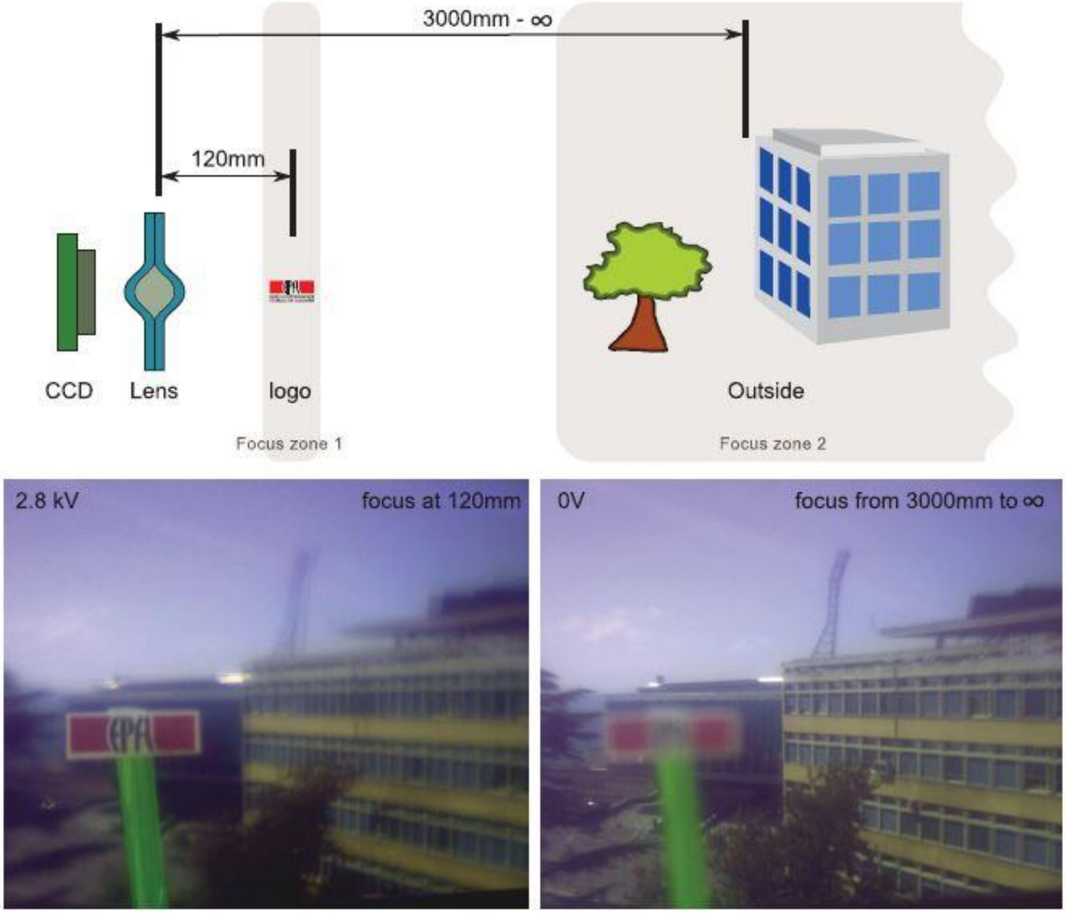


*Figure 18. Schematic and results of the lens [7]*

Another example of the versatility of these robots is the use of **cylindrical** shapes that pursue different applications. For instance, the soft robot implemented by Qibing Pei *et al* [8], uses cylindrical actuators as legs that bend in different directions to reach multiple degrees of freedom. Therefore, the robot can walk in every direction. The following figure shows the maximum achievable movement of each leg of the robot.

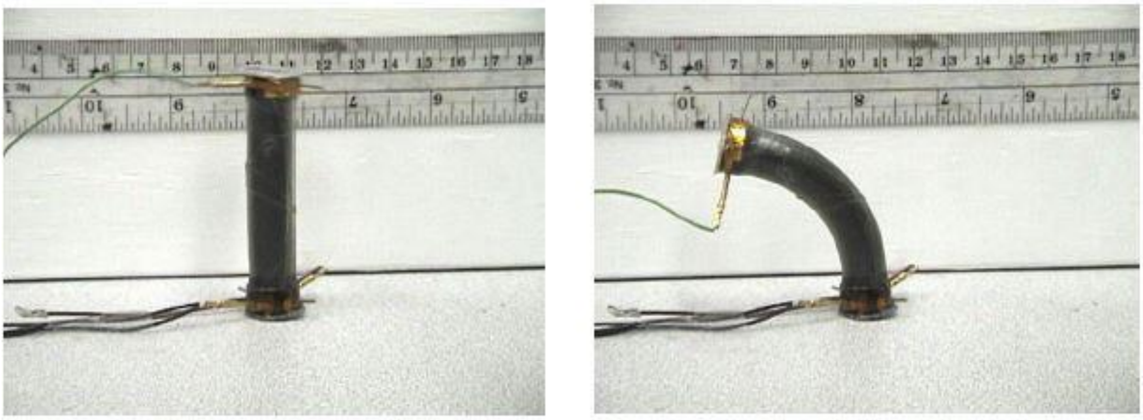


*Figure 19. Cylindrical actuator bending [8]*

These cylinders are manufactured by winding several concentric actuator layers around each other. Thanks to this, the cylinder can be provided with different polarities, depending on which parts are provided with the difference in potential. This picture illustrates the processing of each cylinder inside:

*Figure 20. Cylindrical soft configuration inside [8]*

The six legged robot designed by Qibing Pei *et al* [8], was based on this two-degrees-of-freedom legs to implement a soft system that could walk in every direction when the voltage was applied properly to the different legs of the system.

Their design was very original and stable, allowing the transportation of lightweight material on top of it, thanks to its flat surface on top.

*Figure 21. Six-2-DOF-legged soft robot [8]*

## 3.2 APPLICATIONS

In addition to the variety of configurations that can be implemented, the versatility of soft robots is shown by the multitude of application fields they have. Their properties such as light weight, mobility, and rapid response, provide them with abilities that make them suitable for applications in land, air, and water environments, as well as in the field of humanoid robots.

An example of **terrestrial** application is the robot developed by Guoying Gu *et al* [9], which used electro adhesion feet and DEAs to implement a soft robot with the ability to climb vertical walls.

This robot uses bending actuators for the body, with a sophisticated system of electro adhesive feet that allows it not only to move, but also to move along vertical walls made of certain materials such as wood, paper and glass. In the following figure we can see the schematic of the robot.

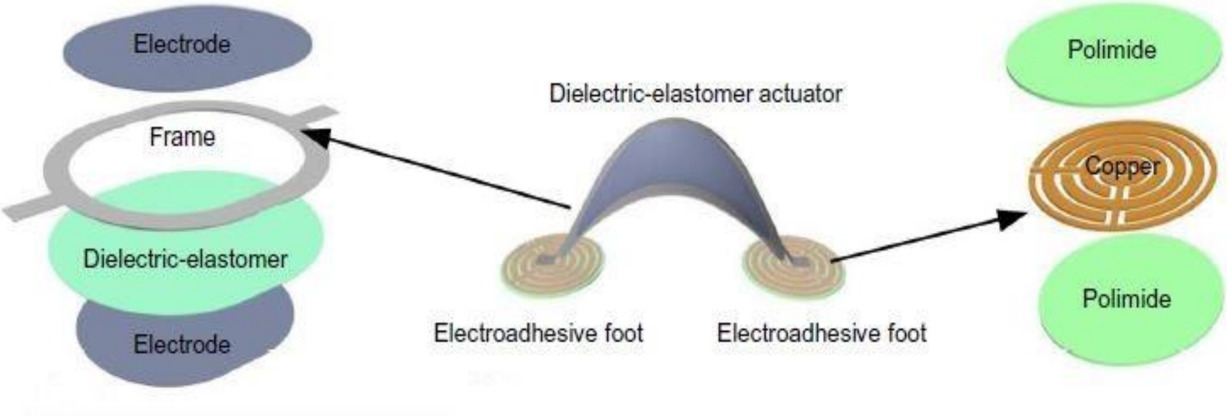


*Figure 22. Soft wall-climbing robot's structure [9]*

The bending actuator allows the robot to change the curvature of the body, increasing the distance between its feet when voltage is applied. On the other hand, the electro adhesive feet create a force of attraction between the feet and the floor or wall, that fixes the foot in a certain point when voltage is applied.

The way this robot works is very simple but original. For the robot to move forward, the back foot is fixed to the floor, and then voltage is applied to the body to expand, separating the feet. Right after that, the front foot is fixed, and the voltage is released from the body and the back foot, pushing it forward. This process would be repeated for the robot to walk.

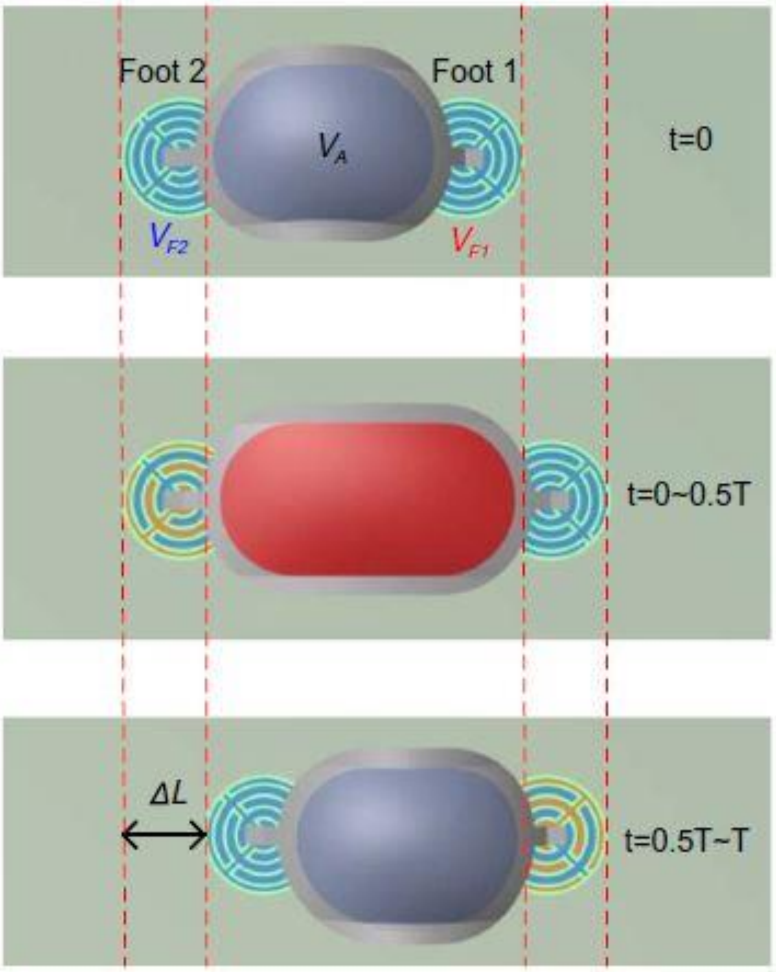


*Figure 23. Soft wall-climbing robot's operating principle [9]*

Here is a sequence of the robot walking, where we can see that it not only works and follows a straight line, but also it works fast, reaching a maximum pace of 88.46 mm/s on the wood plane, equivalent to1.04 body lengths per second.

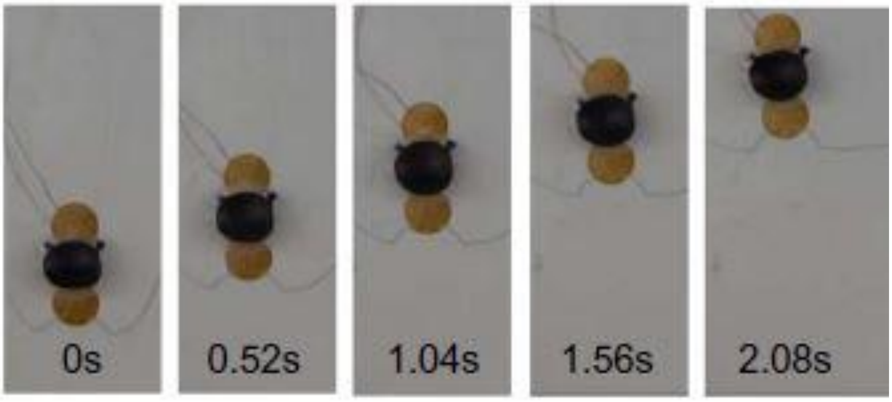


*Figure 24. Wall climbing motion with no weight [9]*

Now, another sequence of the robot climbing is presented, but this time it was carrying a weight of 10g. The system experimented an obvious reduction in the speed, but it completed the task successfully.

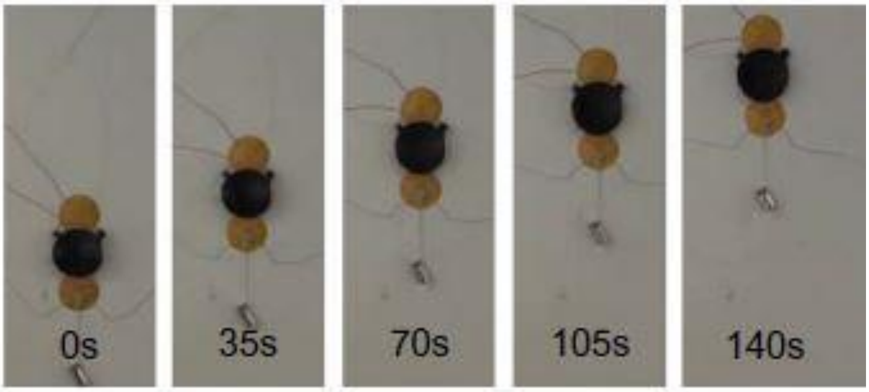


*Figure 25. Wall climbing motion carrying 10g [9]*

Finally, Guoying Gu *et al* included in the system a way of turning. It consisted of duplicating the structure, both the body and feet, and sticking them together in parallel. Thus, to turn, they could fix the feet 1 and 3 or 2 and 4. The next image illustrates this.

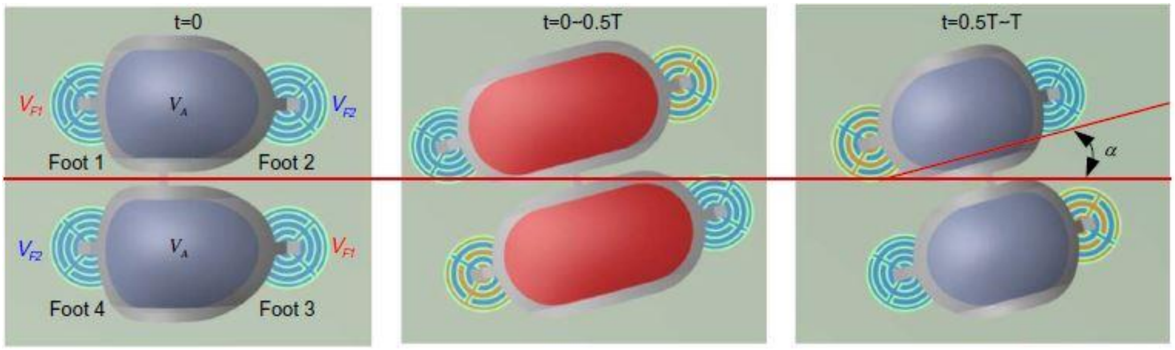


*Figure 26. Climbing robot rotation principle [9]*

This robot is a very good example of the wide range of terrestrial applications that this technology can develop in the future. In the experiments, it was successfully used to climb a vertical tunnel with a small camera attached, to record what was inside the tube. It also crawled through a very low corridor, and finished a labyrinth with difficult turns in a very surprising time. However, surely there are still many interesting applications to be discovered for this soft robot and others like it. The following is a photo of the result of the last experiment, in which it comes out of a maze.

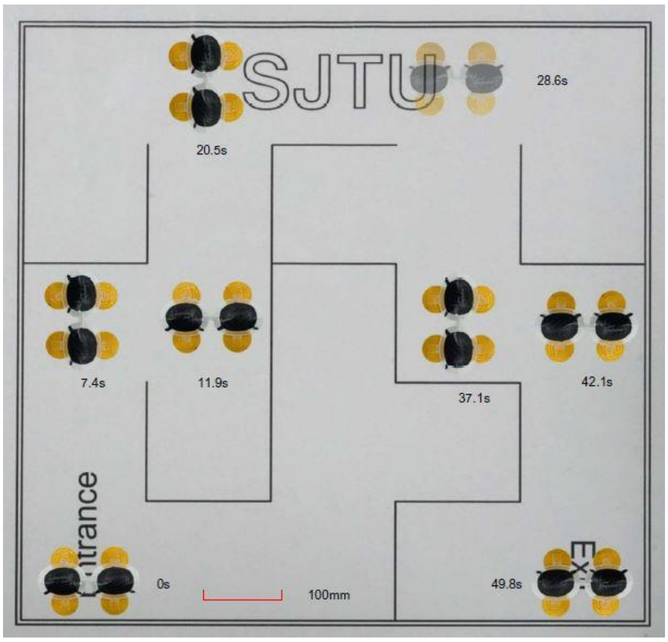


*Figure 27. Soft robot exiting a maze [9]*

Even though the most part of soft robots presented yet by researchers have terrestrial applications, the lightweight and their muscle-like movements made this technology suitable also for **underwater** situations. In particular, DEAs have a density similar to that of water, and they are naturally transparent.

The main problem this can present is, of course, that water and high voltage are not usually good friends. However, with the existing technology for electricity isolation, we are more than capable of designing units unaffected by the polarity of water.

A good example of the integration of soft robotics for aquatic environments is the frog inspired swimming robot designed and implemented by Yucheng Tang *et al* [10]. This robot has a body where all the electronics are safely hidden, and a total of four actuators, two for each leg.

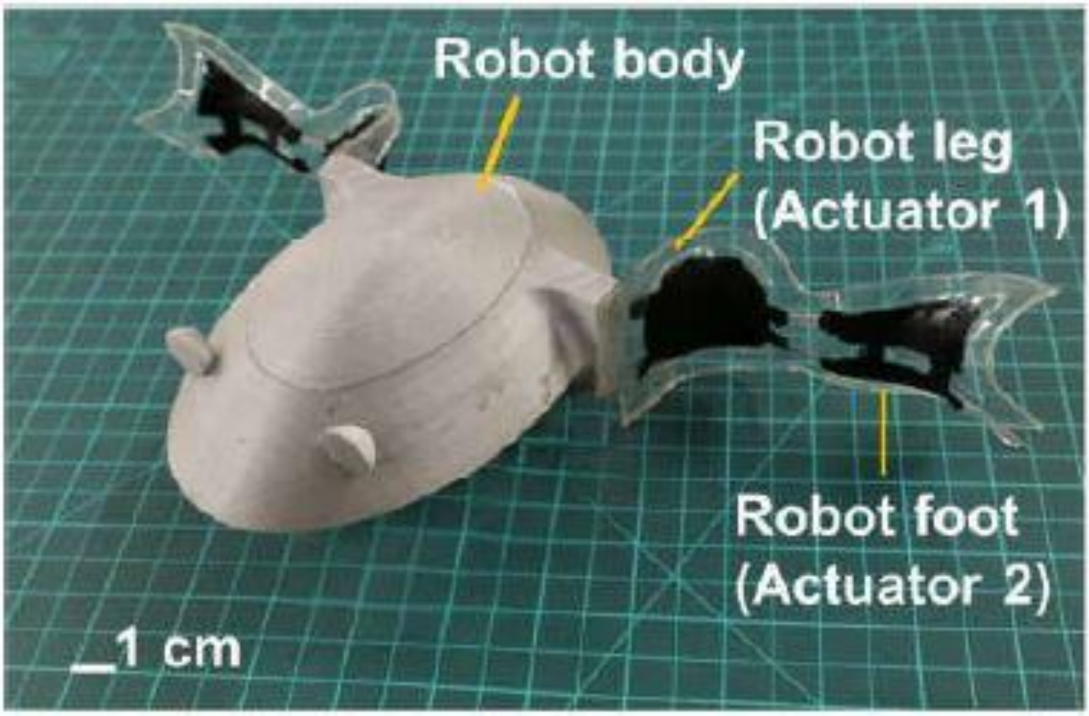


*Figure 28. Frog inspired soft robot [10]*

Upon application of voltage, the leg actuators achieve rotational movement which pushes water backward to generate propulsive swimming motion. Inspired by the webbed feet of frog, the designed foot actuator is able to increase its projected area more than 60% when subject to high voltage. The next picture shows the manufacturing process of both actuators, pre-stretched together to optimize the result.

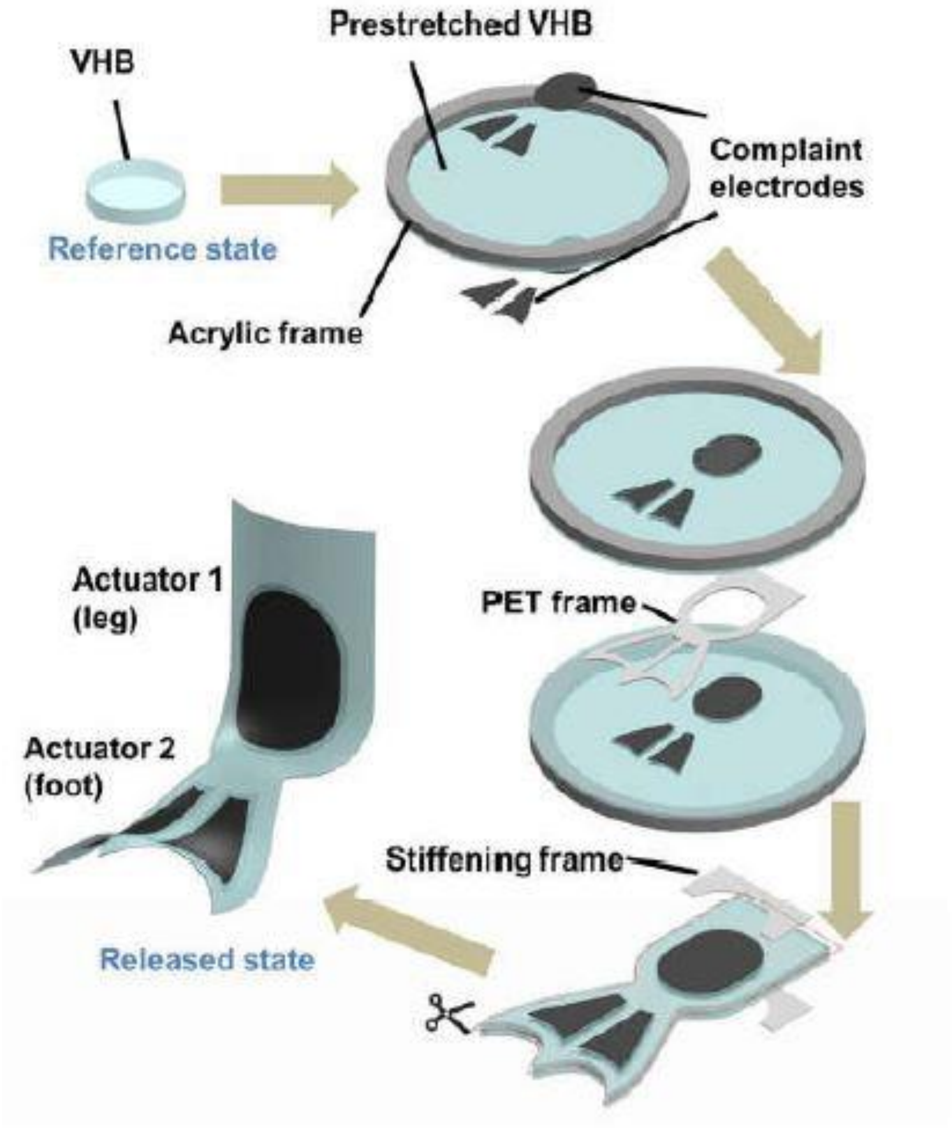


*Figure 29. Frog actuators elaboration [10]*

Subject to square wave voltage, the frog inspired robot based on dielectric elastomer actuators can achieve effective swimming in water. Analogous to the swimming cycle of a common frog, the propulsion of the robot is also composed of three phases: propulsion, gliding, and recovery phase.

In the propulsion phase, a high voltage is applied simultaneously to both leg and foot actuators. The leg actuator rotates to push the water back, while the foot actuator expands its projected area to maximize the thrust force generated by the leg rotation movement.

In the gliding phase, the leg and foot actuators are still energized to maintain their deformation in the propulsion phase. In the recovery phase, the voltage applied to both actuators is removed, causing them to be restored to their initial state. The foot contraction ensures a minimum projected area leading to a minimum braking force.

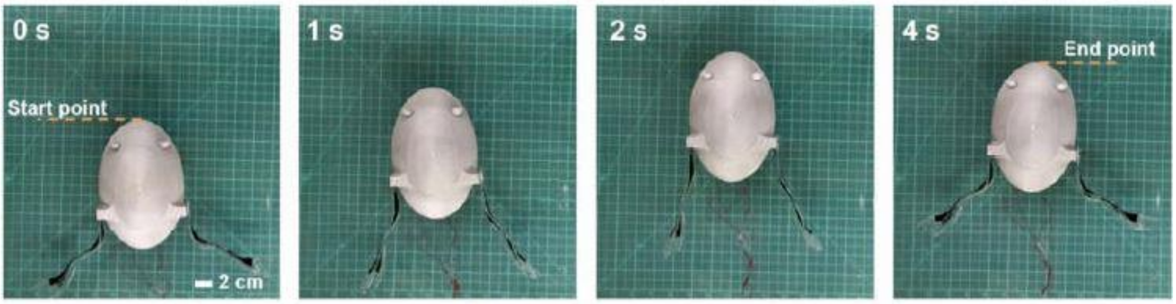


*Figure 30. Soft artificial frog swimming sequence [10]*

The morphing of the projected area in the foot actuator makes the thrust generated in the propulsion phase larger than the drag generated in the recovery phase, which is validated experimentally by measuring the thrust using a force sensor. As you can see in the picture, the robot moves forward with an average speed of 19 mm/s.

Another field of application being explored nowadays is the **aerial environment**. Advances in this experimental field would be a great success, as it would be a big step for soft robotics' science. The main objective would be to imitate the flight of animals, which would bring many practical and scientific advantages.

This is a particularly difficult challenge, because in order to maintain flight, the structure must not only function, but it must do so very quickly and at an appropriate frequency. Because of the magnitude of the challenge involved, research is at a much less advanced level than in other fields of application.

Autonomous air propulsion using only AEDs has not been achieved so far. However, it has been possible to control the flight and trajectory of lightweight flying elements.

An example of this research in the development of air applications is the soft mechanism developed by Jianwen Zhao *et al* [11], a bird inspired soft robot designed to mimic the flying motion of these animals. This picture illustrates the full implementation of the light structure.

*Figure 31. Bird inspired soft robot [11]*

The prototype consists of a rotatory joint used as a flapping wing, formed by three curved actuators. Applying high voltage to the three actuators in different combinations allows the system to reproduce several positions similar to those observed in birds. To imitate the natural flight of animals, the researchers tried to represent the four poses shown below with their soft artificial bird.

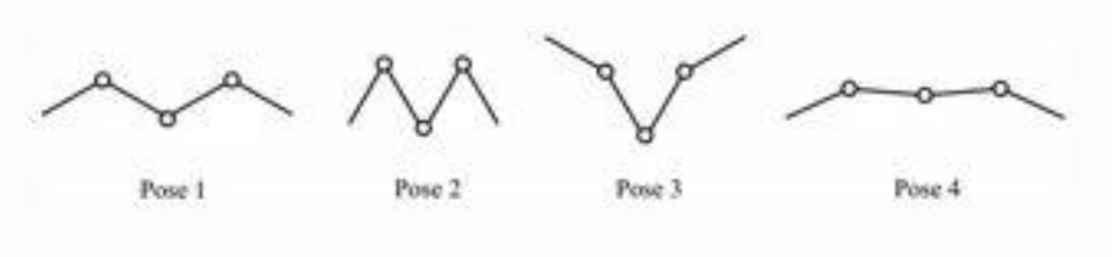


*Figure 32. Flying motion of the soft bird [11]*

Even though the prototype still cannot fly by itself, it shows promising results for future development of the structure, in terms of high energy density and strength. The following image shows the deformation experimented along the axis depending on the joint torque.

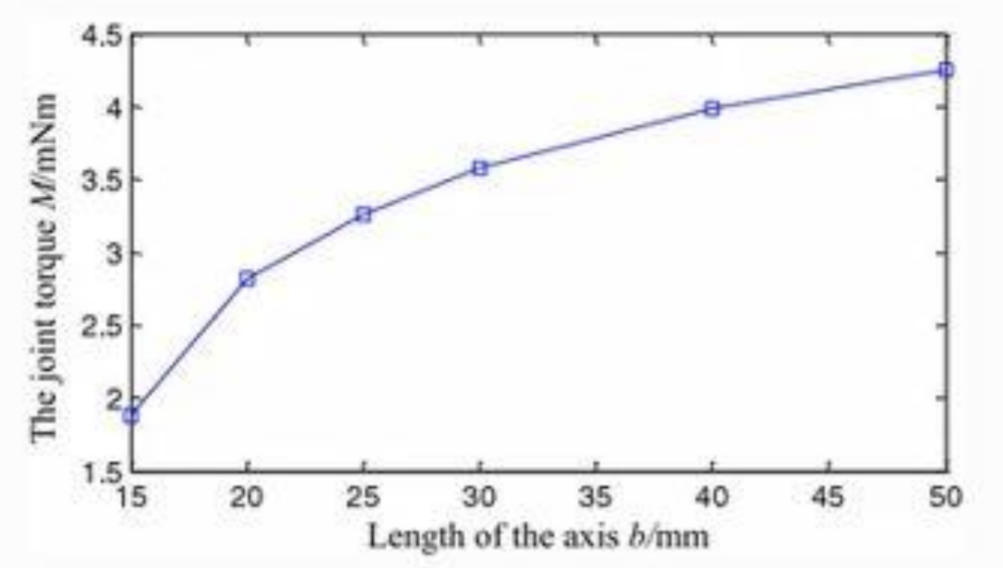


*Figure 33. Axial deformation when torque applied [11]*

Finally, the last big group for this technology to be applied would be the development of **humanoid robots**. This field has become a booming field of research recently, due to their extensive applications to nursing, reception, child tutoring and old people serving, says Ujjaval Gupta *et al* [2].

The reason why soft robotics plays an important role in humanoid robots is because of their capability to imitate facial expressions or other complex movements such as those of the fingers.

DEAs are one of the most promising actuation technologies to mimic human muscles in terms of appearance, response time, and actuation strain. An example of the use of dielectric elastomers in this field is the soft structure created by Lu Li *et al* [12], which proposes the use of three rolling DEAs to create a Two-Degrees-of-Freedom movement to mimic the human eyeball. Here is a picture of the structure implemented for each artificial humanoid eyeball.

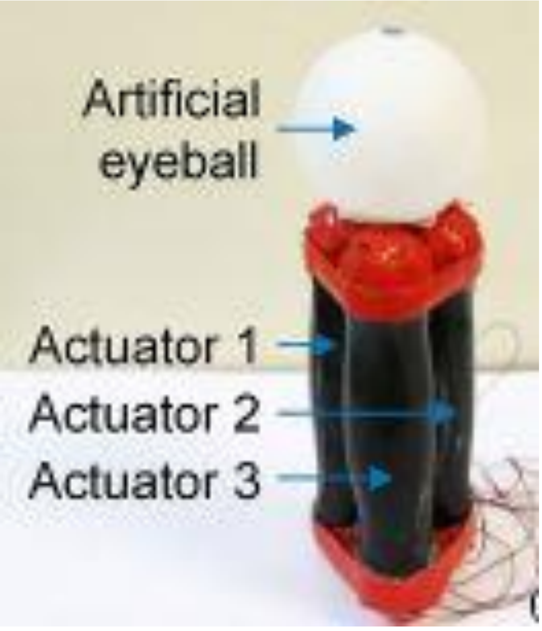


*Figure 34. Artificial soft eyeball structure [12]*

Each rolling actuator is manufactured by rolling a spring inside the pre-stretched actuator, with the compliant electrodes already spread on. The following image illustrates the process, as well as the effect of the voltage.

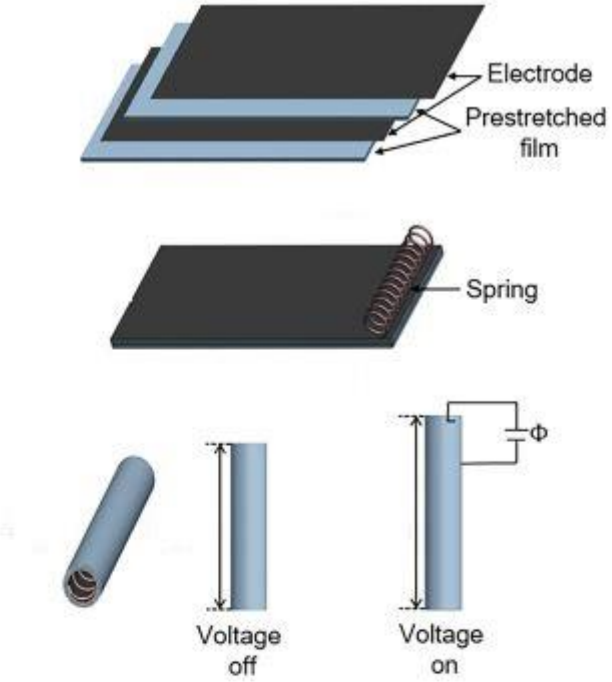


*Figure 35. Soft robotic eyeball manufacture process [12]*

As we have seen above, upon application of high voltage, each actuator can increase in height. The motion of the eyeball is reached applying different voltages to each actuator, so the full structure bends to one direction. The following image shows, with only two actuators, the effect of applying voltage to only one of them.

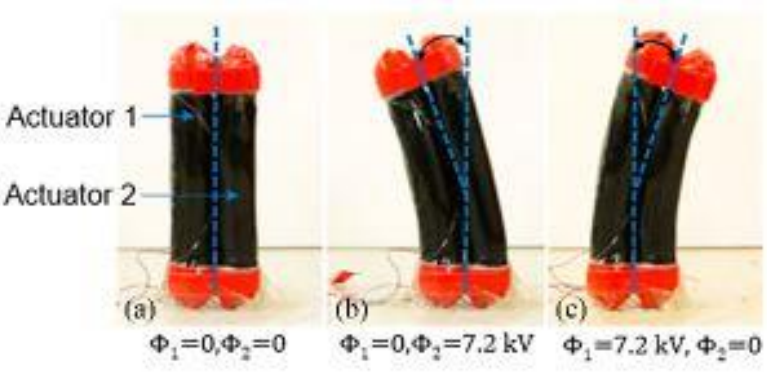


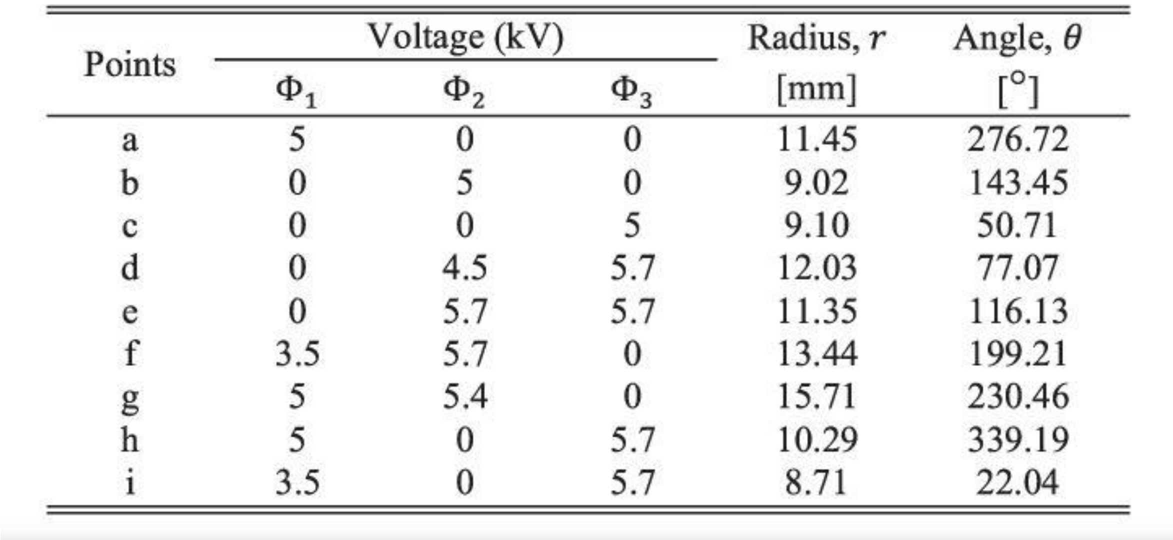
*Figure 36. Eyeball's operating principle [12]*

When using three actuators instead of two, the complete eyeball motion is achieved, obtaining full rotation of the eye. The position is measured as an angular rotation (in degrees), with respect to the horizontal line that marks 0º in the initial position (without voltage) of the eyeball, and as a radius (in mm), also with respect to the centre of the voltage-off position.

The first picture below shows graphically the position and the angle of the eyeball when 5 kV are applied to each actuator independently, with respect to the initial position. The second picture shows numerically the angle and the distance from the initial state of the eyeball when applying different combinations of voltage to the three actuators.

$\Phi_1 = 5\text{kV}$, $\Phi_2 = \Phi_3 = 0$ | $\Phi_2 = 5\text{kV}$, $\Phi_1 = \Phi_3 = 0$ | $\Phi_3 = 5\text{kV}$, $\Phi_1 = \Phi_2 = 0$

*Figure 37. Soft eyeball's movement sequence [12]*



| Points | Voltage (kV) | | | Radius, $r$ | Angle, $\theta$ |
|---|---|---|---|---|---|
| | $\Phi_1$ | $\Phi_2$ | $\Phi_3$ | [mm] | [°] |
| a | 5 | 0 | 0 | 11.45 | 276.72 |
| b | 0 | 5 | 0 | 9.02 | 143.45 |
| c | 0 | 0 | 5 | 9.10 | 50.71 |
| d | 0 | 4.5 | 5.7 | 12.03 | 77.07 |
| e | 0 | 5.7 | 5.7 | 11.35 | 116.13 |
| f | 3.5 | 5.7 | 0 | 13.44 | 199.21 |
| g | 5 | 5.4 | 0 | 15.71 | 230.46 |
| h | 5 | 0 | 5.7 | 10.29 | 339.19 |
| i | 3.5 | 0 | 5.7 | 8.71 | 22.04 |

*Figure 38. Results obtained when different voltages applied [12]*

The following image is a screenshot of the experimental results obtained by Li Lu *et al*, showing: (a) the movement (in mm) of each eyeball, (b) the voltage applied to each of the three actuators, (c) the error (also in mm) of each eyeball compared to the aimed movement, and (d) pictures of the real implemented system on each situation.

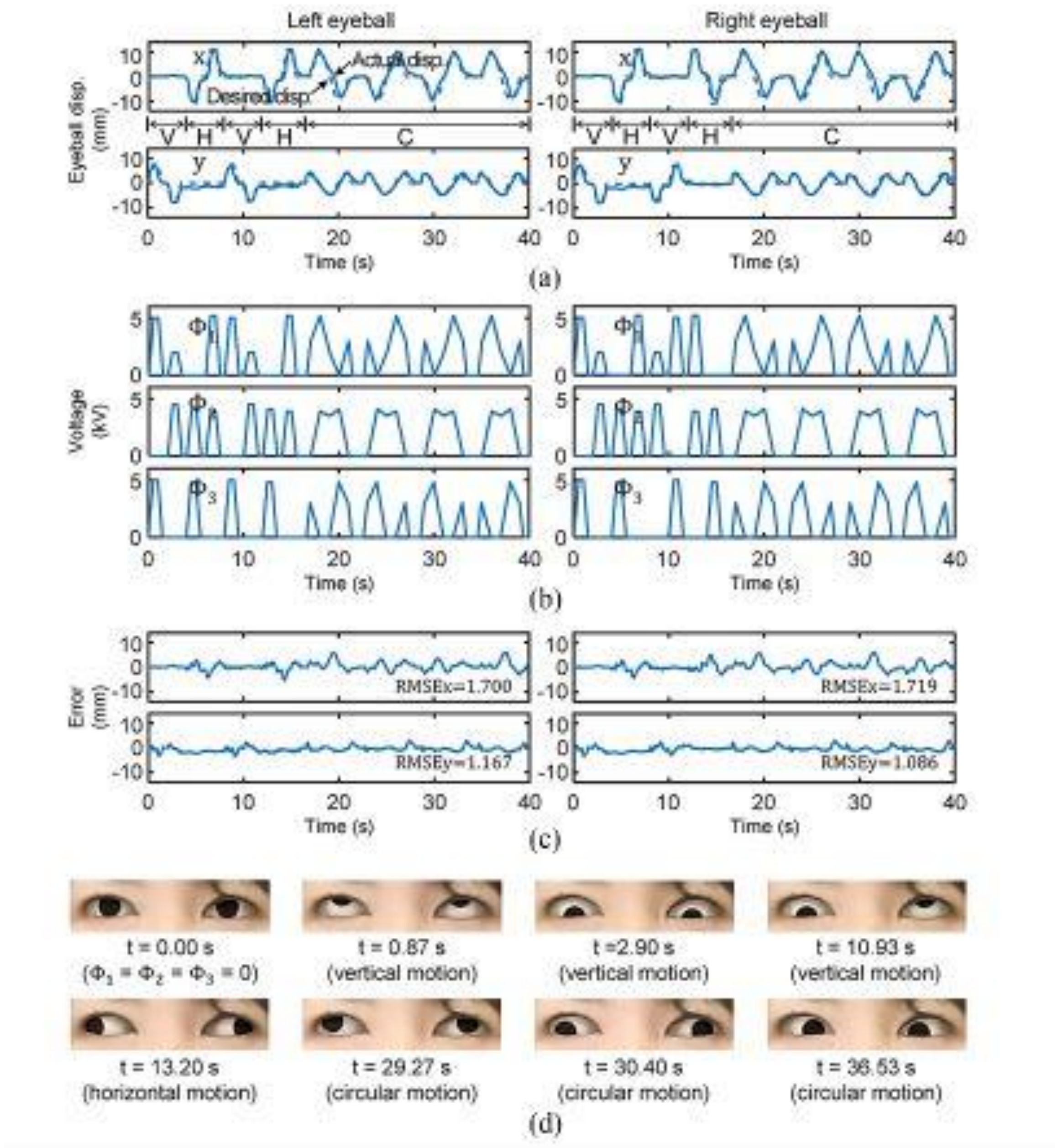


*Figure 39. Illustration of eyeballs working [12]*

# 4 PROJECT STATEMENT

## 4.1 OBJECTIVES

This project pursuits three main goals. The first one is to understand soft robotics more in depth, the progress made around this technology in the last years, and the potential they can develop in the following years.

Secondly, once the possibilities offered by these soft systems have been better understood, a series of prototypes will be conceived, in the creative part of the project. They will be presented, developing the operating principle, shape, and the possible practical applications of the robot.

Afterwards, the model considered to have the greatest potential will be selected, the prototype will be manufactured, and experiments will be carried out. Finally, the design will be developed and improved as much as possible to obtain more satisfactory results. This will be the third goal.

Finally, the possible environmental impact of the robots and their applications will be addressed. We will try to keep the project as aligned as possible with the Sustainable Development Goals from the United Nations.

The rationale for the final prototype is now developed, along with its background and an explanation of the need to which it responds.

## 4.2 RATIONALE

In recent years, there have been great improvements in the field of electromedicine. Nowadays, there are very sophisticated devices, which arise from the need to face diseases that require complex treatments.

An example of these advances are the machines that dose therapeutic gases into the respiratory flow of patients. In order to dose the exact amount, the device must take into account not only what phase of treatment the patient is in, but also what flow he is breathing, for which they have precise sensors.

The product proposed in this work is an electrically activated flow meter, which instantly modifies the air flow when it receives an external stimulus in the form of high voltage. This would a further step in the development of this equipment, since at present, manual external flow meters are required to regulate the flow in a determined range. With our soft mechanism incorporated, the machine would be even more autonomous.

The application of this flowmeter is particularized in the electromedical equipment called NOXtec, from the Spanish company Ingeniería y Técnicas Clínicas, S.A. This device doses a therapeutic gas, Nitric Oxide, in the respiratory flow of patients, most of them suffering from pulmonary arterial hypertension. More about this machine can be read in Annex I, at the end of this document.

The equipment has hot wire and differential pressure sensors, as well as complex electronic and mechanical modules for the control of gas doses. It also measures and minimizes the concentration of nitrogen dioxide, a highly toxic gas that can endanger the patient if not controlled.

With the incorporation of our system, the machine would be much more precise, since in addition to measuring the flow rate, it could regulate it itself with the built-in flow regulator. This would allow it to better calculate and provide doses of medicinal gases.

## 4.3 METHODOLOGY

Prior to starting to handle the material, a tough research on the technology has been carried out to know the possibilities offered by the soft robots, the different types of actuators, how they work and the advantages and limitations of each. This research process was followed by some demonstration and experiment in the laboratory, to visualize what was learned theoretically, and to observe empirically the real behavior of these materials.

For the development of the prototypes, a few digital design tools were used. With it, several designs will be made, drawing the structures in two or three dimensions to clarify the operation and the application thought for each mechanism. The main tools used to design and present the ideas were SolidWorks, Paint, PowerPoint, and Paint 3D.

After presenting the first models, they were manufactured for try and error tests, to check their functioning and potential. Then, one of them was selected to keep working on it and develop the best version of the robot.

In the manufacturing stage, we used the 3D printing technology called Fused Deposition Modeling (FDM), using as material Acrylonitrile Butadiene Styrene (ABS) to print the harder structure where the actuator will be placed and stretched. This is a very critical part of the process, since the structure must be light but strong, for a proper functioning of the robot.

As we have seen, the actuator is composed by a dielectric elastomer layer and two electrodes. For the dielectric elastomer, we chose VHB 4910 from 3M, and the stretchable electrodes will be made of carbon grease (846-80G, MG Chemical).

Finally, to control the external stimuli applied to the robot, the Glassman FX20P15 will be used. It allows working with ranges up to 20kV and 300W. Typically, the materials selected for the actuators cannot withstand more than 8kV before the dielectric breakdown is reached, so the machine was suitable for our experiments.

## 4.4 ECONOMIC PLAN

Given the experimental nature of the project and the lack of commercial solutions in the field of soft robotics, an economic analysis does not apply in this document.

# 5 SYSTEM DEVELOPMENT

As mentioned above, the development of the soft robot consists of three steps: the elaboration of designs, experimentation for choosing the prototype to be developed, and improvement of the final prototype implemented.

## 5.1 DESIGNS

This is the first step in the creation process of a device. In this section, the designer's creativity is developed and the knowledge acquired in the research process is put to use. This section details the first ideas conceived, detailing the configuration of the actuator and its structure, as well as the proposed application for each of them.

The first model presented was a wheel with a variable diameter. The design consists of a fixed circular frame, made of a hard plastic, on which a pre-stretched dielectric is fixed. The electrodes are placed on both sides of this tensioned dielectric. To do this, a mold is placed with the shape to be given and the paste that makes up the electrodes, i.e. carbon grease, is spread.

Once the actuator is ready, a series of legs are placed at the edge of the electrode so that they move in the radial direction. When the voltage is applied, the dielectric expands in the radial direction due to the Maxwell pressure generated, causing the legs to protrude from the initial diameter. It is these legs that make up the moving diameter. That is to say, under the high voltage action, the legs of the wheel would become the new support points, turning it into a discontinuous wheel.

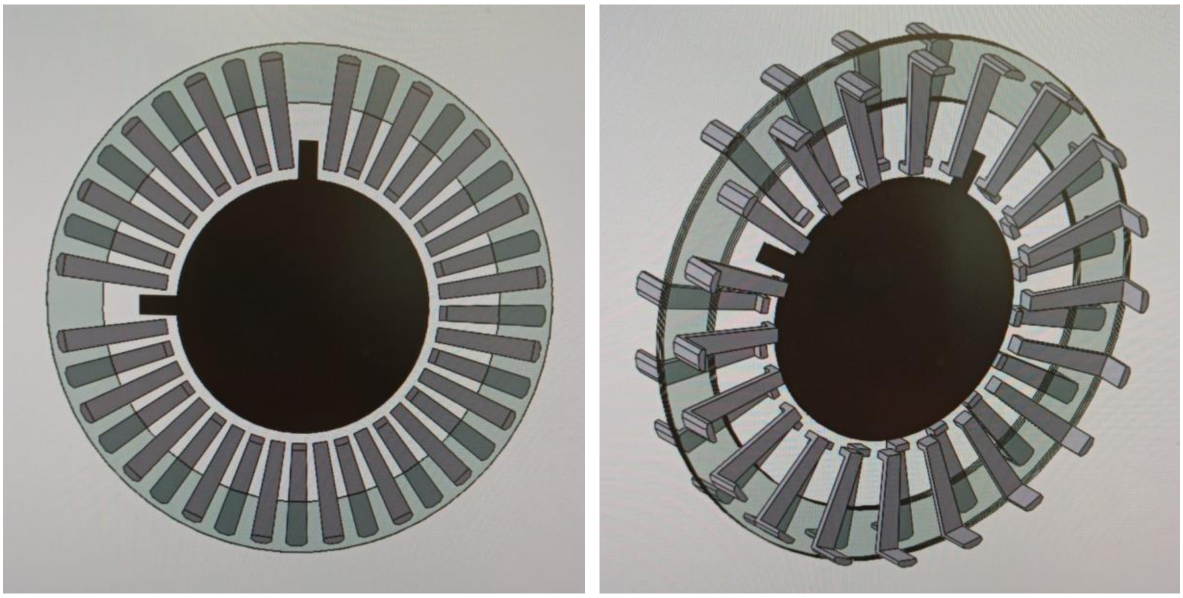


*Figure 40. Front and isometric views of the soft discontinuous wheel*

The possible applications that have been found for this mechanism are mainly two. In either case, this prototype is designed to complement another larger system, not to have autonomy and utility of its own. Firstly, it can be used as part of a soft vehicle to provide it with the ability to turn. Thus, a two-wheeled vehicle can turn right or left if one of its wheels is larger than the other, functioning as a cone trunk that is pushed forward.

The second possibility is to use it as part of a gear system. The way to implement it would be to use it as a variable diameter gear to achieve different speeds. This would not be practical at the moment, since soft robots today are very light mechanisms with not much force, which would not fit well in a modern vehicle. However, in the future this application could be considered for a soft robot whose weight is very light and the system presented would not have to support such high loads.

The next idea was to develop a nozzle-shaped flowmeter to regulate the airflow through it. The mechanism is based on the fact that the flow rate through a pipe can be calculated by multiplying the velocity it carries by the cross-sectional area of the pipe. In this way, if the flow velocity is maintained by controlling the pressures, and the flow area is increased, the total flow rate increases:

$$Q = v * A$$

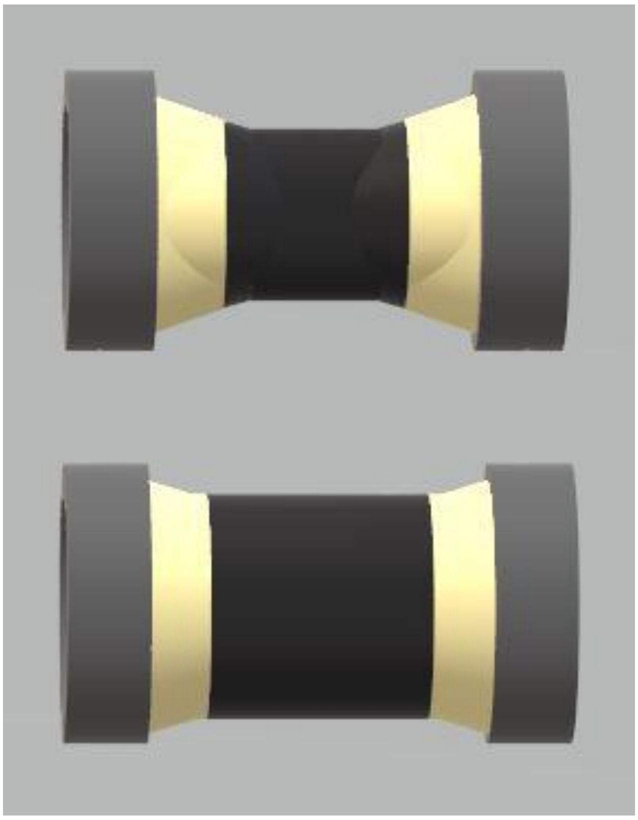


*Figure 41. Cylindrical Flow meter operating principle*

The figure shows, at the top, the relaxed system in its natural situation. As can be seen, the area of passage is much smaller in the center than at the ends. On the other hand, when the voltage is applied, as shown in the figure below, the elastomer expands and tightens, increasing in surface and cross-sectional area.

Originally, the construction of this system was designed to be carried out by joining two half-cylinders. The model was designed using the SolidWorks tool, which generates a .SLDPRT file, which is then transformed into a format compatible with the 3D printer software.

The illustration below shows one of the two structural parts on which the two actuators would be placed, each forming a semi-cylinder, which together would form the complete nozzle-shaped flow meter. The parts are printed, as specified in point 2.2 of this document, by Fused Deposition Modeling, extruding ABS plastic.

*Figure 42. Half of the 3D printed frame for the cylindrical flow meter*

As can be seen in the figure above, the design is symmetrical, in order to facilitate the 3D printing of both parts, and their subsequent joining. When the two parts are joined, both elastomers would overlap manually to form the complete nozzle.

The following image shows the structure that results from joining the two equal halves, in each of which the actuators would be placed, with the elastomer stretched and the electrodes placed. The main advantage of manufacturing it in this way is that it allows to spread the inner electrode easily having already stretched the dielectric.

*Figure 43. Full frame for cylindrical flow meter*

The main application foreseen for this system is medicinal. Its use is proposed for the regulation of a patient's respiratory flow, in order to dose the precise amount of some therapeutic gas required in the patient. The flowmeter could work manually, regulated by the health personnel according to the patient's needs, or as part of a more complex system, equipped with sensors, in which it would act automatically, varying the flow from the measurements of these sensors, which would determine the patient's needs.

Finally, it was proposed to develop the flow meter with a square cross-sectional area, in which the sides and the top would be fixed, and the bottom would be mobile. Two curved actuators, whose operation has been detailed in point 2.4 of this project, would drive the floor of the flow meter up and down, thus modifying the air flow. This is another way of implementing the system explained above, so the application of the mechanism would be the same.

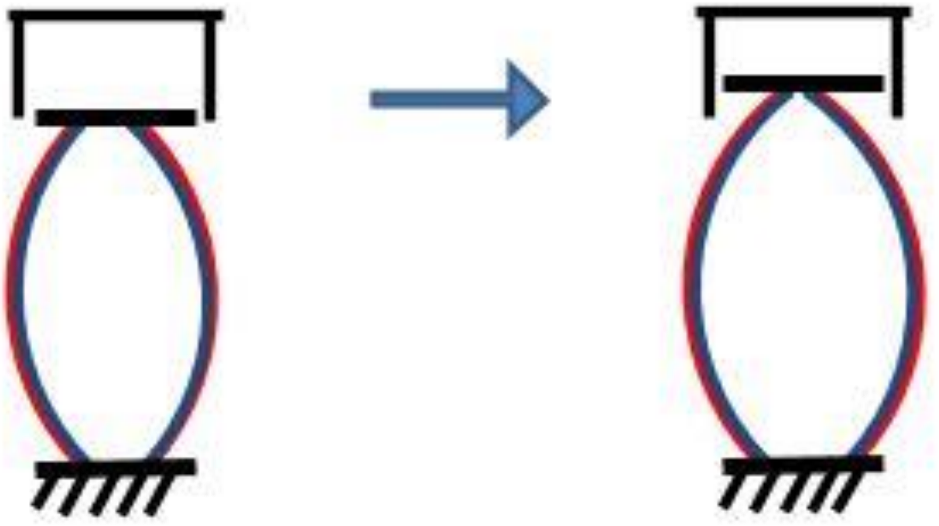


*Figure 44. Rectangular Flow meter operating principle [13]*

## 5.2 PROTOTYPE CHOICE

With the designs presented, simple prototypes were made to test by means of experimentation whether the mechanisms worked, and to get an idea of the potential they have.

The first tests that were carried out were on the first prototype presented, the wheel-shaped structure. Below is a sequence of images illustrating the assembly of the mechanism. First, the dielectric material is stretched and fixed on a hard platform to keep it in tension. Then, the hard-plastic frame is placed on both sides of the elastomer and the excess material is trimmed.

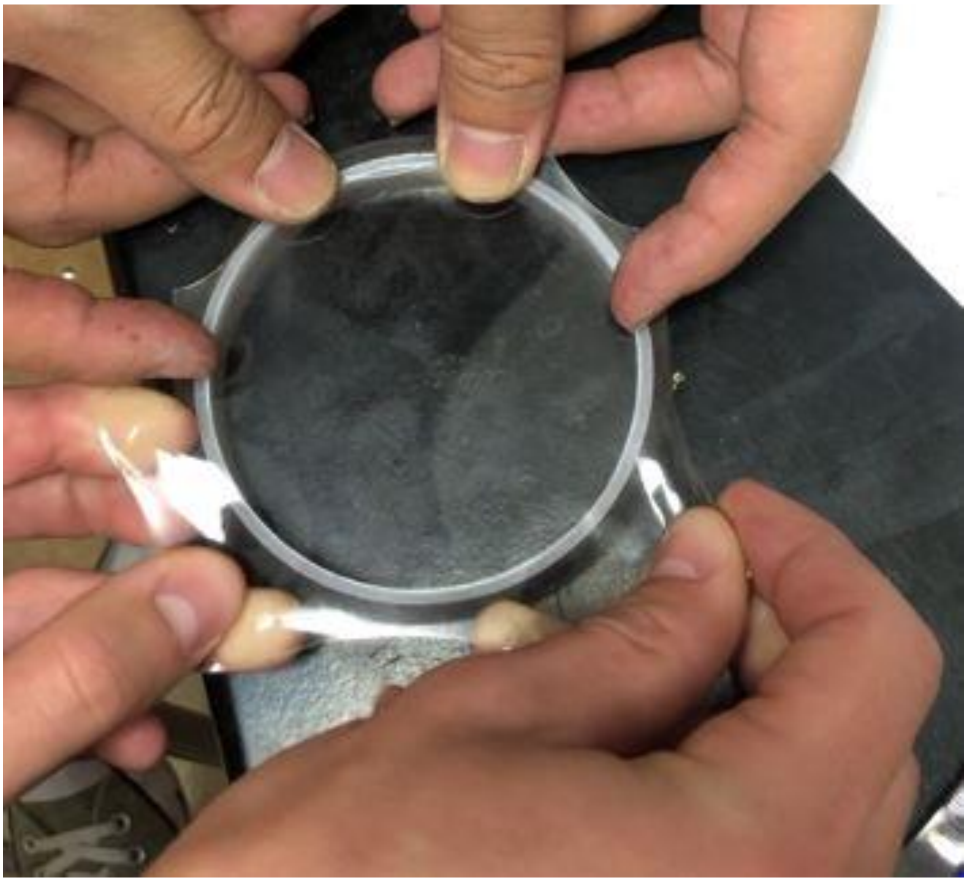


*Figure 45. Material pre-stretch*

After incorporating the hard frames and fixing them with tape, removing the protruding material, the elastomer is fixed and tensioned. As explained in previous points, the electrodes must be able to adapt their shape to the expansion of the elastomer.

For this reason, a paste is used which must be spread on both sides of the dielectric. To give it the precise shape, the next step is to cut a mold with the desired shape and glue it to the AED, as shown below.

*Figure 46. Placement of mold*

Then, the carbon Grease 846-80G is spread inside the mold. This material is the one chosen to form the compliant electrodes, because of its capacity to vary its shape along with the movement of the elastomer.

Afterwards, the process is repeated in the lower part of the elastomer, placing the mold in such a way that the projections where the electric current will be placed do not coincide, so that the negative pole can be differentiated from the positive one.

*Figure 47. Compliant electrodes spreading*

Finally, the legs are placed at the edge of the newly applied electrodes. For an optimal design, the legs should be perfectly placed in the radial direction, keeping a minimum separation between one and another, so that they fit as many as possible, and the structure is as stable as they can be.

The distance of each leg from the electrode should also be the smallest possible, as this will ensure that the legs all advance at the same time. The following image shows the final result of the prototype, on which the tests were carried out.

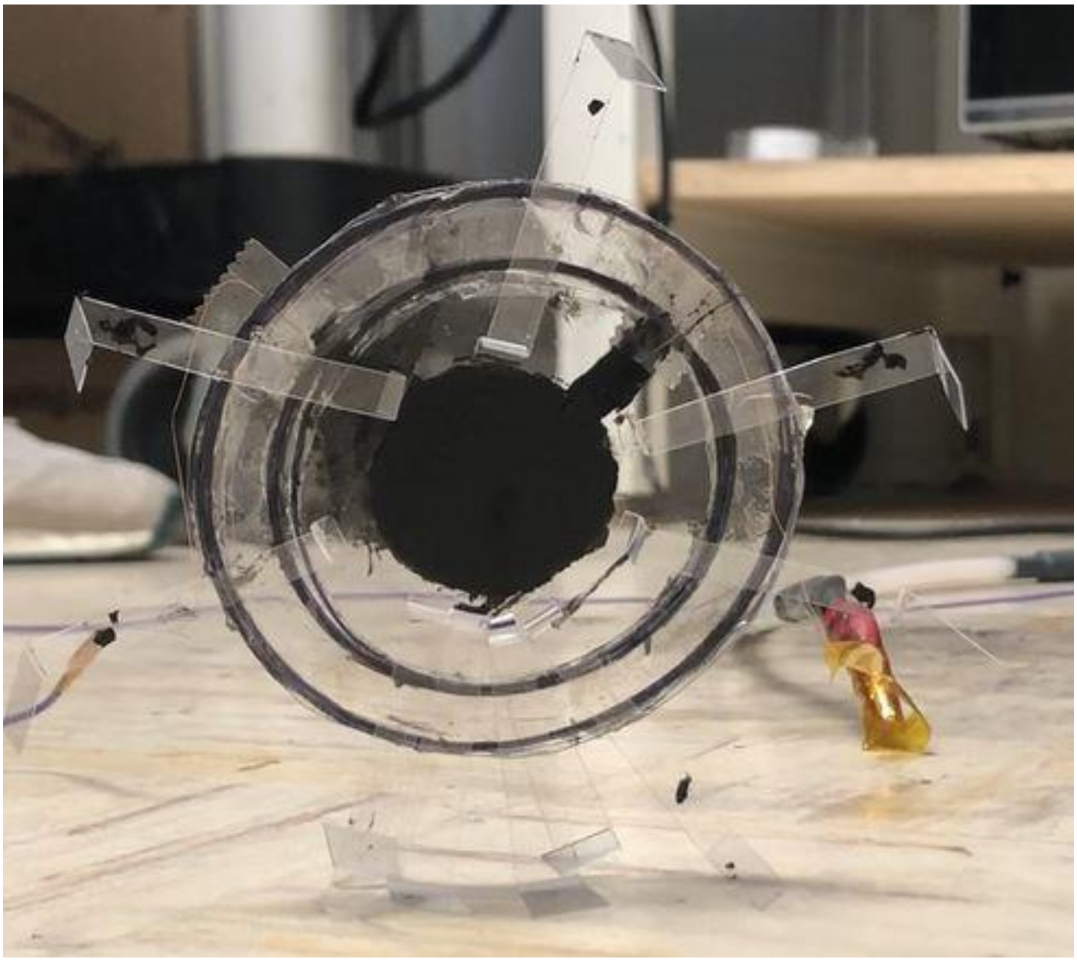


*Figure 48. First prototype tested*

For a first experiment, the thin plastic strips folded into the shape of a leg shown in the image above were used. However, the real prototype was designed with legs that were later manufactured by 3D FDM printing technique using ABS material, and would have the following appearance:

*Figure 49. Wheel leg isometric view*

*Figure 50. Wheel leg side view*

First, experiments were carried out with the wheel in a horizontal position to check its proper functioning. In these experiments it was found that the system was capable of expanding as expected, increasing its diameter by up to 50% over the original, thus moving the legs up to half a centimeter.

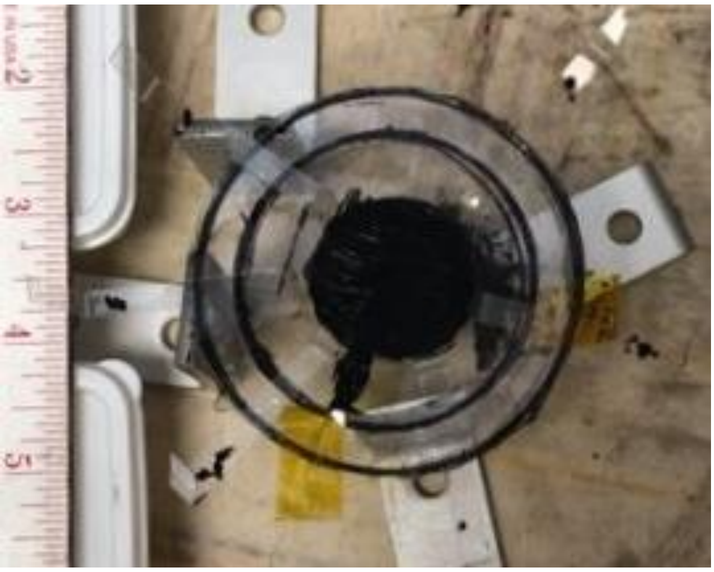


*Figure 51. Horizontal wheel voltage off*

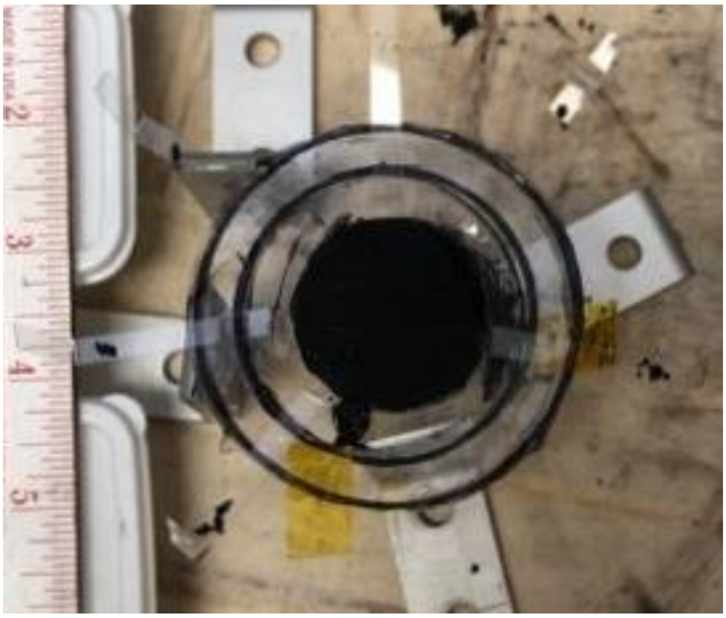


*Figure 52. Horizontal wheel voltage on*

Once it was proven that the mechanism was functioning and that it was moving the legs in the right direction, a new experiment was carried out with the objective of testing the stability of the prototype standing on its legs, in an upright position.

This test was of vital importance, since for the main application proposed, the mechanism had to work properly in this position, which is the one it would adopt if it were the prototype chosen for its in-depth development and eventual implementation.

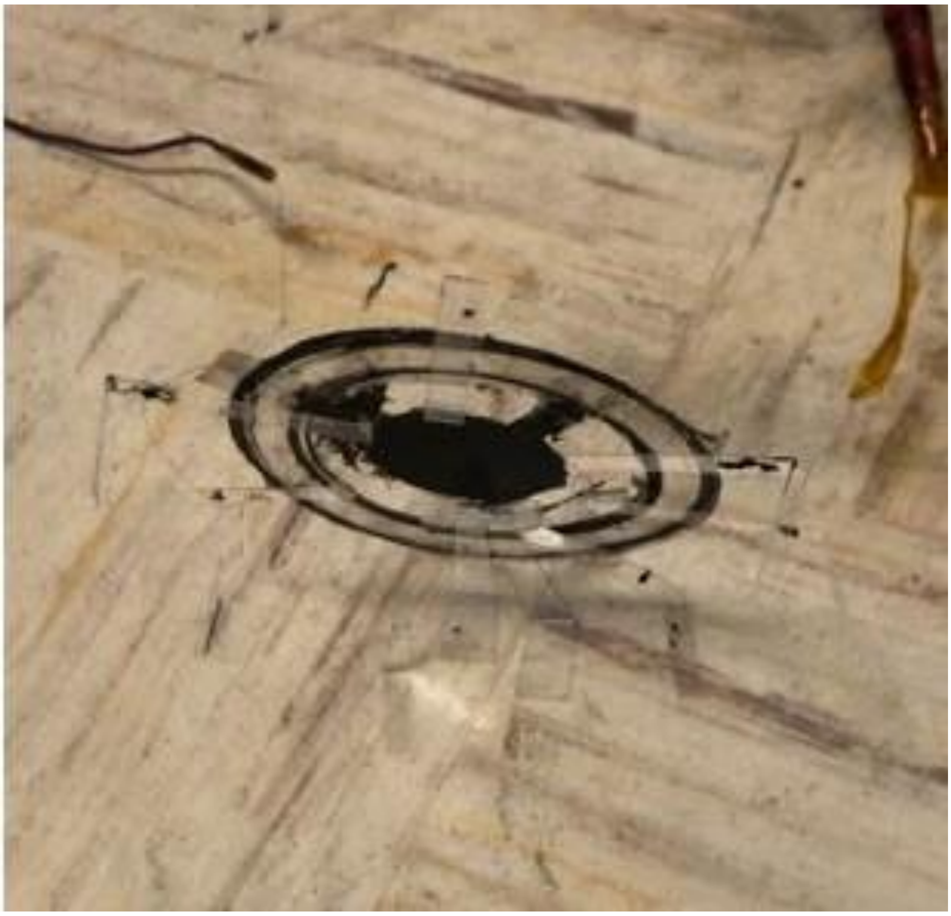


*Figure 53. Isometric view of the standing wheel*

Unfortunately, the legs did not all move the same way, and when the experiment was performed with the wheel resting on the legs, the structure became unsteady and fell. This led to the decision of discarding the prototype, because without stability the soft robot did not work properly. Below is a sequence of images obtained from a laboratory experiment, showing the instability of the system, which when given high voltage collapses and falls to the ground.

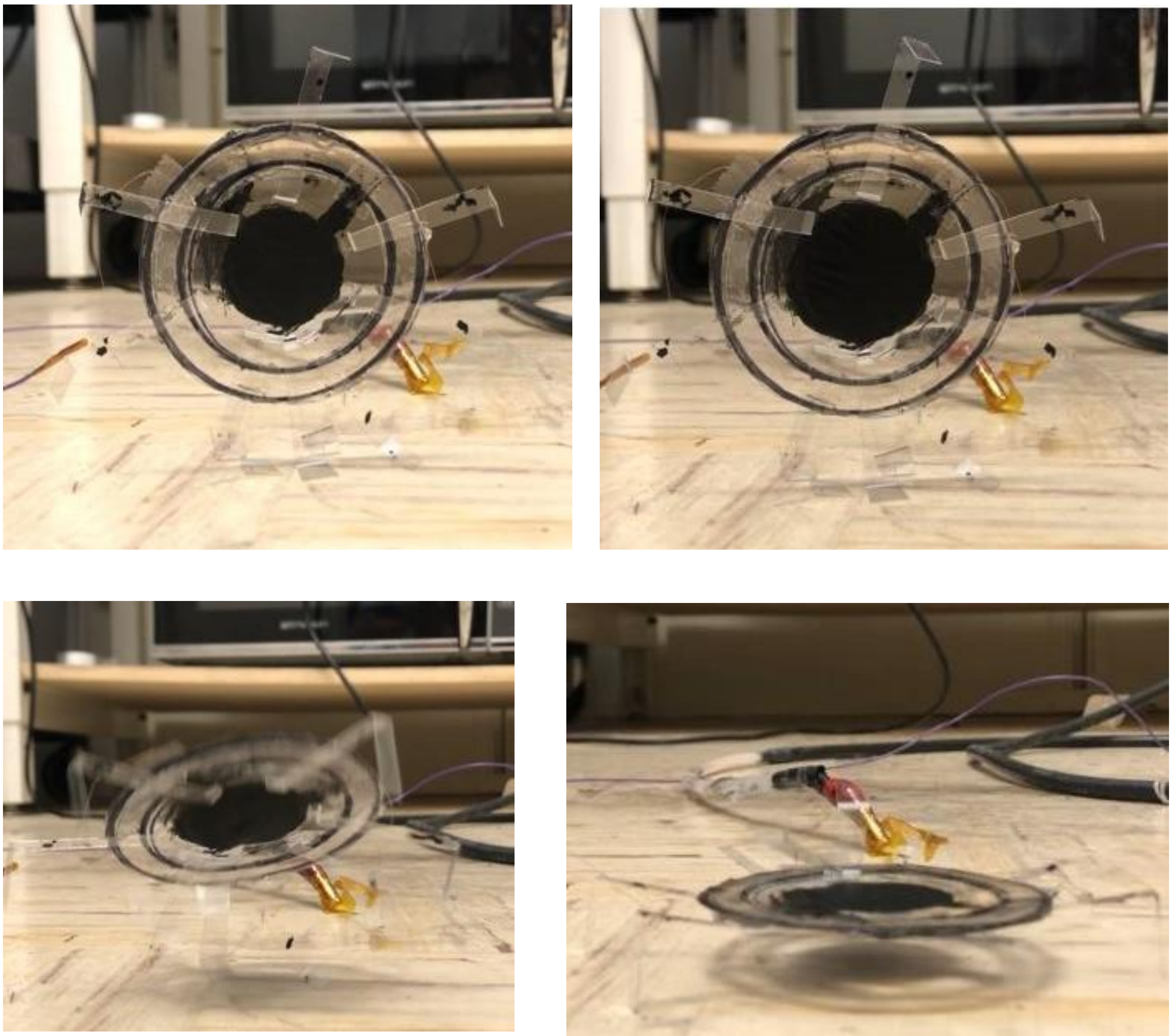


*Figure 54. Sequence of wheel falling upon voltage actuation*

The next step in the investigation was to test the two semi-cylinders that would make up the nozzle-shaped flowmeter. Here is the plan view of the first design for the mechanism. As can be seen, the dielectric was bent inwards when stretched, which complicated the formation of the complete cylinder when the two pieces were put together.

*Figure 55. Top view of the first flow meter design*

When voltage was applied, the change in the structure was practically unnoticeable. This, added to the difficulty of forming a complete tube, prompted the development of a different design.

This remodelling of the prototype proposed an anti-symmetrical design, allowing the complete tube to be formed by printing the same piece twice. The main advantage of this design with respect to the previous one, is that due to the protrusions of the new one, the elastomer has more distance, and the effect of the pre-stretching is not so negative.

That is, it would be easier to overlap the elastomers and form a complete cylinder. The following image shows the SolidWorks design of each of the halves that would make up the system, once they were produced.

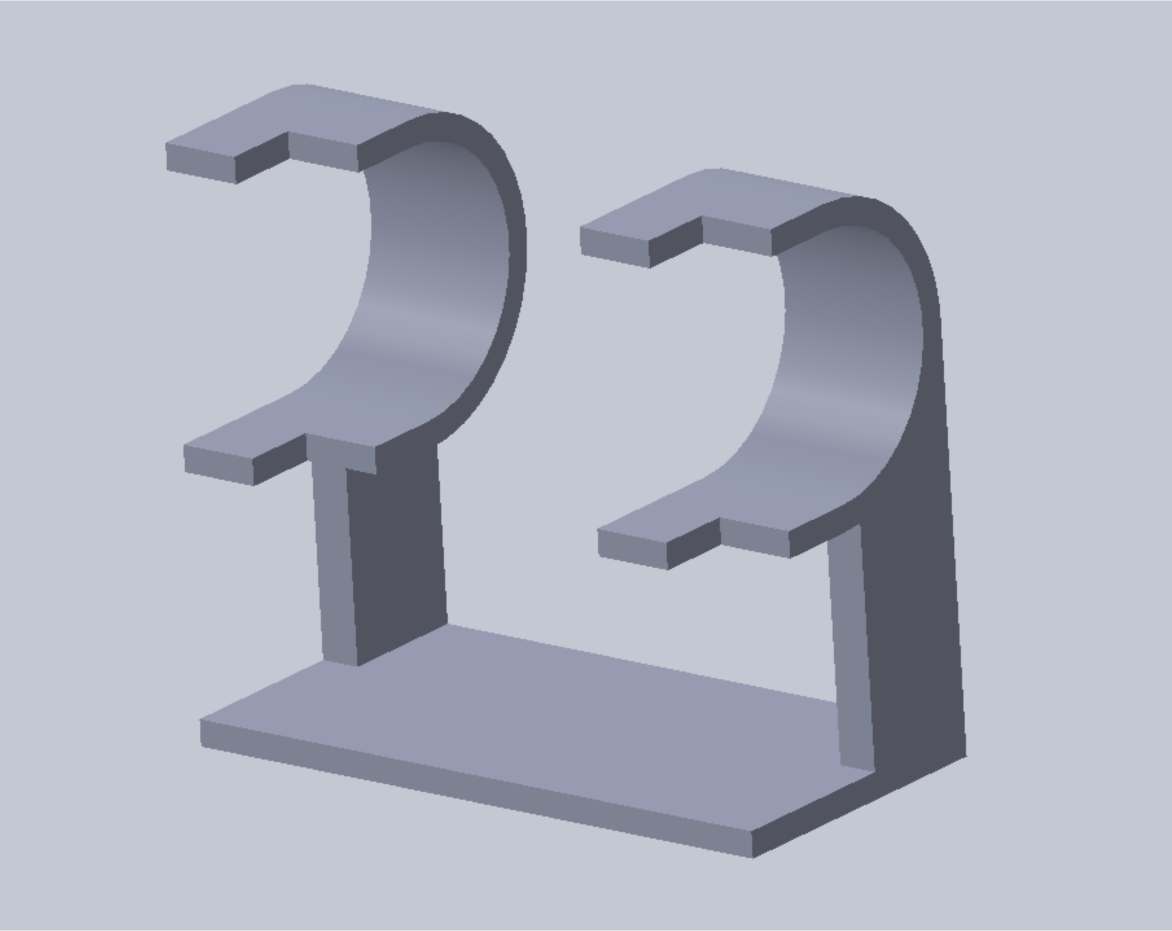


*Figure 56. SolidWorks antisymmetric design for the flow meter*

Once the new design was printed, the same experiment performed previously with the other design was carried out, to check the operation of the robot. Again, this was done on only half of the final structure, for simplicity.

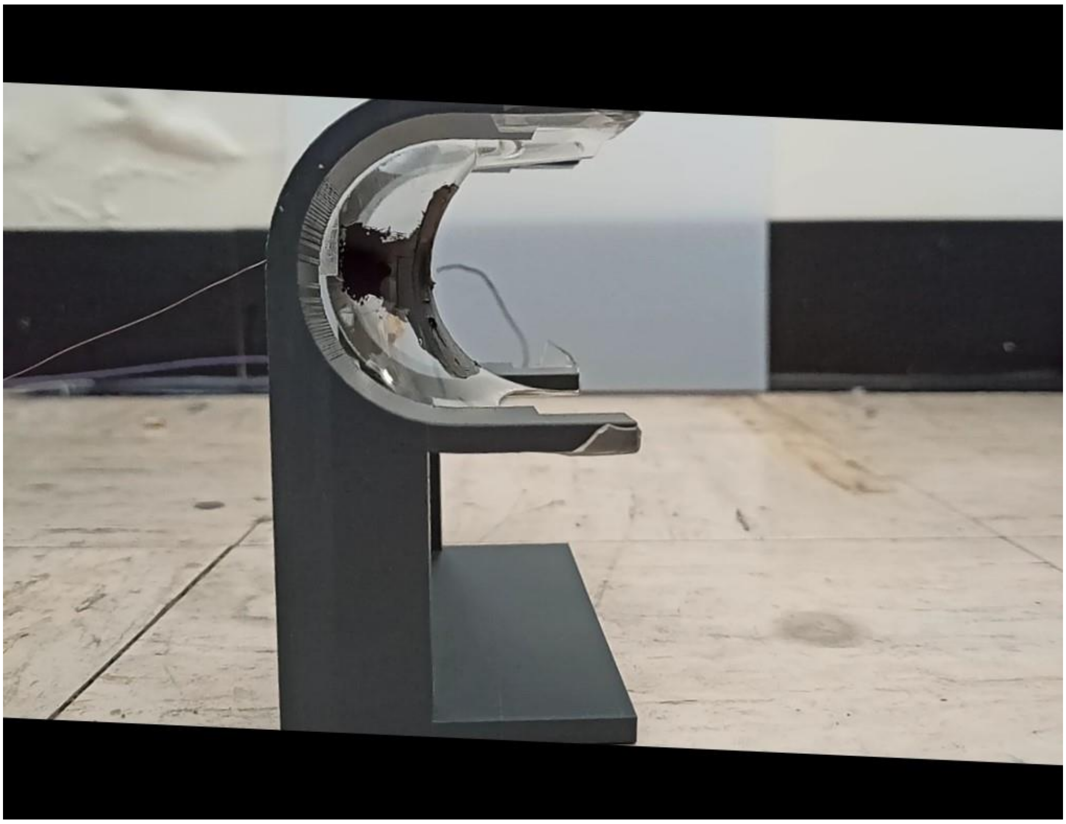


*Figure 57. Antisymmetric Flow meter implementation, side view*

This design did allow for an easier configuration of the tube. A complete tube was formed by joining the two half-cylinders. However, in the tests, the prototype again did not show the desired behavior, showing very little movement when applying voltage, so this model was also discarded. Eventually, the last design for the soft robot was tested.

As explained in section 5.1 of this document, the latest prototype uses curved actuators as the generator of the desired motion. This movement would consist of the vertical translation of the base of a rectangular section tube. In this way, the air flow through the tube could be varied by bending more or less two of these actuators attached to each other.

The following images show the experiment of a single curved actuator, to determine its range of action. As can be seen, the change is very noticeable, even reducing the angle to the ground by half.

*Figure 58. Bending actuator voltage off*

*Figure 59. Bending actuator voltage on*

After checking that the curved actuators worked properly individually, they were put together to test how they worked when they moved in conjunction with each other. To do this, the inner electrodes were joined on one side, and the outer electrodes were joined separately with another cable. The following images show a sequence in which the movement of the mechanism can be observed, ascending satisfactorily.

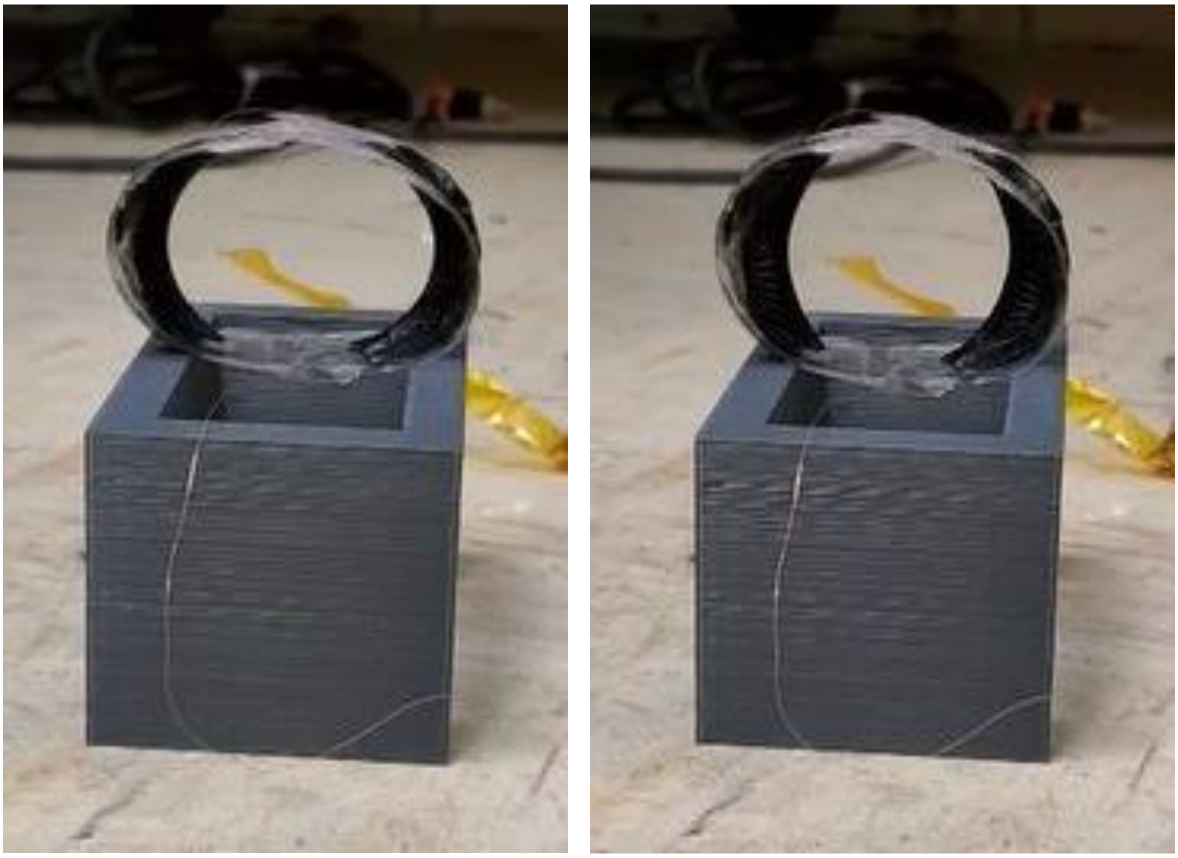


*Figure 60. Experiment results for definitive prototype*

These tests showed promising results, so this design was chosen as the definitive one and we proceeded to its implementation and optimization, which is developed in the next chapter of this work.

## 5.3 IMPLEMENTATION

In this section, the manufacturing process of the curved actuators used for the final design of our soft robot implemented with DEAs is further developed. It also explains the optimization process that has been followed, pursuing the configuration with better characteristics. Finally, the operation of Noxtec is explained in more detail, and how our system would be integrated in the equipment.

The first step in the production of a curved actuator is to pre-stretch the material and attach it to the ends. To do this, we take a structure approximately four times larger than the elastomer strip we intend to use. In this case, the frame was 120 mm and the VHB 4910 about 30 mm.

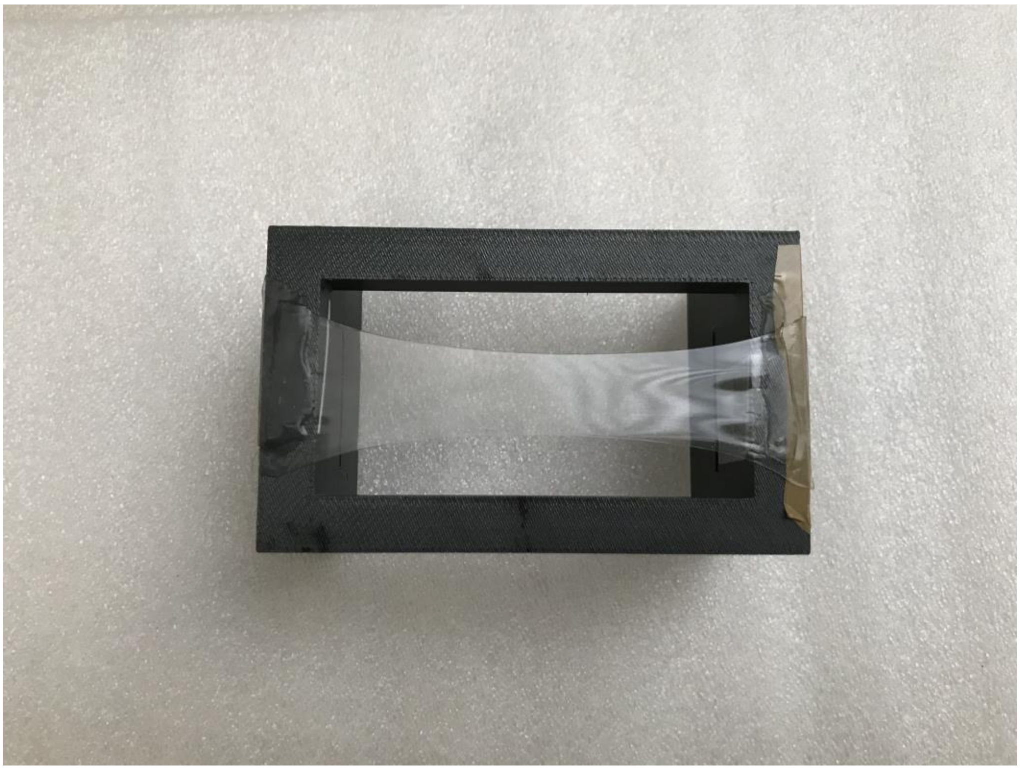


*Figure 61. Elastomer pre stretch*

The second step in the production of the curved actuators consists of fixing the thin and hard plastic frames to the live dielectric. Two frames will be required for each actuator, one on the top of the AED, and the other on the bottom. The dimensions of the frame are 65 x 7 mm inside, and 90 x 20 mm outside.

Due to the high viscosity of the VHB 4910, the frame is strongly fixed to the material. However, for a more reliable and durable fixation, adhesive tape is placed on the weakest points of the system, i.e. on the long and slender sides.

*Figure 62. Frame placement*

The next step would be to smear the carbon grease in the inner space of the frames, in direct contact with the dielectric elastomer. It is crucial that the electrodes remain uniform and fill all the holes, because in case of cracks in the material, electric arcs could be produced on the surface of the dielectric when high voltage is applied, which would damage the material and may even tear or burn it.

With the compliant electrodes in place, the actuator is now ready to be removed from the external fixture. Afterwards, the excess dielectric material should be removed to achieve a clean finish.

*Figure 63. Electrodes spread*

Finally, the actuator is released and the curved part is obtained due to the elastomer stress explained in section 3.1 of this report. Finally, all the previous process is repeated: pre-stretching, sticking the frame, spreading the electrodes and finally release and remove the exceeding material.

In this way, 2 curved actuators are obtained, which are attached at the ends maintaining a concave structure. In the picture below, you can see the complete mechanism, once both actuators have been placed together. In the picture, the actuator is shown horizontally, but its operation would be vertical, as shown in point 5.2 of the document.

*Figure 64. Final configuration*

To carry out the implementation, the materials specified in section 4.3 of the project were used, the double adhesive dielectric tape VHB 4910 of the 3M brand, and for the compliant electrodes, the carbon grease 846-80G, MG Chemical. Pictures of both materials are shown below.

*Figure 65. Carbon Grease 846-80G*

*Figure 66. VHB 4910*

Once the prototype to be developed was chosen, a series of processes were carried out to try on improving and optimizing the operation of the robot. First of all, we tried to manufacture Eco Flex 0030 and Eco Flex 0050 as a dielectric to replace the VHB 4910, as they had very good elasticity and resistance to breakage.

However, they did not prove to be sufficiently adhesive, so the material did not adhere properly to the plastic frame, and the system did not work as it had been intended to. Therefore, we continued with VHB 4910, even though their other properties were very promising.

To make these dielectric elastomers, with which we intended to experiment so as to compare their properties with those of the current VHB 4910 being used, the first step was to mix in a tube the parts A and B of the composition, at a proportion of 50% the part A (yellow pot) and 50% the part B (blue pot).

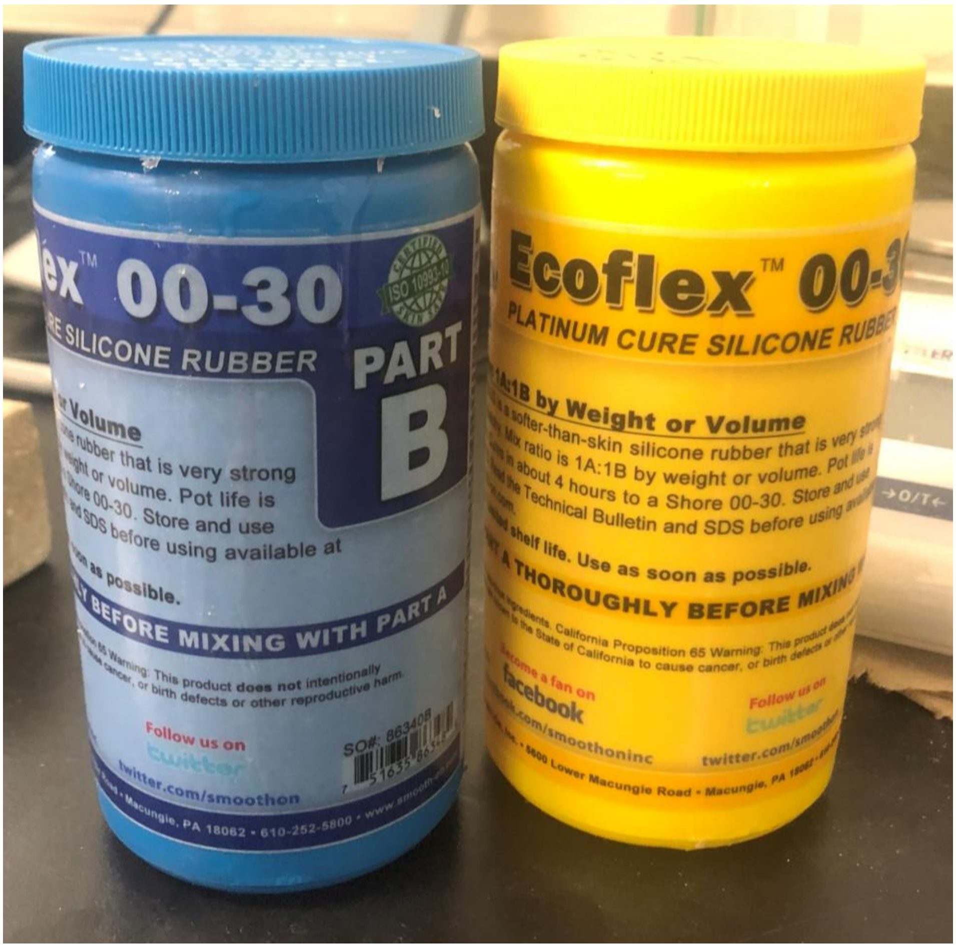


*Figure 67. Eco Flexx 00-30 parts A and B*

When the concentration was ready, the tube is sealed and agitated to check that the material does not come out. Once this check has been made, the mixture is introduced into a centrifuge, which moves the material at 3000 revolutions per minute for 5 minutes.

The aim is for the mixture to be completely homogeneous, and to eliminate any bubbles or any imperfections that may appear. The image below shows the panel of the machine that was used to carry out the purification of the compound, which was the Centrifugue 5804 R.

*Figure 68. Centrifugue 5804 R Control Panel*

With the compound mixed correctly, the last step was to pour the liquid into a container with the shape that was to be given to the material. The volume to be poured is calculated according to the area of the container and the thickness desired on the piece. As it is a circular section, the volume was calculated as:

$$V = \pi \, r^2 \, t$$

Where *r* is the radius of the base and *t* is the thickness of the material.

Finally, the containers with the final shape and volume are placed in a laboratory oven, at 80º C, for approximately two hours. The precise time should be left until the material solidifies completely, but not too long in case it burns. In this picture you can see Eco Flex 0030 on the right, and Eco Flex 0050 on the left of the image, which have a different color from each other and different from the transparent VHB 4910.

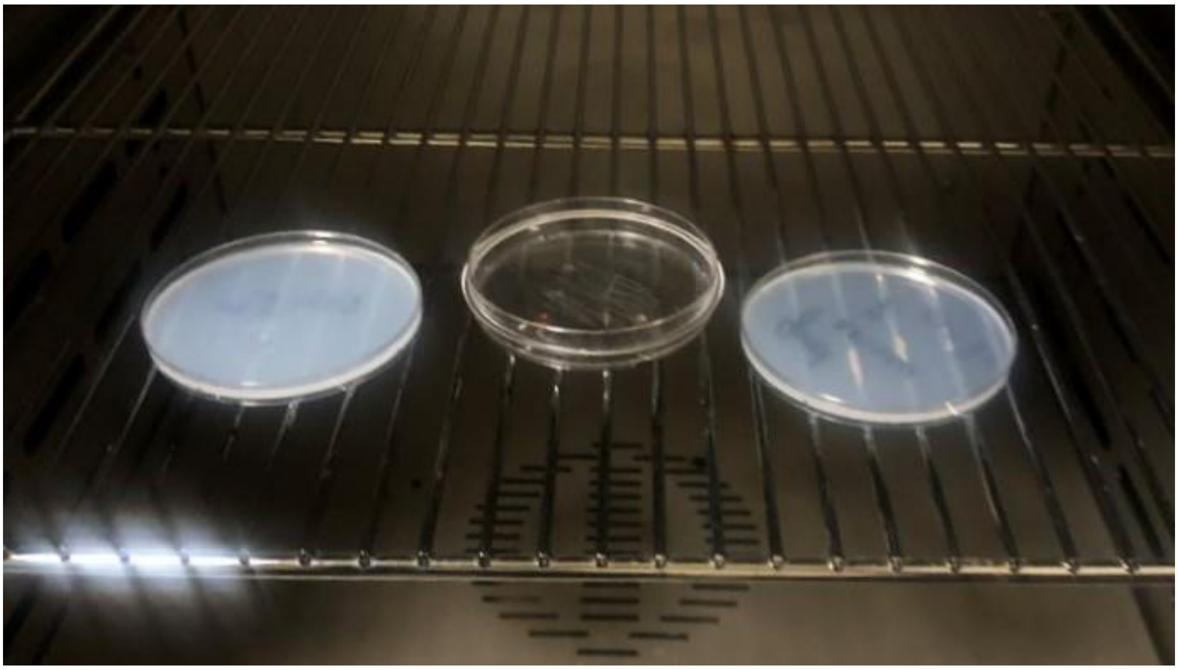


*Figure 69. Eco Flex silicon rubbers in the oven*

On the other hand, bending actuators of different dimensions were manufactured to determine which was more effective and had greater thrust and load resistance. In all cases the dimensions of the external hard plastic frame were 90 x 20 mm, and for the space where the dielectric would go, spaces of 65 x 5 mm, 65 x 7 mm, and 65 x 9 mm were cut out with the help of a cutter. The image below shows the differences between the three possible models.

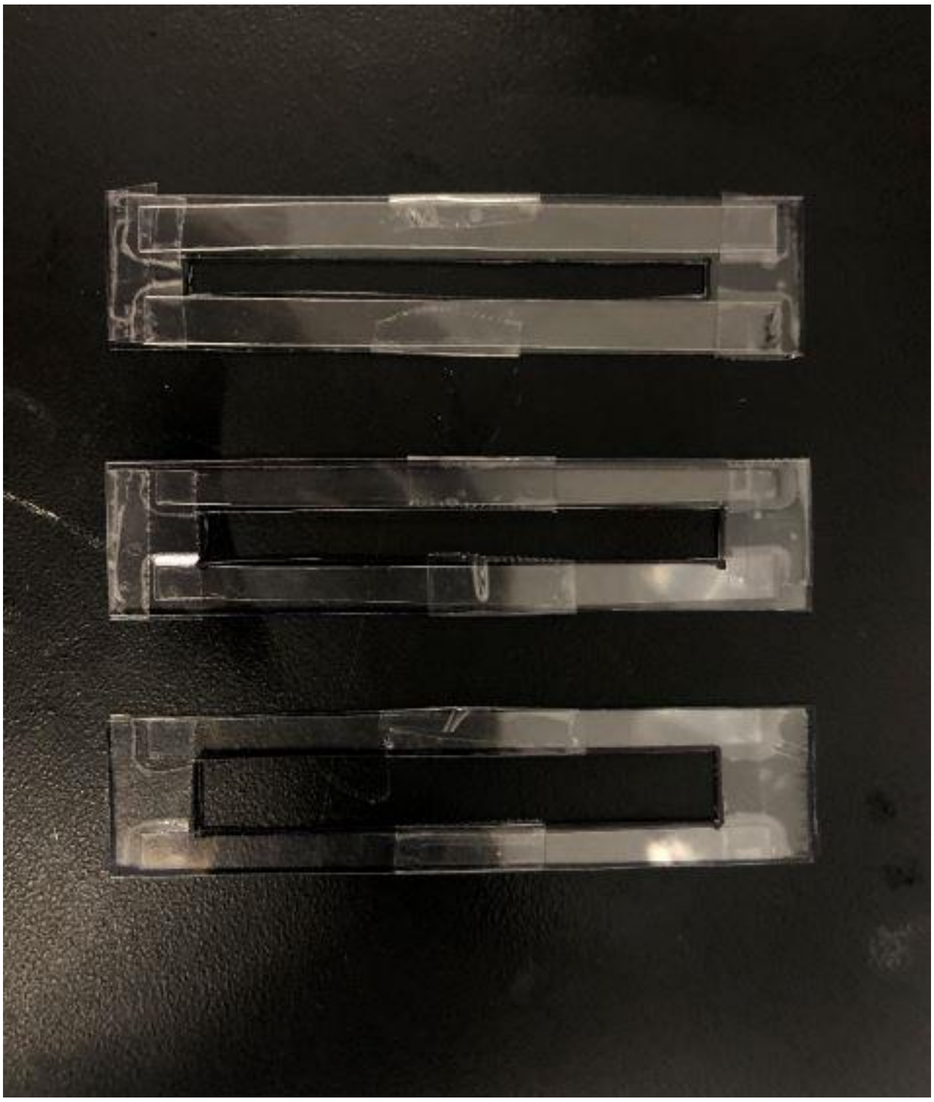


*Figure 70. Different measures for the bending actuators*

After several tests, it was found that the most efficient model is the one that occupies the central position, both in the image above and in the size scale, whose dimensions are 65 x 7 mm inside, where the elastomer is located.

In addition, several degrees of pre-stretching the material were tried, by changing the length of the VHB 4910 tape used for each actuator. After several experiments, a length of 30mm was selected.

The last step to incorporate the mechanism would require a machine where it could be fully tested. In this work, we propose the integration of the soft robot developed in the breathing channel of the NOXtec machine, whose technical data sheet can be seen in Annex I of the project, at the end of this document.

# 6 RESULTS ANALYSIS

Due to the recent birth of soft robot science, this technology is still at a very early stage of development. This confers an innovative and experimental nature to the project, which means that the main objective of the project is to investigate possible applications and configurations of Dielectric Elastomer Actuators (DEAs).

Consequently, in this section a summary is made of the performance achieved by the different mechanisms designed and manufactured throughout the research, making a more critical and detailed analysis of the prototype finally chosen for implementation and optimization.

Firstly, the implementation of a discontinuous wheel of variable diameter was carried out, thanks to the circular implementation of the dielectric elastomer. Although the mechanism behaved as expected when tested in a horizontal position, and managed to increase its diameter by up to 50% by moving the legs outwards by 5mm, it did not show the stability and reliability necessary for further development when the model was tested standing on its legs.

The second design was risky and original, as no similar system had been observed in any paper. However, the idea a priori seemed consistent with the behavior of the materials used. These are the first and second proposals for the electrically operated flowmeter, which are very similar to each other. However, when the parts were produced and the actuation was fully tested, the results were insufficient. The movement in the desired direction (increase in cross-sectional area) was so small that it was negligible.

Finally, a third design was constructed to carry out the proposed flowmeter application. This is the configuration developed in section 5.3 of the document, using curved actuators to drive the base of a rectangular-section tube. Below is a picture of the initial design in 2D, together with the implemented prototype.

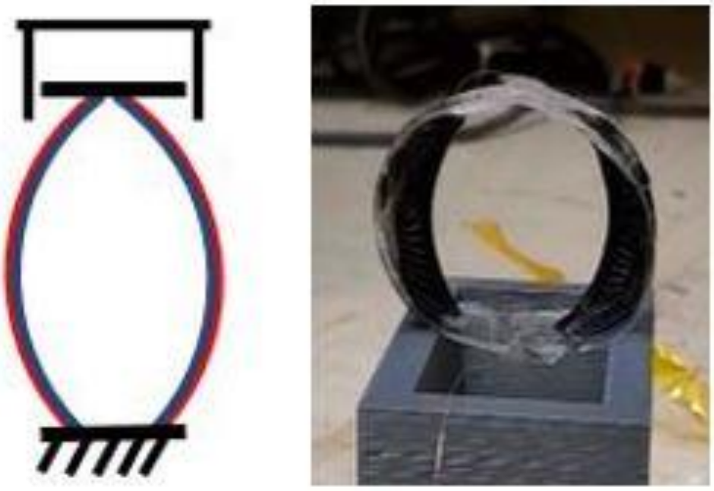


*Figure 71. Results shown next to 2D design*

This soft mechanism showed the ability to increase its height by approximately 10% of the total, about 5mm. Choosing a 4cm wide rectangle as the base of the structure, it would reach a transversal area variation for the airflow of 2 $cm^2$. If the velocity of the air was known, it could also be obtained the flow rate variation, by applying the fluid mechanics formula relating to the flow rate:

$$Q = v * A$$

Being *v* the velocity of the fluid, and *A* the transversal area. As this is a rectangular area, the change in area would be obtained by multiplying the width of the base (4cm) by the increase in height (5mm).

# 7 CONCLUSIONS AND FUTURE WORK

After the presentation of the project, several conclusions can be drawn. First of all, it has been proven experimentally that soft robots still need a lot of development to reach a level of usefulness and long-term reliability that will allow them to go to the market with the real capacity to satisfy the needs of the population.

There are three main reasons why this level of quality has not yet been reached. The first is that the materials do not have a long useful life, since they are subjected to great mechanical and electrical stresses, being materials that do not behave in a totally elastic way, but degrade and deform plastically with use. With this deformation the material loses strength and resistance, and ends up breaking when the same voltage is applied.

Secondly, a level of perfection of the soft systems in terms of efficiency has not yet been reached that would make them a better alternative than their equivalent made up of traditional robotic elements. In other words, although the technology has shown a lot of potential, there are currently no applications in which it differentiates clearly from traditional technologies, other than for some specific and concrete tasks.

Finally, the very soft nature of the technology makes it fragile and delicate. That is why the manufacture of each element must be careful and meticulous. This makes the production of soft robots a process difficult to automate, to be manufactured with the help of conventional robotics, and not purely manually. This leads to a considerable increase in the variable cost of production of each robot, which complicates the profitability of the industry.

However, the complicated and novel nature of soft robot technology was known from the beginning of this project. Therefore, the main objective of the work is focused on the research and development of new implementations, which can serve as a basis for future commercial applications.

In this sense, the main goal has been satisfied, developing a new functional application in the field of automatic regulation, for which no similar implementations are known, even less with the specific application proposed for electromedical devices.

However, there is still a lot of work to be done so that this application can have a real commercial purpose. The first improvement to be implemented in the system would be to introduce a lever mechanism, which transforms a small movement of the actuators into a larger one of the structure, providing a greater capacity to modify the passage area. A diagram of the mechanism described above is shown below.

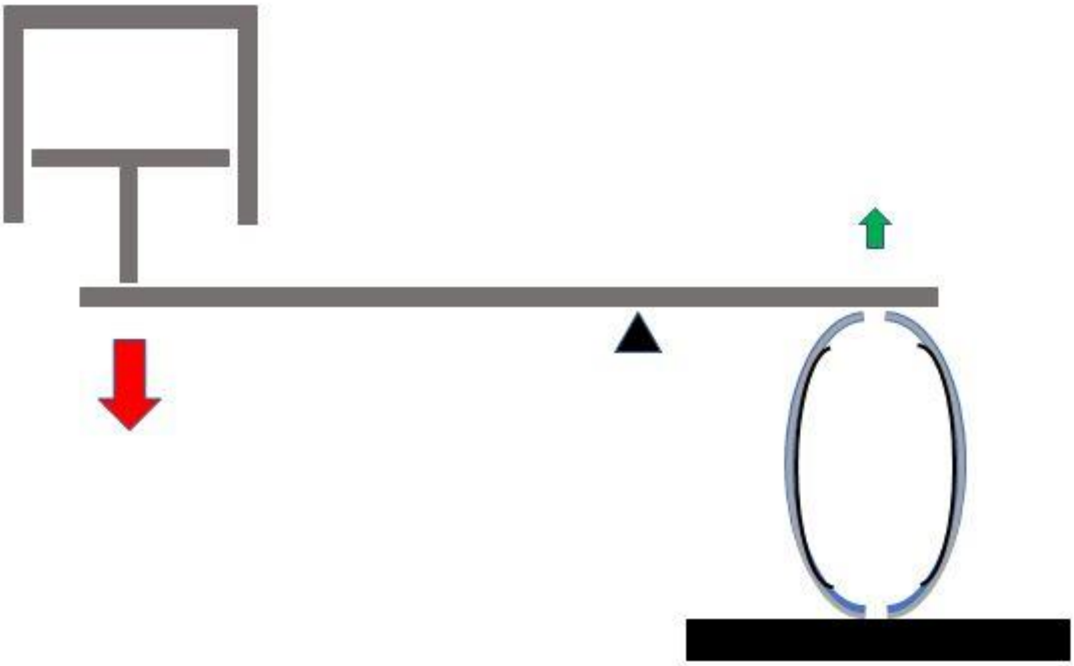


*Figure 72. Lever implementation*

The effect of the lever is based on the proportionality of Thales, who elaborated a theorem of similarity of triangles that indicates that, if the hypotenuse is multiplied by four, so are the legs, as long as the angles are maintained.

In this way, two objectives would be achieved: increase the range of flow that the robot can modify, and reduce the voltage to be applied to achieve the same movement. The consequences of these two objectives would be a higher quality of the system, and also more durability in lifetime, since a lower voltage wears the materials at an exponentially lower rate.

Finally, to ensure the efficiency and reliability of the system, it would be necessary to carry out exhaustive tests on each of the electro-medical equipment in which this soft system is intended to be implemented, each with its own operating conditions. The first necessary tests would be checks that the system can work at the required pressure and flow level.

Specifically, the Noxtec Engineering and Clinical Techniques machine has been chosen for an initial implementation. It is known that the machine works in a range of pressures up to 500 Pa, and a range of flow rates up to 120 l/min, so it would be necessary to subject the soft robot to these conditions and see how it behaves.

Finally, if positive results are obtained in the above tests, a reliability and durability test should be carried out. This test consists of maintaining changing voltage in the structure during a whole therapy cycle at the previously established conditions. This period is approximately one week, so the system should last at least ten days, to ensure a certain safety coefficient.

# 8 SUSTAINABLE DEVELOPMENT GOALS

The United Nations is a world organization created in 1945, with the aim of improving the standard of living of society globally and protecting the environment, wildlife and nature. One of its most important initiatives has been the creation of the Sustainable Development Goals. The following image shows the complete list of objectives for the Agenda 2030.

*Figure 73. Sustainable Development Goals [14]*

There are 169 targets that can be summarized in a list of 17 objectives, which are called Sustainable Development Goals. They seek to realize the human rights of all and to achieve gender equality and the empowerment of all women and girls. They are integrated and indivisible, and balance the three dimensions of sustainable development: the economic, social, and environmental [12].

The United nations, through these goals, aims to stimulate action over five main areas, which can be summarized as follows:

1. Taking care of people, by ending poverty and hunger, to ensure that all human beings can fulfil their potential in dignity and equality.

2. Protecting the planet from degradation through sustainable consumption and production, sustainably managing its natural resources and taking urgent action on climate change.

3. Ensuring that all human beings can enjoy prosperous and fulfilling lives.

4. Fostering peaceful, just, and inclusive societies, free from fear and violence.

5. Mobilizing every country to implement the Agenda 2030 through a revitalized Global Partnership for Sustainable Development.

After a review of the Agenda 2030 for Sustainable Development, an analysis of how the project fulfill these objectives is presented. The first contribution that the presented project can offer refers to goal number three. This objective is entitled: Good health and well-being. The reason why our robot can have a positive impact, is because it is designed to be implanted in an electromedicine machine, whose purpose is to save the lives of patients with respiratory diseases. Therefore, our objective is to contribute to the optimal functioning of the machine, and thus try to bring health to many patients, especially newborns, who are strongly affected by this type of disease.

Secondly, the development of a robot whose only source of energy is electricity makes a positive contribution to Affordable and clean energy, the seventh objective of Sustainable Development. In contrast to the action of other conventional machines, operated by fossil fuels, electricity is increasingly obtained by clean and renewable methods, such as wind, hydro and solar energy.

The third point related to this work is the ninth in the list of seventeen, which refers to industry, innovation and infrastructure. The project presented is fundamentally about researching a purely innovative technology, and it aims to offer an idea that, if successfully completed and implemented, when advances are made in the field, could become very interesting.

Finally, this work also refers to point number twelve on the list, entitled: Responsible consumption and production, as it relates the process of creating a soft robot. At the moment, the materials used to implement these robots are not the best option in terms of recyclability. This is because, being an innovative technology, it requires custom-made frames, and the most economical, simple and quickest way to produce them is through 3D printing on ABS plastic. The moment the technology is at a higher level of development, allowing the mass production of soft robots for commercial application, it will be possible to produce them with more sustainable materials.

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# ANNEX I

Below is the technical data sheet of the NOXtec device, an electromedical machine marketed by the company Ingeniería y Técnicas Clínicas S.A., in which the implementation of the soft system developed in this document is specified. This appendix provides a more detailed explanation of the operation and working conditions of this equipment.

NOXtec by ND

# NOXtec 1000

## *Automatic or Manual dosing Nitric Oxide Monitor*

| Dose System | | | | | | Monitor system | |
|---|---|---|---|---|---|---|---|
| Real time Mode | Automatic Mode | Semi-automatic Mode | Manual Mode | Cylinder Exchange | Automatic Venting | Automatic Calibration | Room measurement |
| ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

**NOXtec 1000** is a medical device which both **dosifies and monitors the supply of nitric oxide (NO)**.

NO is a gaseous vasodilator used to treat pulmonary arterial hypertension. It is supplied to the patients mixed with medical oxygen. NOXtec 1000 supplies a **stable dosis** throughout the therapy, even triggering an **automatic exchange of the cylinders** (it can harbour two cylinders) if needed.

NOXtec **calculates automatically the necessary dosing flow**, thanks to a **disposable breathing flow sensor** applied to the patient's circuit. Alternatively, the dosing flow can be set manually.

Thanks to the **continuous sampling of the NO-$O_2$ mixture flow** supplied, NOXtec is able to monitorize the NO concentration that the patient is receiving, and to check if this value is placed within predetermined thresholds.

NOXtec 1000 also **monitors trace quantities of nitrous oxide ($NO_2$)** in the mixture, a highly toxic gas which can compromise the patient's safety during the treatment. NOXtec 1000 triggers and alarm when this trace surpasses a threshold value.

## MAIN FEATURES

- **Dosing and monitoring modules and user interface independent from each other to guarantee the patient's safety.**
- **Automatic cylinder exchange** to increase the treatment autonomy and optimize the gas consumption.
- **Automatic venting procedure** to minimize the $NO_2$ supplied to the patient at the beginning of the treatment and during the cylinder exchange, and also to depressurize the system when the device is not in use.
- **Automatic calibration of the NO, $NO_2$ and $O_2$ sensors**, available even when the device is dosing.
- Dosing mode options: Real time, Automatic, Semi-automatic or Manual.
- **NOXtec includes an emergency manual dosing mode**, which can be used even when the device is off.
- **Negligible liberation of NO to the environment**. The device includes a purge outlet to gather and canalize the residual gas.
- **Measurement of the concentration of NO, $NO_2$ and $O_2$ in the room.**
- **Hot wire and differential pressure technologies for the external breathing flow sensors.**
- Ethernet port for **remote technical assistance**.
- USB port to retrieve **therapy data files**.

## NOXtec 1000: Basic Set

| REFERENCE | DESCRIPTION | QTY |
|---|---|---|
| 01NXTC1000 | NOXtec 1000: Nitric Oxyde Monitor with Automatic Deliver System.<br>*Main Box with pneumatic, electronic and user interface.* | 1 |
| 01NTMNPG0A | Manifold with calibration gas sensors: NO, $NO_2$ y $O_2$, including PCB battery power. | 1 |
| 01NTDSEG1D | Flow sensor cable. | 1 |
| 01NTDSEGxx | Power cable "xx". | 1 |
| 10BiT3xxxx0X | Stainless steel gas regulator for NO supply, with high pressure sensor incorporated. | 2 |

## NOXtec 1000: Calibration Set

| REFERENCE | DESCRIPTION | QTY |
|---|---|---|
| 10Bi02****0X | Stailess steel gas regulator for gas de calibration. | 1 |
| 01NTMNPG19 | Gas calibration 5 L cylinder, 70 ppm of NO and 10 ppm of $NO_2$ in $N_2$. | 1 |

## NOXtec 1000: Optional Set

| REFERENCE | DESCRIPTION | QTY |
|---|---|---|
| 01NTCG0000 | Trolley for holding the device, space for 2 x 20 L cylinders, 1 x 5L calibration cylinder and 1x 5 L backup oxygen cylinder *(cylinders not included).* | 1 |

# TECHNICAL SPECIFICATIONS

## PHYSICAL SPECIFICATIONS

**Dimensions and weight:**

- **Main unit:** 205 x 300 x 345 mm; 9,2 kg.
- **Cart:** 1250 x 570 x 630 mm; 47,5 kg

**Cart's capacity for cylinders:** 2 cylinders of 20 L

**Materials:** AISI 304 and AISI 316L stainless steel, PTFE and ABS.

**Screen:** Touch colour 10,1" screen

## DOSING MODULE

**Dosing options:**

- Real Time
- Automatic
- Semiautomatic
- Manual

**Measuring range:**

- Automatic: 0 - 4 L/min
- Manual: 0 - 0,02 - 0,03 - 0,05 - 0,07 - 0,1 - 0,15 - 0,2 - 0,25 - 0,3 - 0,45 - 0,6 L/min

**NO dosing interval:** 0-100 ppm (upgradeable upon request)

**Dosing accuracy:** ±5%

**Dosing resolution:** 0,1 ppm

**Ventilation range and accuracy:**

| | | Adult | Paediatrical and neonatal |
|---|---|---|---|
| Differential pressure | Range | 2,0-120 L/min | 0,5-60 L/min |
| | Accuracy | ±10% or 0.5 L/min<br>*(wichever is higher)* | ±10% or 0.2 L/min<br>*(wichever is higher)* |
| Hot wire | Range | 0,5-100 l/min | 0,2-60 L/min *(not available yet)* |
| | Accuracy | ±10% or 0.1 L/min<br>*(wichever is higher)* | *(Not available yet)* |

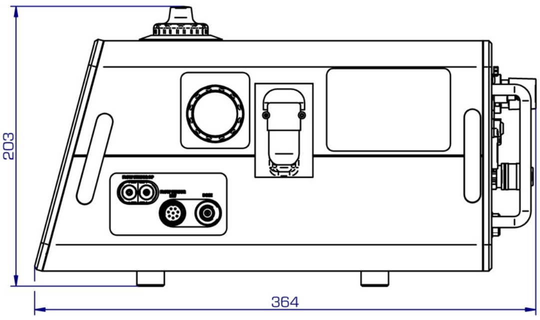
**Set up time:** < 2 min fs

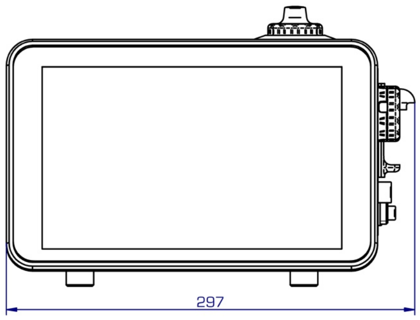
## MONITORIZATION MODULE

| | Gas sensor type | Measuring range | Measuring accuracy | Resolution | Response time |
|---|---|---|---|---|---|
| NO | Electrochemical cell | 0-160 ppm | ±10% + 0,5 ppm | 0,1 ppm | <10s |
| $NO_2$ | Electrochemical cell | 0-20 ppm | ±10% ó ±0,2 ppm<br>(whichever is higher) | 0,1 ppm | <40s |
| $O_2$ | Electrochemical cell | 0-100% | ±3,5% | 1% | <20s |

**Sampling flow:** 90 - 250 mL/min (configurable, 150 mL/min by default)

**Operational life of the sensors:** 12 months





## Operating and storage conditions

**Operating conditions:** 10 - 40ºC; 15 - 90% de humidity

**Storage conditions:** -10 - 60ºC; 15 - 90% humidity

## Electrical specifications

**Power:** 100-240 VAC, 50-60 Hz

**Battery:**

- Duration: 4h
- Charging time: 2,5 h approx.

**Classification:** Clase I, type B

## Electromagnetic and RF specifications

***Guidance and manufacturer's declaration - electromagnetic emissions***

*NOXtec is intended to be used in the electromagnetic environment specified below. The client or the user of NOXtec should ensure that it is utilized in such environment.*

| Emission Test | Accordance | Electromagnetic environment - Guidance |
|---|---|---|
| RF emissions CISPR 11 | Group 1 | NOXtec uses RF energy only for its internal function. Therefore, its RF emission are very low and are not likely to cause any interference in nearby electronic equipment. |
| RF emissions CISPR | Class B | NOXtec is suitable for use in all establishments, including domestic establishments and those directly connected to the low-voltage public network. |
| Harmonic emissions<br>IEC 61000-3-2 | Class A | |
| Voltage fluctuations / flicker emission IEC 61000-3-3 | Meets | |

## In compliance

CEN/TS 14507-1:2003
CEN/TS 14507-2:2003
UNE-EN 60601-1:2008/A12:2015
IEC 60601-1-8:2006+A1:2012
IEC 60601-1-6:2010/A1:2013
IEC 62366-1:2015
IEC 62304:2006/A1:2015
UNE-EN 55011:2016/A1:2017
UNE-EN 61000-3-3:2013
UNE-EN 61000-4-2:2010
UNE-EN 61000-4-3:2007/A1:2008/A2:2011
UNE-EN 61000-4-4:2013
UNE-EN 61000-4-5:2015
UNE-EN 61000-4-6:2014
UNE-EN 61000-4-8:2011
UNE-EN 61000-4-11:2005
UL requirements
RoHS Directive