

École polytechnique de Louvain

Peano-HASEL actuators

Design of tools to manufacture Peano-HASEL
actuators and demonstrator using their properties

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AI disclaimer

ChatGPT was used in this work to correct the grammar and orthograph.

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1 Introduction

Actuators are a key component of all robotic systems. However it exists a lot of different types, none to these day can mimic the capabilities of the muscles. This is the challenge researchers in the field of artificial muscles are trying to achieve since the work of Robert Hooke in the 17th century [1]. Through the years, many types of artificial muscles came to light such as dielectric elastomers actuators [2], fluid-driven soft actuators [3], ionic polymer-metal composites [4], etc. While these types excel in specific performance metrics, they also perform poorly in others.

In 2018, a new class of soft actuators, Hydraulically Amplified Self-healing Electrostatic actuators (HASEL) actuators [5, 6], was introduced to the scientific community. Combining a deceptively simple operating principle with good versatility, these devices quickly captured the attention of researchers worldwide. They became the subject of many studies, each of them focusing on different aspects like electro-mechanical models, performance optimization or adapted controller design. They also featured in different applications ranging from small robots to biomedical pumps. Since it is a quite new technology, the HASEL still has potential aspects to discover and to optimize.

Despite their growing prominence, HASEL actuators had never been produced at UCLouvain. It is Professor Ronsse that took an interest in this technology. In his team of PhD students, Thomas Pomponio started to work on the subject and experimented on the manufacturing method. In order to pursue the matter a bit further, Professor Ronsse decided to add a master student to clear the ground on possible future work. This is where this master's thesis comes in, as it pursues a dual objective: to establish a robust and repeatable manufacturing protocol ensuring consistent actuator performance, and to design a demonstrator capable of showcasing one of their functional properties.

Section 2 will provide an overview of the state of the art. After a brief introduction to the history of HASEL actuators, we will focus on their working principle, with particular emphasis on the Peano-HASEL actuator. We will also review previous studies describing manufacturing processes. Finally, we will examine the notable properties of HASEL actuators and explore various potential applications.

The manufacturing methodology developed in this work will be presented in Section 3. The different stages-heat-sealing, pouch filling, and electrode placement-will be explained in detail. For each stage, we will discuss the solutions and alternatives tested, as well as the key parameters to be controlled. The section will conclude with a description of the tests performed and a discussion of the results obtained.

The description of the demonstrator designed for illustrating the co-contraction phenomenon enabled by our Peano-HASEL will be the subject of Section 4. After an explanation of its working principle, we will focus on outlining its design rationale to its achievement. The constructed prototype will be presented.

In Section 5, we will explore potential avenues for improvement that emerge from a critical analysis of the obtained results and will offer recommendations for future researches. Material choices will be critically examined and designs for potentially more efficient manufacturing solutions will be proposed.

Section 6 will draw the conclusions of this work, highlighting the benefit it brings me in the framework of my formation.

2 State of the art

HASEL actuators descend from the long history of artificial muscles. More precisely, they were designed to replicate the benefits of Dielectric Elastomer Actuators (DEAs) while solving some of their drawbacks.

The DEA [2, 7, 8] is a type of actuator that gained popularity among the research community in the early 2000s. It uses Maxwell stress to deform a pre-stretched rubber with an electric field, enabling an actuation strain of over 100%. Two different types of DEAs have influenced the creation of HASEL actuators. The first is the hydrostatically coupled DEA, which uses liquids to transmit deformation to other membranes. The second is the DEA-based pump, which introduces electrostatic zipping to pump fluids. DEAs, in general, offer the interesting properties of large actuation strain along with the benefits of electric control. However, DEA suffer from some inconvenients like the pre-stretching and the rigid frames that limit design flexibility, the membranes and electrodes that suffer from electrical and mechanical degradation under high strain, and the actuators are prone to electrical failures.

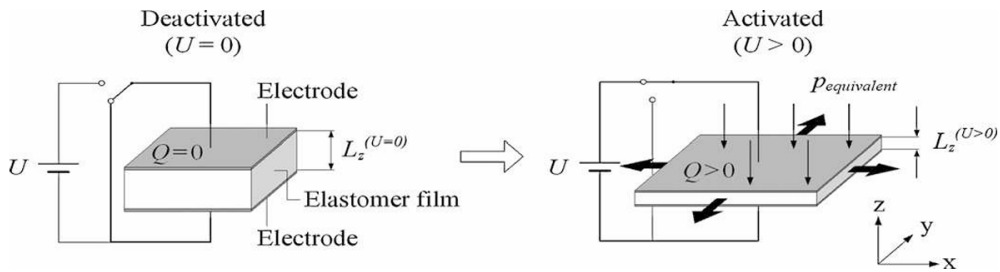


Figure 1: *Structure and working principle of DEAs [7].*

In 2018, a team of researchers led by Christoph Keplinger designed Hydraulically Amplified Self-healing Electrostatic actuators [5], or HASEL actuators. Two types were developed. The first one featured a circular pouch composed of an elastomeric shell filled with a liquid dielectric, with two opposing electrodes centered on each side. The term "self-healing" refers to the ability of the liquid to self redistribute within the pouch after an electrical failure, one of the major issues with DEAs. These actuators also exhibit an abrupt transition in actuation strain as voltage increases, a phenomenon referred to as "pull-in" or "snap-through". The second type was planar, pre-stretched and extended linearly but works on a different basis. Therefore it was not further considered in the current thesis.

Less than a month later, another team, also led by Christoph Keplinger, introduced the Peano-HASEL actuator [6]. These are the type of HASELs that we will focus on in this work. The actuators described in this article consisted of rectangular pouches, with electrodes covering their upper part. This time, a linear actuation strain was observed as voltage increased.

Since then, many different studies focusing on different aspects of these actuators have been published. While some focused on analytical or numerical models, others explored various applications. In these latter, different geometries for pouches were explored.

2.1 Working principle

Although different types of HASEL actuators have been developed, they are all based on a common working principle. HASELs are composed of pouches filled with a liquid dielectric, with opposing electrodes on each side of the pouch. When a voltage is applied, an electrostatic force is created that makes the electrodes attract each other. This force pushes the liquid to the sides, deforming the pouch. However, different types of HASEL actuators use this principle in different ways.

2.1.1 Peano-HASEL

The basic Peano-HASEL actuator is composed of rectangular pouches made of deformable but inextensible plastic, with electrodes on their upper parts. As voltage increases, the electrodes come together in a "zipping" effect, as shown in Figure 2. This effect allows a better control of the actuation strain, since it does not involve a snap-through transition.

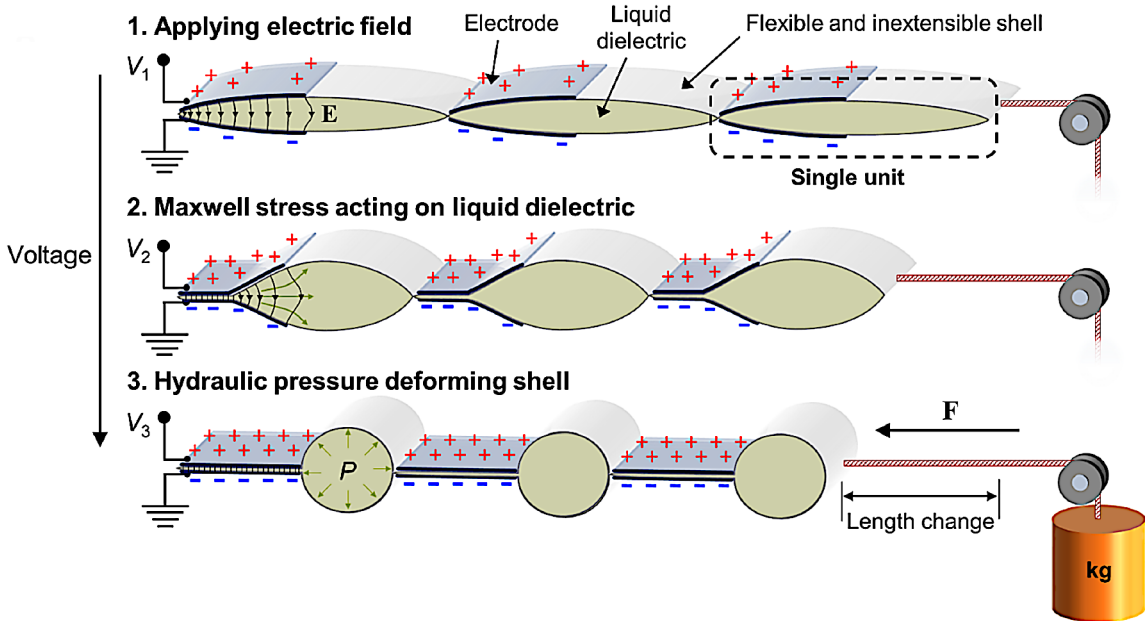


Figure 2: 3D Schematic view of the working principle of a Peano-HASEL actuator [6]. When voltage is applied, an electric field E induces an electrostatic force that causes the electrodes to attract each other. The liquid is pushed into the remaining portion of the pouch, deforming it into a more cylindrical shape and reducing its overall length. As voltage increases, the electrodes gradually zip together, resulting in full actuation.

In 2019, an article by Keplinger's team described an analytical model [9] that helped improve the performance of the Peano-HASEL actuator. The model focused on the deformation of the pouch's cross-section to deduce the geometry, the force, and the strain based on the liquid volume, the electrode coverage, and the applied voltage.

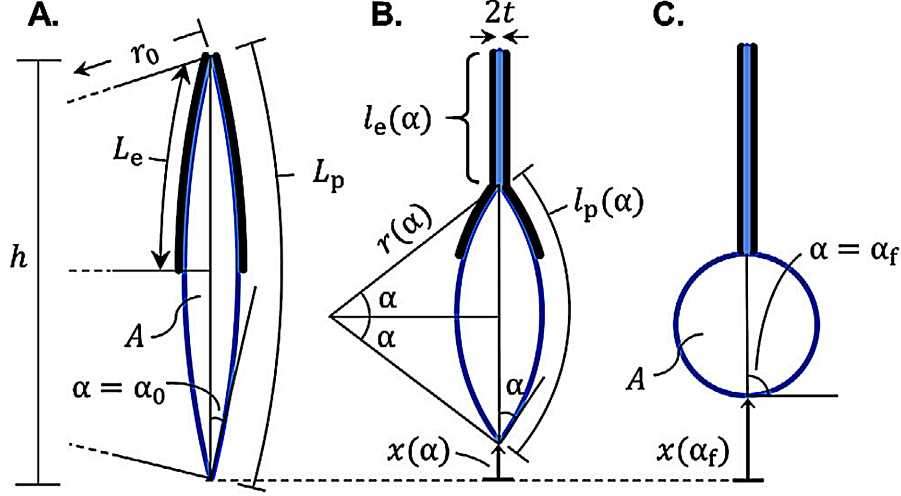


Figure 3: Schematic of the actuator's geometry and parameters [9]. Plastic films are represented in blue and electrodes in black. Electrodes cover just enough length to form a circular shape when fully actuated. The area A remains constant. (A) Not actuated: the pouch has an initial length h . α_0 is derived from A and L_p . (B) Partially actuated: electrodes are zipping, separated by twice the film thickness t . The rest of the pouch takes a more circular shape. With angle α , one can calculate arc length l_p , zipped length l_e , and stroke $x(\alpha)$. (C) Fully actuated: electrodes are fully zipped, and all the liquid is in the circular section. Here, $\alpha_f = \frac{\pi}{2}$ and stroke $x(\alpha_f)$ is maximal.

For this model, they started with the assumptions that the deformation was the same along the width w of the pouch. This means that the liquid when fully actuated takes a cylindrical shape. They computed the cross-sectional area of the pouch at rest given the liquid volume. From the formula of the area A depending on the undeformed length L_p , they could find angle α_0 shown in Figure 3:

$$A = \frac{L_p^2}{2} \left(\frac{\alpha_0 - \sin(\alpha_0) \cos(\alpha_0)}{\alpha_0^2} \right) \quad (2.1)$$

Using this parameter, they determined the initial length h with:

$$h = L_p \left(\frac{\sin(\alpha_0)}{\alpha_0} \right) \quad (2.2)$$

As voltage increases, the electrodes begin to zip, separating the cross-section into two regions: the electrode-covered part (separated only by $2t$), and the rest filled with liquid.

Geometry at each state is fully determined by α . For example, they expressed the arc length $l_p(\alpha)$ and zipped length $l_e(\alpha)$ as:

$$l_p = \sqrt{\frac{2A\alpha^2}{\alpha - \sin(\alpha)\cos(\alpha)}} \quad (2.3)$$

$$l_e = L_p - l_p(\alpha) \quad (2.4)$$

From these, they calculated the stroke $x(\alpha)$:

$$x = h - \left(l_p(\alpha) \frac{\sin(\alpha)}{\alpha} + l_e(\alpha) \right) \quad (2.5)$$

Using equations 2.2 and 2.5, they found the strain ϵ formula:

$$\epsilon = 1 - \frac{\alpha_0}{\sin(\alpha_0)} \left(1 + \frac{\sqrt{2A}}{L_p} \frac{\sin(\alpha) - \alpha}{\sqrt{\alpha - \sin(\alpha)\cos(\alpha)}} \right) \quad (2.6)$$

The maximum angle α_f depends on the electrode length L_e and the maximum zipping length $l_{\max}$. The pouch deforms until its cross-sectional surface becomes circular or until the electrode is fully zipped. If $L_e \geq l_{\max}$, then the zipped length $l_e = l_{\max}$ and $\alpha_f = \frac{\pi}{2}$. Otherwise, if $L_e \leq l_{\max}$, then $l_e = L_e$ and $\alpha_f < \frac{\pi}{2}$.

Next, they deduced the total free energy of the system. This included mechanical and electrical energy stored in the actuator, the energy from an external force F , and electrical energy from a battery at constant voltage V . Mechanical energy was neglected due to the assumption of inextensible films and negligible bending stiffness. The electrical energy was considered only in the zipped region (as the field decays rapidly in the unzipped area). Capacitance was given by $C(\alpha) = \frac{\epsilon_r \epsilon_0 w}{2t} l_e(\alpha)$, where ϵ_r is the relative permittivity and ϵ_0 is the vacuum permittivity. The electric free energy was:

$$U_e = \frac{Q^2}{2C(\alpha)} \quad (2.7)$$

with Q as the electric charge. The battery made the the electric energy is reduced by $-QV$, and external work is $Fx(\alpha)$. Using $Q = CV$, they obtained the total free energy:

$$U = Fx(\alpha) - \frac{C(\alpha)V^2}{2} \quad (2.8)$$

They plotted $U(\alpha)$ in Figure 4 for different voltages. Above a certain voltage V_1 , $U(\alpha)$ displayed local minima for $\alpha > \alpha_0$, representing the system's equilibrium states.

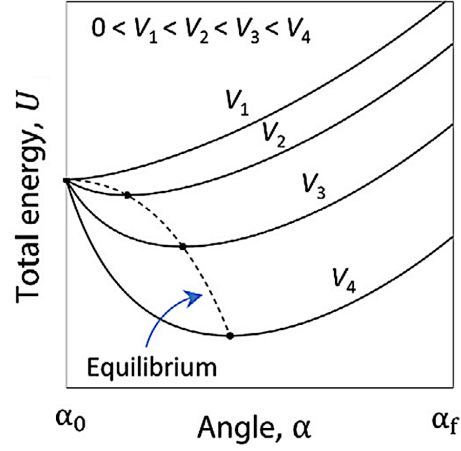


Figure 4: *Free energy U as a function of α for different voltages [9]. When voltage exceeds V_1 , U has local minima for $\alpha > \alpha_0$. These minima indicate equilibrium states for each voltage. Analytical solutions for an external force give the dotted curve for angle α vs voltage.*

Solving these equilibrium conditions analytically, they derived the expression for the applied force:

$$F = \frac{w}{4t} \frac{\cos(\alpha)}{1 - \cos(\alpha)} \varepsilon_r \varepsilon_0 V^2 = wt \frac{\cos(\alpha)}{1 - \cos(\alpha)} \varepsilon_r \varepsilon_0 E^2 \quad (2.9)$$

The second form comes from substituting $E = \frac{V}{2t}$. This equation predicts four behaviors:

- F is independent of the pouch length L_p .
- F scales linearly with the pouch width w .
- F scales linearly with the film thickness t for a given electric field E .
- F depends on a Maxwell stress term $\varepsilon_r \varepsilon_0 E^2$.

Using equations 2.5 and 2.9, they plotted the force-strain curve of the actuator, given in Figure 5A. In this graph, the force is normalized, and a new parameter f_e is introduced to represent electrode coverage, defined as:

$$f_e = \frac{L_e}{L_p} = 1 - \sqrt{\frac{\pi}{2} \left(\frac{\alpha_0 - \sin(\alpha_0) \cos(\alpha_0)}{\alpha_0^2} \right)} \quad (2.10)$$

When $f_e = 0$, $\alpha_0 = \frac{\pi}{2}$, meaning that the pouch is fully filled with liquid and has a circular cross-section without electrodes. Conversely, when $f_e = 1$, $\alpha_0 = 0$, indicating an empty pouch fully covered by electrodes. The effect of this parameter on the force and the strain is shown in Figure 5B. In this plot, we observe that a lower electrode coverage allows for a large free strain (around 23%) but results in a weak blocking force—and vice versa for a higher electrode coverage.

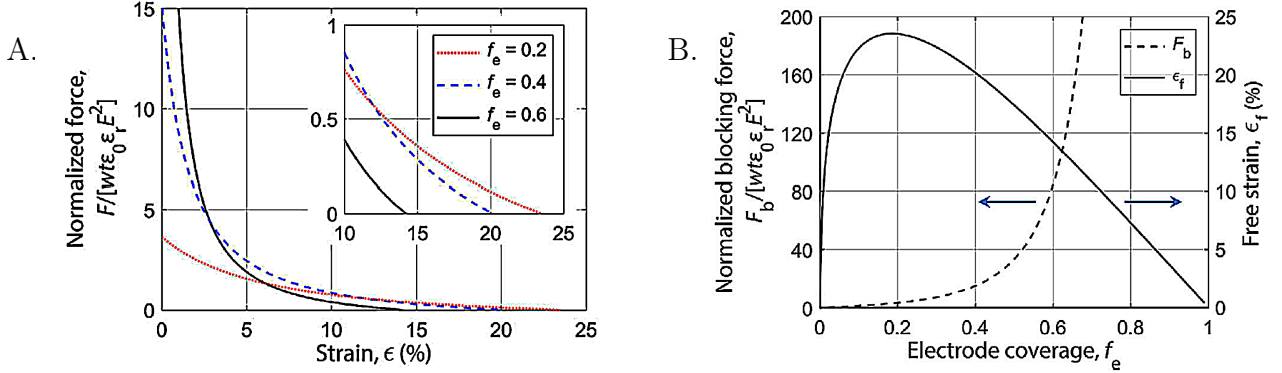


Figure 5: Force-strain curves calculated for different f_e [9]. (A) Force-strain curves for different values of the parameter f_e . In this graph, the free strain (when no load is applied) corresponds to the intersection with the x-axis, while the blocking force (the load at which the actuator can no longer produce displacement) corresponds to the intersection with the y-axis. The zoomed view shows the plots in the high-strain region. (B) Normalized blocking force and free strain as a function of f_e . Here we see that the free strain decrease as f_e increases, but only when $f_e > 0.19$.

The force-strain curve they obtained matched the behavior observed when they first introduced Peano-HASEL actuators [6]. To show the accuracy of their model, they tested the effect of different parameters on this curve. To further demonstrate the four behaviors predicted by equation 2.9, they changed the parameters one by one and showed the graphs of the force F normalized by each parameter. This resulted in a collapsing all the data together, confirming the predicted scaling laws. While the plots closely followed the model curve, overall, the Peano-HASELs slightly underperformed compared to the model's predictions. They attributed this discrepancy to a residual layer of liquid between the zipped electrodes, which increased the separation distance between them and reduced the electric field in that region.

However, under high loads, the behavior of the actuators seemed to outperform the model's predictions. They observed that, under such loads, instabilities caused the electrodes to zip asymmetrically. They predicted that this asymmetry increases the zipping area, leading to more electrical energy being stored in this region. This prediction was demonstrated by Rothmund, Kellaris, and Keplinger [10] in an article where they developed a model for inhomogeneous zipping.

This new model is based on the one previously described, but generalizes the geometry into two distinct states. The new geometry is illustrated in Figure 6. They followed the same reasoning as in the earlier model to determine the energy and minimize it. However, the new model's predictions apply only under high load conditions. It predicted that the equilibrium state always consists of a combination of one part fully zipped and the other totally unzipped, which does not align with experimental observations. The issue appears to be that the new model's assumptions are only valid at high loads. They observed that as the load increases, the actuator gradually transitions from a homogeneous to an inhomogeneous state.

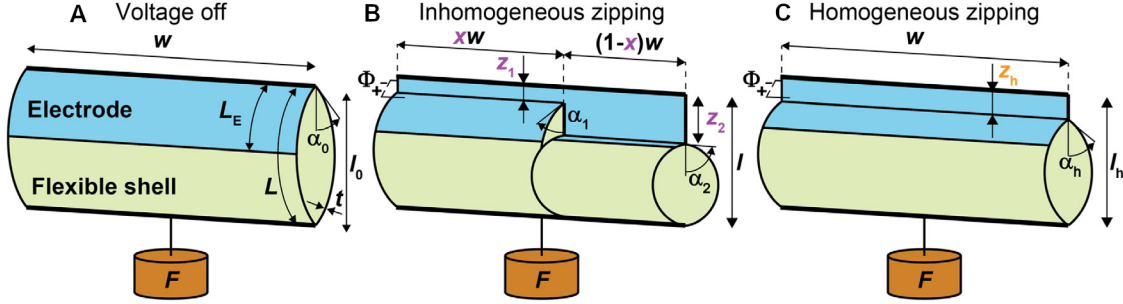


Figure 6: Schematic of the actuator's geometry for inhomogeneous model [10]. (A) Nonactuated mode. The geometry is the same as the earlier model. (B) Nonfully actuated mode for inhomogeneous zipping. The geometry separates into two different states characterized by their portion of the width by the parameter x . The zipped length parameters are z_1 and z_2 . We make the assumption of a discrete transition between the two states. The length l assumed constant and the same for both. (C) Nonfully actuated mode for homogeneous zipping. In the model, homogeneous zipping is a special case where one state covers the all width w .

The model from Kellaris et al. [9] outlined a roadmap to improve performance. For example, it shows that for a given strain ϵ , there is a maximum possible load F achievable using a specific electrode coverage f_e . The model also indicates that dividing one large actuator into many smaller ones increases specific energy. This is illustrated in the schematic in Figure 7A. The length L_p does not affect the force F , but does affect the area A quadratically (as shown in equation 2.1). And since A describes the volume (and thus the mass), a pouch with length $L_p/4$ would have a mass of $m/16$. Therefore, aligning four smaller pouches yields a total mass of $m/4$ compared to a single larger pouch, while achieving the same stroke. However, when L_p becomes comparable to the plastic thickness t , the film's bending stiffness starts to significantly affect the actuation behavior. In reality, the specific energy can only increase to a certain level around a given scale ratio $L_p : t$, like shown in Figure 7B.

The models described above only account for quasi-static behavior, focusing on force and strain at equilibrium. Additional studies have proposed models for dynamic effects. Rothmund, Kirkman, and Keplinger [11] first investigated the actuation time under two assumptions: purely inertial dynamics and purely viscous dynamics. They showed that the two types of dynamic behavior occur at different time scales. Later, Washington et al. [12] developed

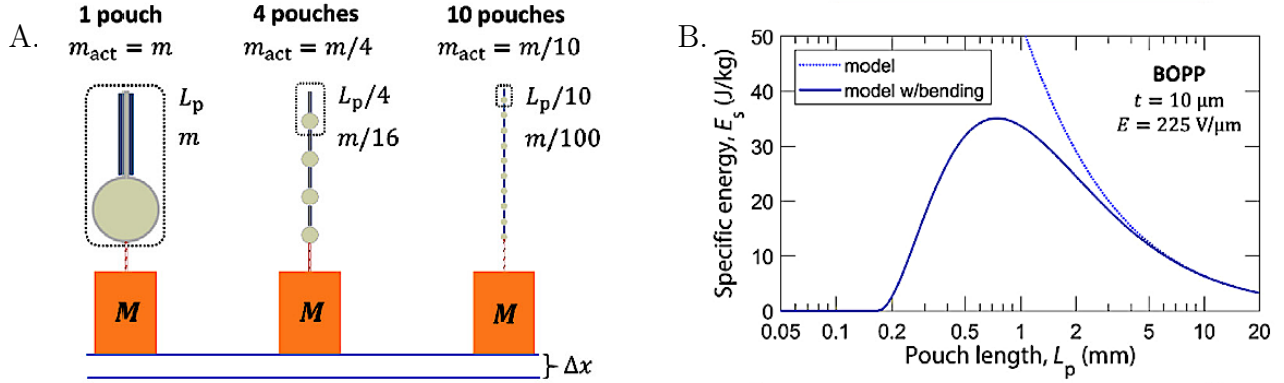


Figure 7: *Effects of reducing the length L_p [9]. (A) Schematic of stacking in series smaller pouches. For the same displacement Δx of the load mass M , the mass of the actuator m_{act} is divided by the number of pouches. (B) Graph of the specific energy E_s as a function of L_p . The basic model predicts that the specific energy continues to increase for still smaller L_p . When the model takes into account the bending stiffness of the film, it predicts that E_s reaches a maximum value for a certain L_p .*

a finite element method to simulate the electric field and were able to predict the response time, displacement results, and the motion of the fluid inside the actuator.

2.1.2 Donut shaped HASEL

As explained before, Peano-HASEL actuators were created after the first types of HASELs. These types, described by Acome et al. [5], works quite differently.

The donut shaped HASEL is composed basically of the same components as the Peano: inextensible but deformable plastic films, liquid dielectric and electrodes. However, the dispositions are different. The donut shaped is made of circular pouches with electrodes at its center. This changes the actuation behavior. First, while the Peano actuates linearly, the donut shaped possesses a pull-in transition. This means that the pouch goes from a non-actuated to an actuated mode when the voltage surpasses a threshold value. The other particularity with this geometry change is that the actuation force is perpendicular to the electrode. The process is schematized in Figure 8.

To eliminate the pull-in transition, Mitchell et al. [13] separated the pouch into four equal quadrants. When activated, the electrodes started zipping from the center to the extremities in a continuous transition. This gave a better control of the actuation state. When they stacked donut shaped HASELs on top of each other, the actuation force was multiplied. At a certain number, this force was able to make the stack jump when they applied a voltage pulse (see Figure 9).

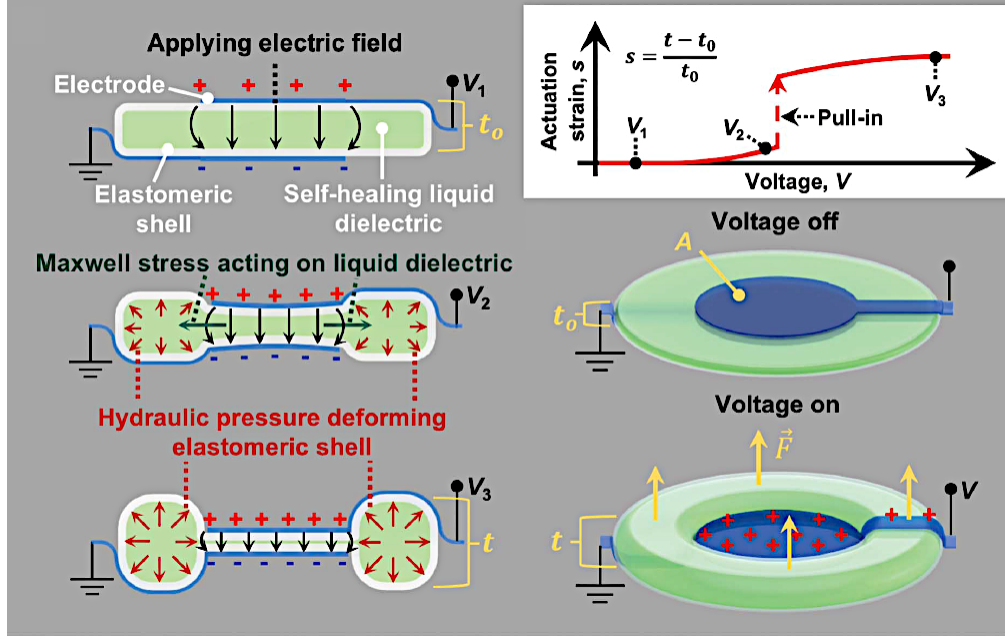


Figure 8: Schematic of the donut shaped HASEL's working principle [5]. On the left, it depicts the actuation states for different voltages $V_1 < V_2 < V_3$. The electrodes come together progressively until the pull-in voltage where the HASEL is fully activated. The graph on the top-right corner shows the strain s as a function of the voltage V . The pull-in voltage is indicated on the center of the plot. On the bottom right, the actuation states are seen from a 3D perspective. When actuated, the HASEL takes a torus shape like a donut. The force F is depicted with its direction normal to the electrodes.

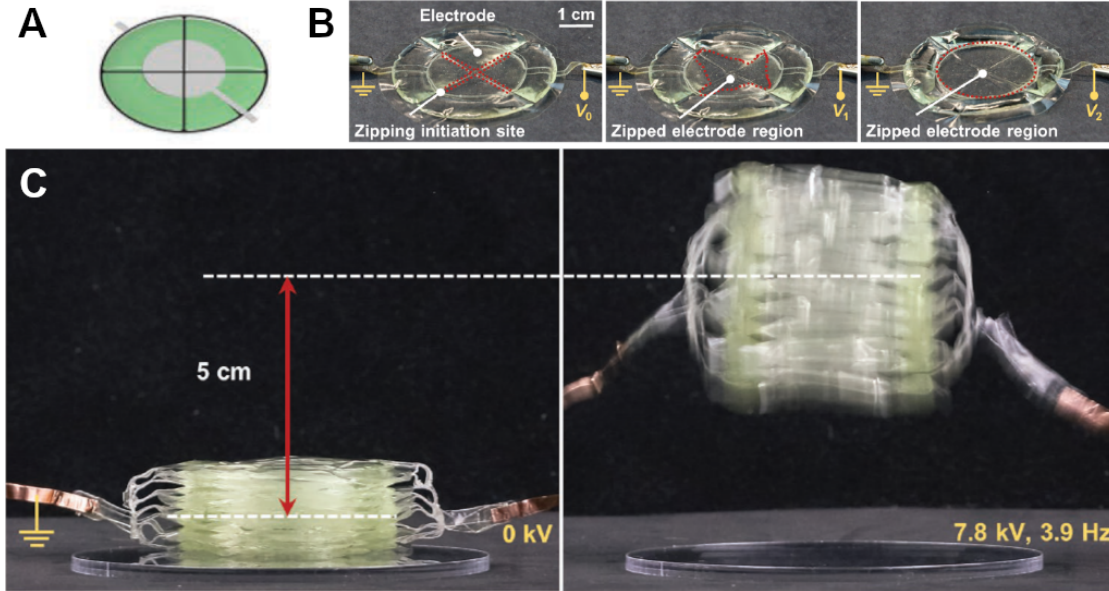


Figure 9: Donut shaped HASEL separated into quadrants [13]. (A) The schematic of the HASEL. (B) Different actuation states of the quadrant HASEL. (C) Jump of a stack of quadrant HASELs.

2.2 Manufacturing

The production process of the HASEL was first described by Kellaris et al. [6] (see Figure 10), but was perfected later by Mitchell et al. [13] (see Figure 11). This method is separated in three main different stages: heat-sealing, pouch filling, and electrode placement.

The heat-sealing stage consists in thermally bonding the plastic sheets together along a determined perimeter to create and delimit the pouch. In the literature, two approaches are reported. The first uses a heat press with a die that will delimit the shape of the pouches. An intrinsic caveat associated to this method is its limitation to produce only simple shapes. The second approach solves this problem by using a CNC heat-sealing machine that is compatible with the creation of HASELs presenting more complex geometries.

For the pouch-filling stage, a syringe's needle with the liquid dielectric is inserted in the pouch. Upon filling, the filling port is sealed using either an heated aluminium rod or a soldering iron.

As for the electrodes positioning, different types are listed in both methods. The main type of electrode used is lasercutted hydrogel, but aluminium or carbon paint are also used.

2.3 Properties

HASEL actuators possess different properties that can be useful for different applications. For example, the main advantage of HASELs compared to DEAs is the self-healing ability. Since the dielectric between the electrodes is liquid, it redistributes itself after an electric breakdown. This is a problem for the DEAs since they are composed of a solid gel that keeps the damages, shortening its lifespan. HASELs are therefore supposed to be more durable. However, the self-healing is not without limitations. As illustrated in Figure 12, the electrical breakdown ultimately creates gaz bubbles that affect the pouch. By dint of breaking down electrically, the pouch can weaken its dielectric properties and lose performance.

Another interesting ability of the HASEL is the self-sensing. As the HASEL is actuated, the capacitance, dependent from the distance between the electrodes, changes. Therefore, by inducing an small alternative component to the voltage and by measuring the capacitance, it is possible to measure the deformation of the pouch. This property was first demonstrated by Kellaris et al. [6] in an experiment reported in Figure 13, where they used the same electrodes for actuation and sensing. However, the actual standard way is to add new low voltage electrodes that sense the capacitance as schematized in Figure 14.

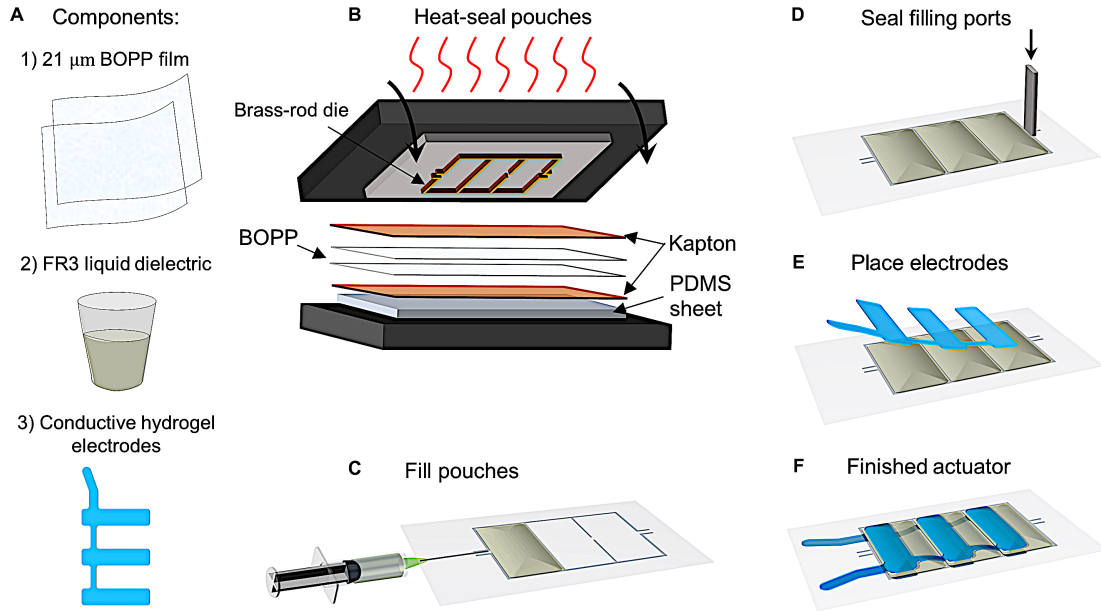


Figure 10: *Schematic of HASEL's the manufacturing method developed by Kellaris et al. [6]*

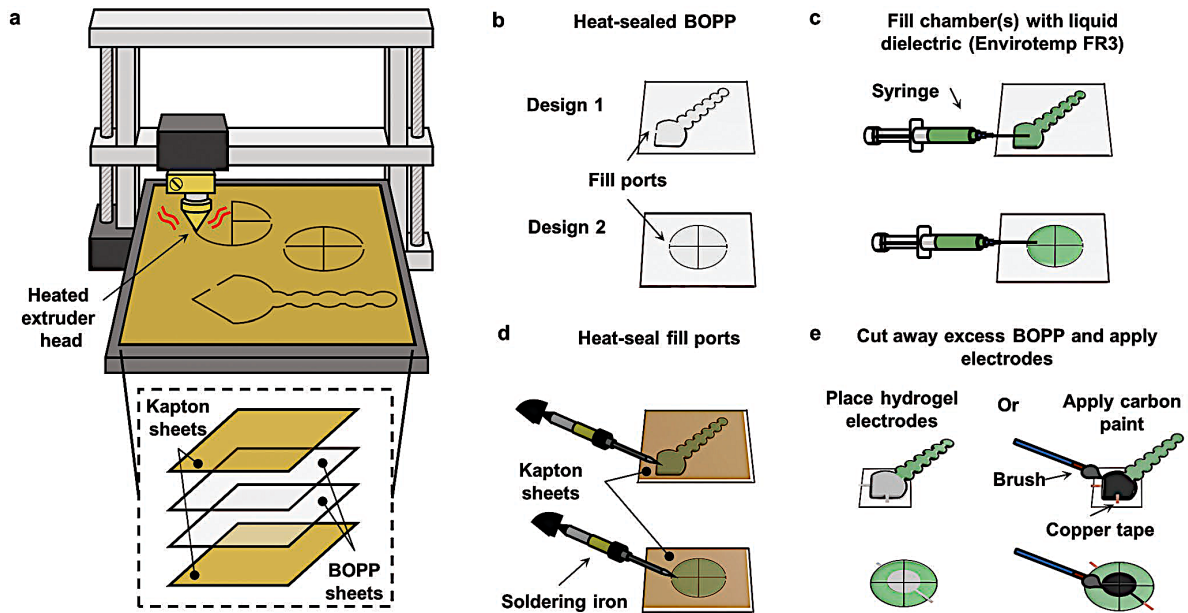


Figure 11: *Schematic of HASEL's the manufacturing method developed by Mitchell et al. [13].*

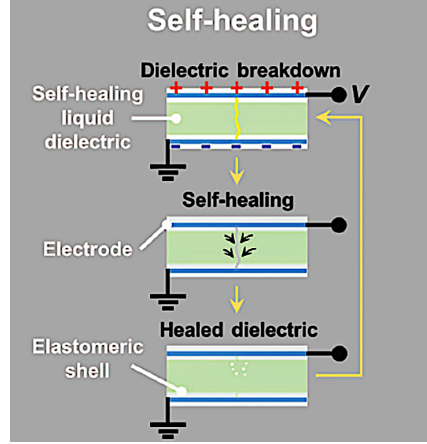


Figure 12: *Self-healing ability of the HASEL. When an electrical breakdown occurs, the liquid redistribute itself in the pouch, allowing it to continue working properly. However, the breakdown creates gas bubbles that affect the dielectric properties, weakening the pouch afterwards.*

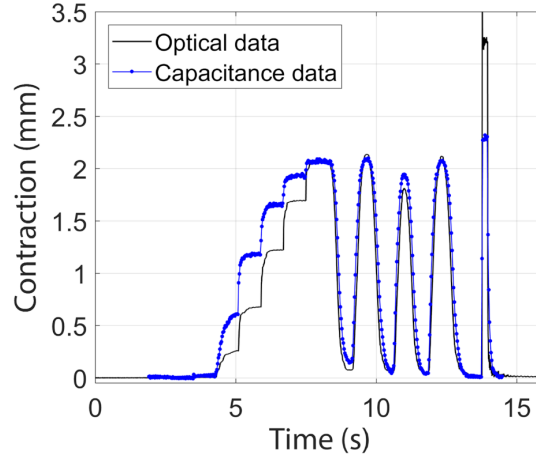


Figure 13: *Graph of the sensed capacitance compared to the visual observation under different voltage signals [6]. A simple scaling factor was applied to the capacitance to match the observations without other calibration.*

A last interesting property we report here pertains to the possibility to associate HASEL actuators. Indeed, stacking them in parallel multiplies the actuation force for the same strain. Figure 15A shows the most efficient way to stack them in parallel in order to reduce the overall volume. By placing 6 actuators like that, Kellaris et al. [6] were able to increase the force by a factor 6 (see Figure 15B). This shows that the force scales linearly to the number of actuators.

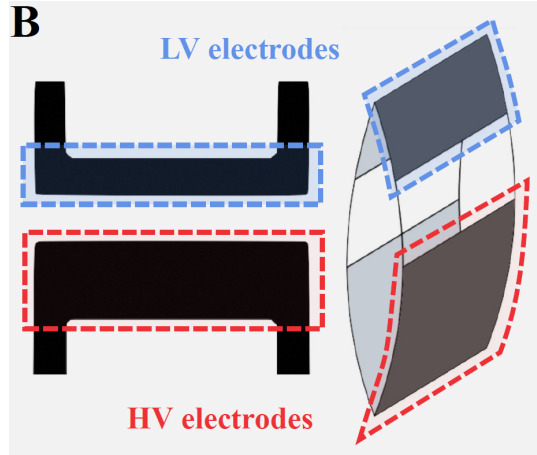


Figure 14: *Schematic of the new standard way for self-sensing HASELs [14]. High voltage electrode actuate the pouch while other low voltage electrodes are placed to the other side to sense the capacitance.*

2.4 Applications

HASEL actuators were used in a diverse range of application: from prosthesis [15, 16] to pumps/valves [6, 17] or even simple applications such as swimming robots [18] or small mimetic robots [19]. While the majority of applications used the basic working principle of HASELs, others used techniques to make them achieve different functions.

As an example, the scorpion tail made again by [13] curved willingly a Peano-HASEL. Using a strain limiting layer on a side of the pouch, they were able to control the curvature of the tail, as shown in Figure 16

This curving HASELs can be used as a grappling. Again, Mitchell et al. [13] used three small curving HASELs to create a grappling that they put over three stacks of quadrant donut shaped HASELs. By controlling each stack separately, they were able to make it move like an elephant trunk that could even lift its own power electronics. This trunk is picture in Figure 17.

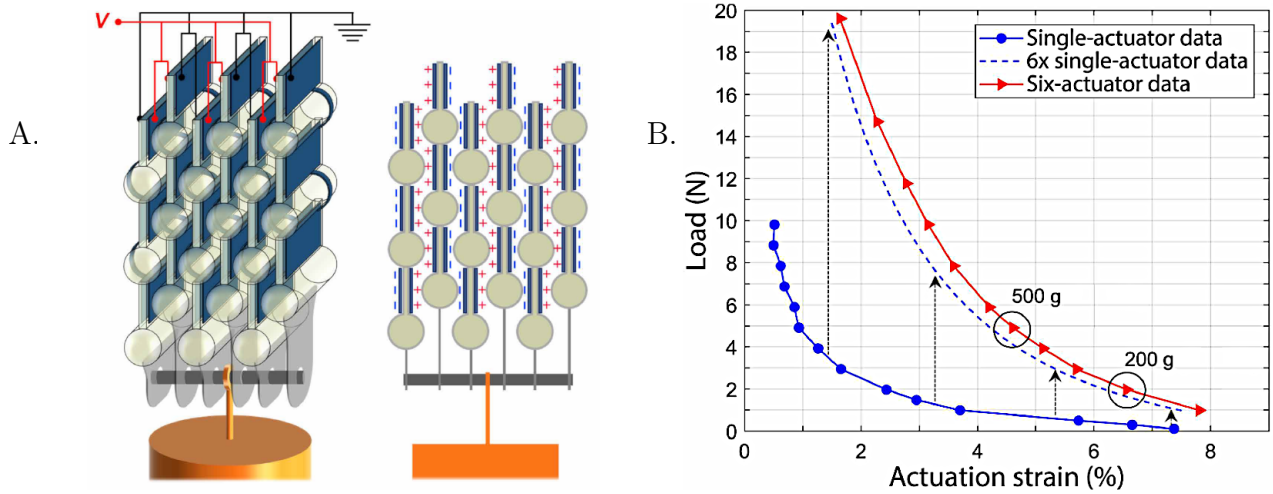


Figure 15: *Stack of six Peano-HASELs in parallel [6]. (A) Schematic of the disposition of the actuators. Electrodes of the same charge face each other to avoid breakdown. (B) Force-strain curve of the stack compared to a single actuator. The stack slightly out-performs the theory. This is certainly due to the fact that HASELs do not have perfectly the same curve.*

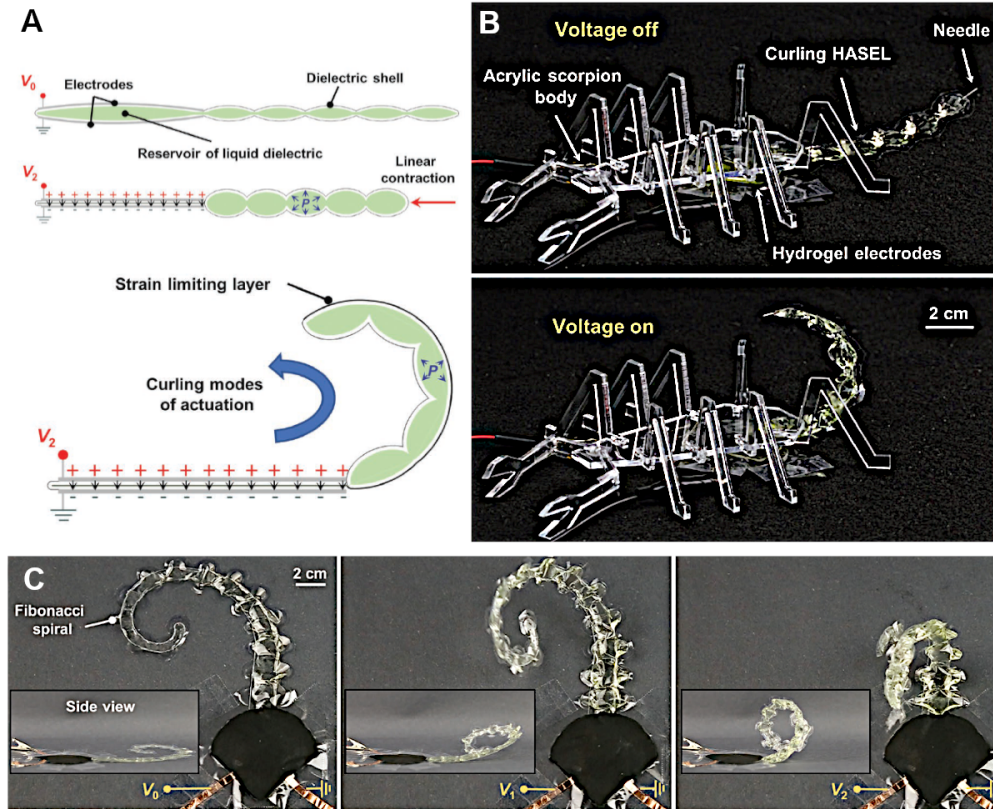


Figure 16: *Mimetic scorpion tail with Peano-HASEL actuator [13]. (A) Schematics of the actuation of the HASEL. As the tail simply contracts, the strain limiting layer bends the rest of the pouch upwards. (B) Actuation states of the HASEL with an acrylic scorpion body. (C) Different curvature of the HASEL.*

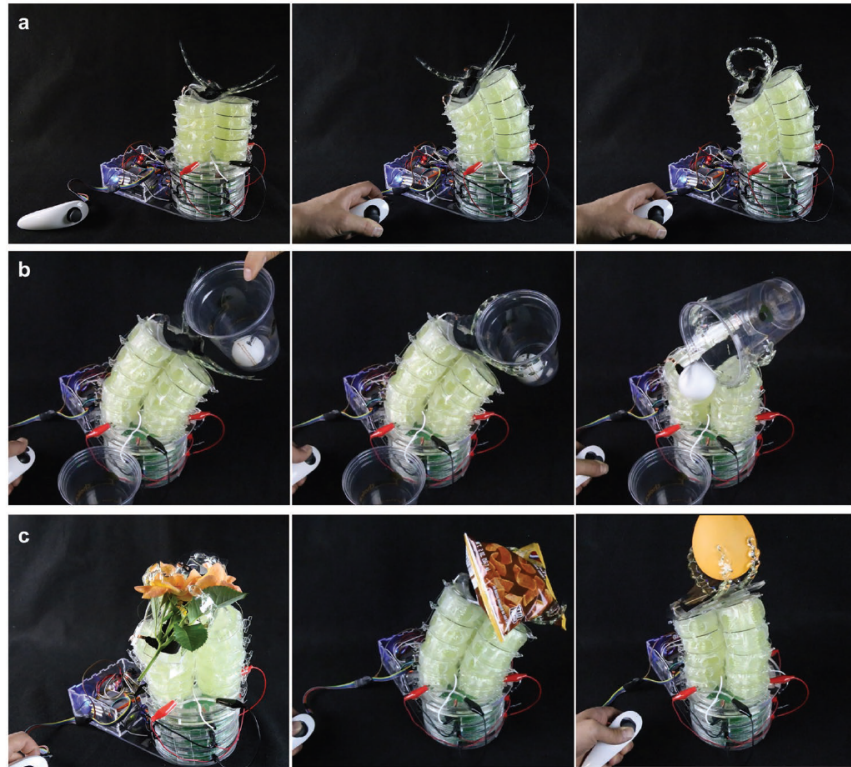


Figure 17: *Trunk with grappling hook [13]. This trunk is composed of three stacks of quadran donut shaped HASELs controlled separately with three curving HASELs on top that serves as the grappling hook. It is able to grab different delicate objects of different shape without damaging them.*

3 Manufacturing method

The objective of this master’s thesis is to produce Peano-HASEL actuators with reliable repeatability. To this end, a dedicated manufacturing method was designed and implemented based on the work initiated by Pomponio [20], who developed some of the tools and processes employed here. The proposed method draws on approaches presented in previous studies [6, 13] and is described in Section 2.2. It consists of the same three main stages: heat-sealing, pouch filling, and electrode placement. In the following sections, each of these steps will be examined in detail to explain both its implementation and underlying rationale.

The dimensions of the Peano-HASEL actuator manufactured in this work are with those tested in Kellaris et al. [6], namely 3 pouches of 40mm in width and 20mm in length. This allows for direct performance comparison between our actuator and theirs. A schematics of these dimensions is illustrated in Figure 18. A complete table with the materials and the tools used in this method is given in Appendix A.1.

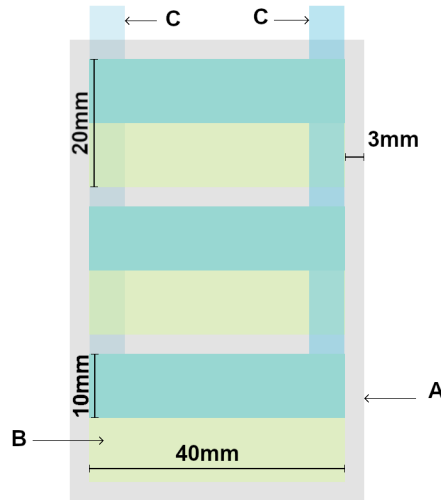


Figure 18: *Dimensions of the Peano-HASEL manufactured in our process. (A) Bonded region. (B) Liquid dielectric. (C) Electrodes.*

3.1 Heat-sealing

Peano-HASEL actuators are composed of two plastic films thermally bonded along a perimeter to delimit the pouches. The main plastic used in the first studies [6, 9, 13] is biaxially oriented polypropylene (BOPP). In this work, we used BOPP but also simple un-

oriented polypropylene (PP), both commercially available online ¹². Their properties are summarized in Table 1. A simple calculation based on those properties shows that the maximum voltage for both films, using two layers, greatly exceeds 10 kV, the maximum value used by Kellaris et al. [6]. The main difference lies in the thickness of the films. While the BOPP films used in previous studies had a thickness of 21 μm , our films were 30 μm or 40 μm thick.

Property	Polypropylene	BOPP
Dielectric constant (ϵ_r)	2.3	≈ 2.2
Dielectric breakdown strength	$\approx 500 \text{ kV/mm}$	$\approx 650 \text{ kV/mm}$
Thickness	30 μm	40 μm
Breakdown voltage for two layers	$\approx 30 \text{ kV}$	$\approx 52 \text{ kV}$

Table 1: *Comparison of properties for plastic films used. Sources are in Appendix A.1.*

The plastic films are supplied in the form of small bags. The first step in the process is to cut two sheets of the desired dimensions. After that, a thin layer of oil (see Section 3.2 for the oil description) is applied between the sheets, spreading it over the area where the pouches will be formed. This ensures adhesion between the sheets and reduces the amount of air trapped in the pouches. It facilitates the pouch filling in the next stage.

Once the sheets are prepared, we heat-seal them using a heat press pictured in Figure 19A. On this heat press, we attach a mount of our own design onto the upper plate. This device features at its center a die with the desired shape of the pouches. As shown in Figure 19B, the die consists of L-shaped profiles mounted on a plate in contact with the upper plate of the press. The section of the profiles heat-seals over a 3mm wide area. When activated, the heating element of the press warms the upper plate, transferring the heat to the die through the intermediate plate.

On the bottom plate, we place a base composed of an acrylic plate, 5mm thick, supported by six pads of solid deformable foam with a 2mm polydimethylsiloxane (PDMS) layer on top. The PDMS serves as a load-dispersing layer. Unlike Kellaris et al. [6], we place the plastic films directly onto the PDMS layer. This does not cause problems, as the films do not damage the PDMS when heated. However, we also add a Kapton sheet to cover the upper side. We also use Kapton strips to form the filling ports on the side. Before using those strips [20], a previous version where nicks had been made in the L-shaped profiles the die was evaluated. It turned out that the nicked profiles made the sheets adhering together, obstructing the port. The Kapton strips avoid this adherence, leaving a cleared opening for the filling. The heat-sealing occurs when we operate the press lever. The different steps are illustrated in Figure 20.

¹BOPP: <https://www.packlinq.be/fr/sac-fond-pliant-avec-insert-papier-100-pieces-fgpbh4.html>

²Polypropylene: https://www.amazon.com.be/-/en/gp/product/B07RY6KSZV/ref=ox_sc_saved_image_1?smid=A2QM9A67WM104E&psc=1

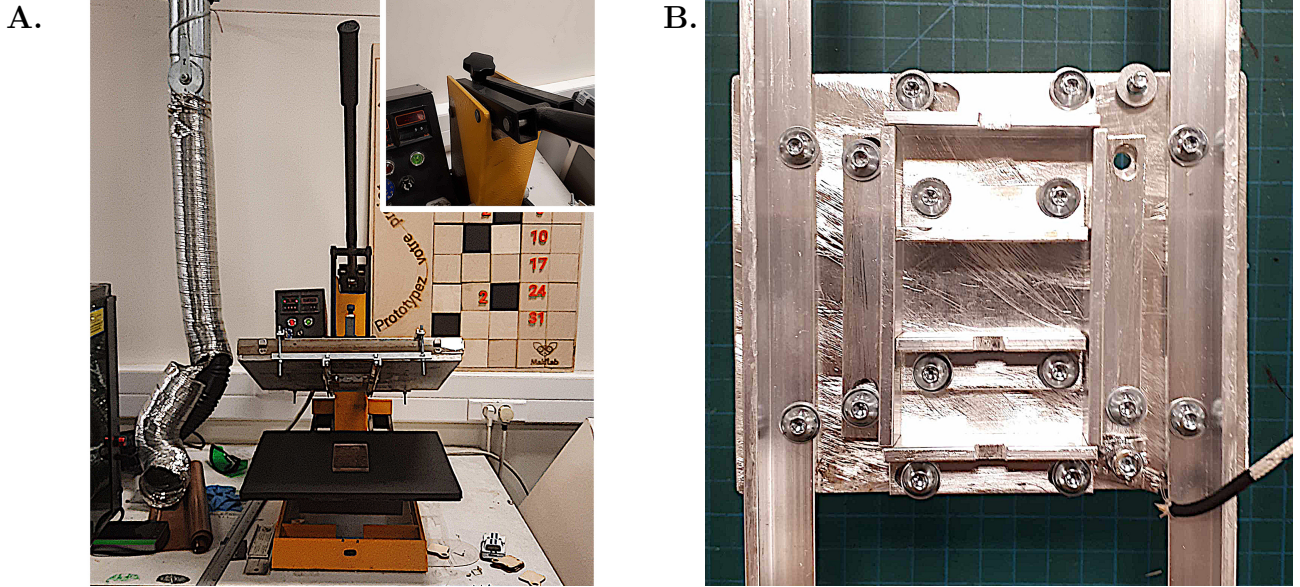


Figure 19: Tools used to heat-seal the pouches (A) Heat press. The mount is clamped onto the upper plate. The press is actuated by the lever and a screw behind this lever adjust the distance between the plates. The black box behind the upper plate sets the temperature. (B) Die [20]. It is composed of a metallic plate on which two L-shaped profiles link it to the mount. L-shaped profiles are positioned to form the shape of the Peano-HASEL. When the press warms, the heat is transferred to the profiles via the base plate.

Three main parameters can affect the quality of the plastic bond: pressure, temperature, and duration. For pressure, the press is equipped with a height-adjustment screw that controls the pressure by setting the distance between its two plates. To ensure consistent pressure, we fully tighten this screw.

We further optimized the other parameters experimentally. We tested different combinations of temperature and duration: durations between 1s and 5s, and temperatures between 180°C and 210°C in 10°C increments, corresponding to a total of 20 samples. To assess bond quality, we first checked which samples could be easily separated by hand. The bonds obtained with both lower temperatures and shorter durations could be discarded based on this criterion. Next, we inspected the bonded regions for imperfections such as holes or deformation, that led us to reject samples produced with both higher temperatures and longer durations. The full set of results is presented in Table 2. Four viable parameter sets remained. In order to choose those remaining combinations, we repeated six time the manufacturing process with these combinations to confirm the repeatability. At the end of the process, some of the created HASELs presented the same defects as rejected combinations, either easily separable or with imperfections in the bonds. Those imperfections are pictured in Figure 21 to highlight the difference with a good bond. The combination of 190°C during 4s, that produces the least imperfections, was selected to be the optimal set.

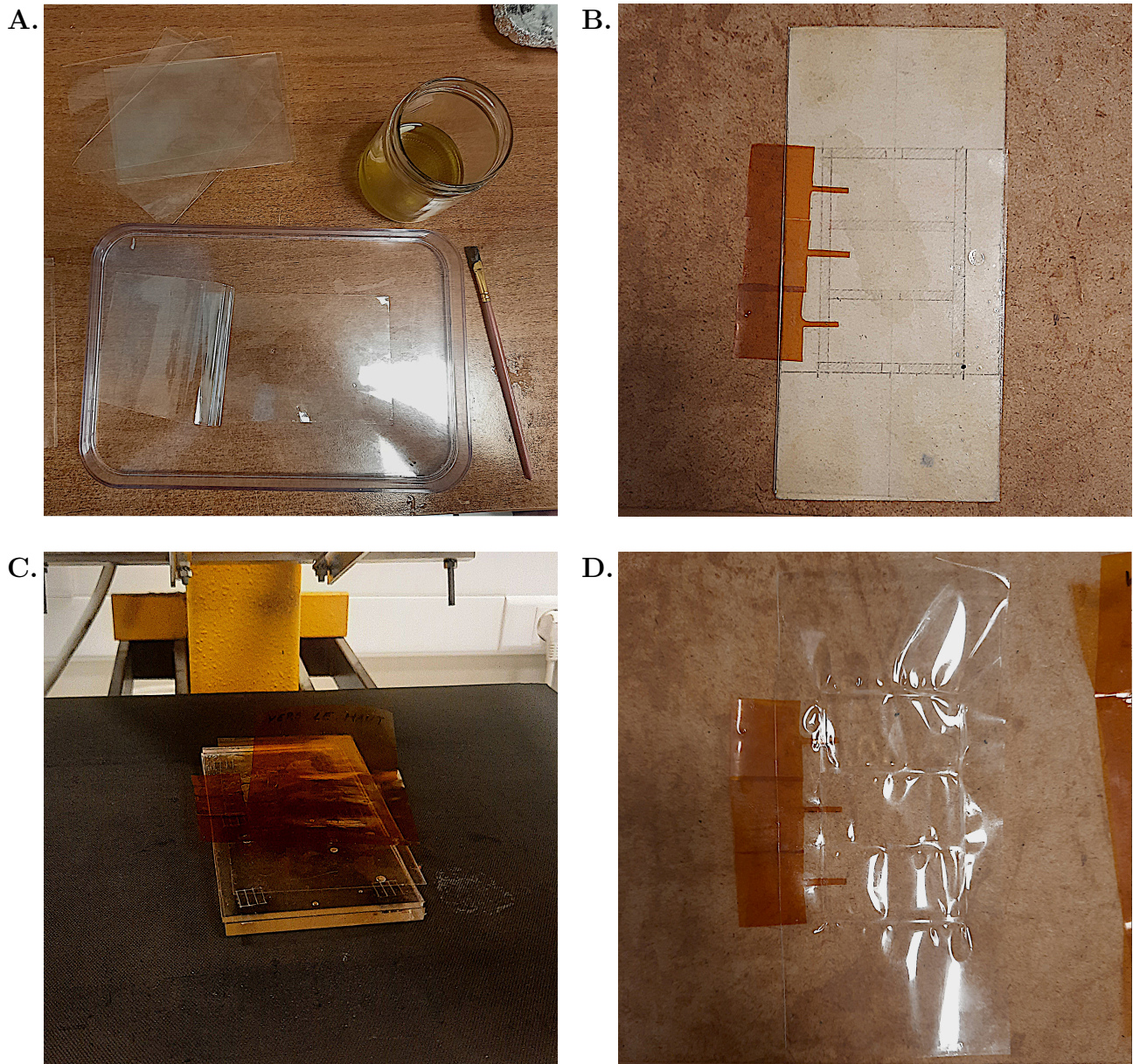


Figure 20: *Peano-HASEL actuator at different steps of the heat-sealing stage. (A) Applying the layer of oil between the plastic sheets. This layer helps to not get air inside the pouch before the filling stage. (B) Positionning the strips of Kapton using the schematic to create filling ports. (C) Plastic sheets placed with the base and the sheet of Kapton. The three are misaligned for a better view. (D) Heat-sealed Peano-HASEL still with the strips. Marking the filling ports' position helps to quickly locate them for the filling stage.*

	180°C	190°C	200°C	210°C
1s	Easily separable	Easily separable	Good bond quality	Imperfections found
2s	Easily separable	Easily separable	Imperfections found	Imperfections found
3s	Easily separable	Good bond quality	Imperfections found	Imperfections found
4s	Easily separable	Good bond quality and best repeatability	Imperfections found	Imperfections found
5s	Good bond quality	Imperfections found	Imperfections found	Imperfections found

Table 2: *Different combinations of temperature and duration of heat-pressing. In blue, the plastic films were easily separable, leading to possible leaks. In red, imperfections such as holes or defects were detected, which could influence the electrical behavior. In green, bonded parts were of good quality, with good strength and no defects. The final criterium that led us to choose 190°C and 4s is the repeatability.*

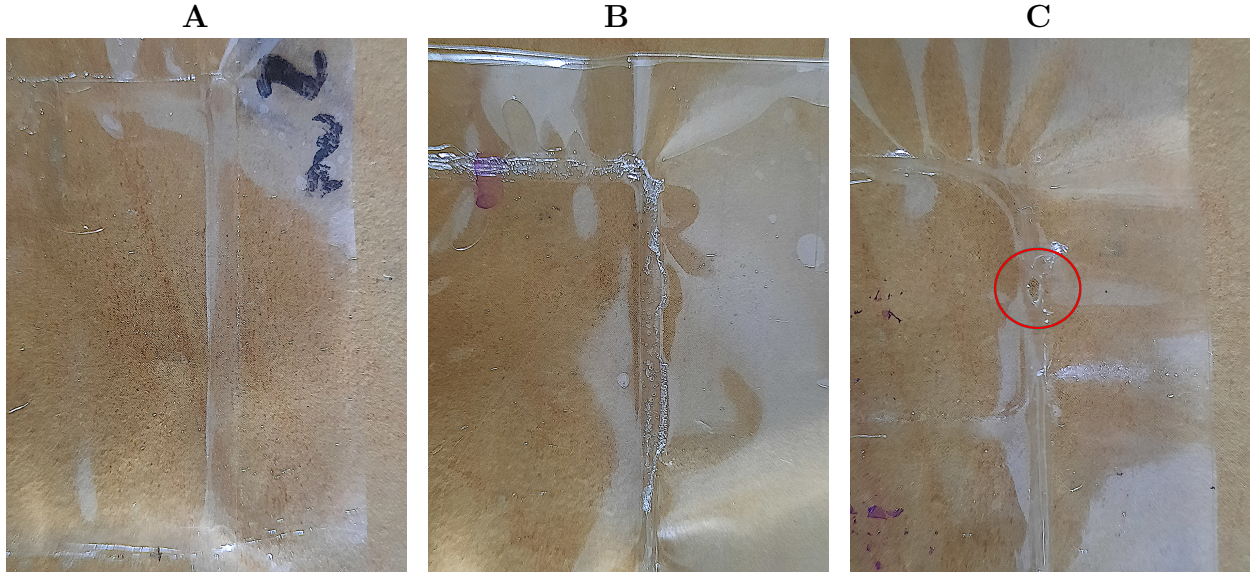


Figure 21: *Quality differences for a bond. (A) Good quality bond. The bonded region is translucent. (B) Poor quality bond. The bonded region shows partial separation of the plastic layers, making the bond line thinner than expected. The thickness is important for the breakdown voltage the actuator can resist. (C) Hole in the bonded region (circled in red). Holes in the plastic films create a passage for the electric current. They can be responsible for electric arcs that ultimately provoke a short-circuit.*

3.2 Pouch Filling

After the heat-sealing of the pouch, the next stage consists in filling them with a liquid dielectric. The liquid used in this work corresponds to olive oil. Its dielectric properties are

comparable to those of the vegetal oil used by Kellaris et al. [6] (Envirotemp FR3), and it has the advantage of being easily available. Its breakdown voltage exceeds $80kV$ [21], and its dielectric constant is approximately $\epsilon_r \approx 3.1$ (see Appendix A.1). The main difference in this case is the viscosity, which is higher than what was used previously ($43mm^2/s$ ³ against $\sim 32 - 34mm^2/s$ [22] used by Kellaris et al. [6]). The viscosity could affect the dynamic behavior of the HASELs, however it should be a good substitute for our prototypes in theory. The different steps of this stage, reported below, are illustrated in the Figure 22.

At the beginning of this stage, we simply have the HASELs with empty pouches. The filling ports are the only access points to the inside and are approximately $2mm$ wide. This size is required since we use syringes with needles having a diameter of $1mm$. The ports need to be large enough to let the needle pass through but thin enough to limit the amount of air entering. We want the smallest volume of air possible because it lowers the breakdown voltage. In this method, we use medical syringes of $5ml$ available on the market. We also use a needle with a flat tip to avoid damaging the pouch when inserting or retrieving it.

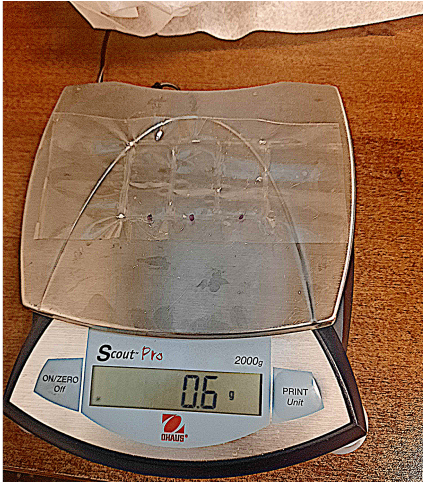
First, the syringe without the needle is filled by aspiration. After mounting the needle on the syringe, a small pressure is exerted on the piston to chase as much air as possible. Then the needle is carefully inserted into the port to avoid piercing the pouch. When the needle is in the pouch, we place the port in a clamp of our design [20] (see Figure 22B). The clamp temporarily closes the area outside the port to block additional air from entering and oil from leaking out. When the port is clamped, we gently fill the pouch with the desired volume. Unfortunately, we could not prevent air bubbles to appear. To remove them, the best technique we found consists of combining them into a single bubble (like in Figure 22C), which we then suck up through the needle. After bubble removal, the missing volume of oil is added (see Figure 22D). We then retrieve the needle and seal the port (see Figure 22E). To check if the port is well sealed, we apply a small pressure by hand and we look if oil starts to drip.

For the sealing step, the surface of the port is much smaller, and using the press would not be optimal as we need better precision. Instead, we use a soldering iron fixed on a mount, shown in Figure 23A. This mount is designed for melting brass thread inserts in 3D-printed components. It consists of a metal bar fixed on a linear slide supported by a spring. The goal of using this mount is to ensure the best positioning of the soldering iron with the filling port. The only thing we needed to adapt was the tip of the iron. A new one was machined in iron with a flat circular surface. The diameter of this new tip is $4mm$ as shown in Figure 23B.

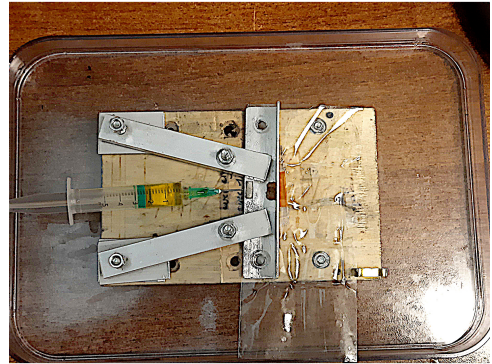
This mount also allows us to control the same parameters than those taken into consideration when using the press, i.e. pressure, temperature and duration. However, the setting values have to be adapted because the two plastic sheets in this case are separated by more oil, but also because the tip of the iron covers an already bonded region when pressed. To avoid deteriorating this overlapping region, we need to apply less pressure than before. Therefore,

³https://www.engineeringtoolbox.com/kinematic-viscosity-d_397.html

A.



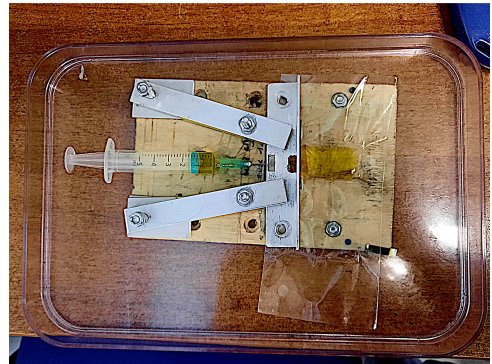
B.



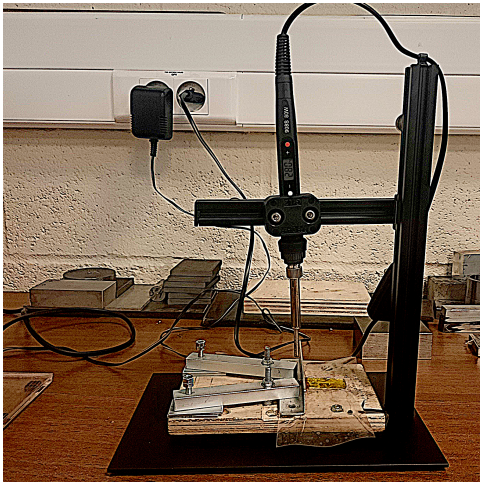
C.



D.



E.



F.



Figure 22: Different steps of filling a pouch (A) Weighing the unfilled HASEL. (B) Inserting the syringe's needle in the pouch through the filling port and clamping the port. (C) Filling the pouch. Rassembling the air bubbles into one (circled in red) and sucking it out. Filling the rest of the oil (D) Pouch filled. Removing the syringe. (E) Sealing the filling port with the soldering iron. (F) Weighing to check the volume filled. Repeating all the steps for all the pouches.

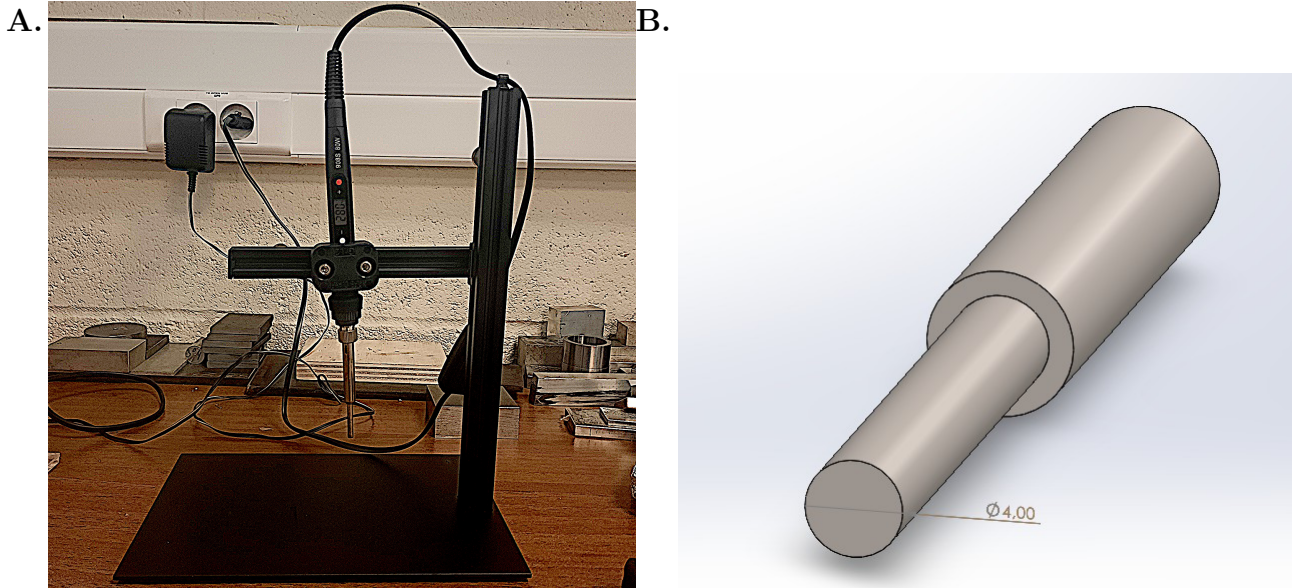


Figure 23: *Tools to seal the filling ports. (A) Mount with soldering iron. This mount is composed of a base with a vertical aluminium profile strut. A linear slide is fixed on this vertical profile and a horizontal one is screwed to the slide. The iron is clamped in a casing. (B) 3D image of the soldering iron's tip. The diameter of the surface in contact with the HASEL is 4mm.*

when sealing, we simply guide the iron to put it in contact with the port. Since we decrease the pressure, we need to increase the temperature. We tested experimentally different possibilities. The goal was to find the best set that created a seal strong enough but without creating holes that could pierce the pouch. After those tests, we settled at a temperature of 280°C and a duration of 3s. Using this method, the port is completely sealed with a bond of good quality, and the overlapping region is not damaged.

To check the volume of oil in the pouch, we weigh the HASEL before and after filling (respectively Figure 22A and F, respectively). The density of olive oil is 0.91g/ml ⁴, and since we want to insert 1.4ml into the pouch, we verify after each measurement if the weight increased by 1.3g . When performing the process on many pouches, the maximum difference in liquid volume inside the pouch is 0.2ml .

3.3 Electrodes setting

Upon the pouches filling, the last stage to finalize the constitution of the HASEL corresponds to the placement of the electrodes. Previous studies [6, 13] used principally hydrogel electrodes laser-cut but proposed different viable alternatives. In this work, we tested three kinds of electrode: spray-painted graphite, painted liquid graphite, and glued aluminium foil. All of them are represented in Figure 24. Of the three, aluminium electrodes were the only

⁴https://www.engineeringtoolbox.com/liquids-densities-d_743.html

ones kept in the final method for different reasons.

First, the spray-painted graphite does not adhere properly to the plastic films of the HASELs. As a result, the electrodes can be wiped away easily after a number of manipulations. To avoid this issue, we tried to apply a layer of acrylic lacquer, but the protection remains insufficient as they are still able to come off. Another problem is the thickness of the electrodes. When spraying at the recommended distance, the electrode layer is too thin and could cause problems in the repartition of the charges. However, When moving the spray closer, although a slightly better adhesion is observed, it can still be easily wiped away. In addition, the graphite gains a liquid form on some parts and seeps under the stencil tape, giving it an uncleaned finish. The situation is not sufficiently improved with the liquid paint approach that leads to the same issues of seeping and weak adhesion on the plastic film.

The best alternative identified consists in aluminium-glued electrodes. To set it up, we simply use food-grade aluminium with a thickness of $13\mu\text{m}$, which we cut into shape and glue directly onto the film. In a first attempt, we glued the electrodes on the filled pouches, but after trying on empty pouch before filling, it turns out that the electrodes are easier to place on the flat film.

3.4 Tests and results

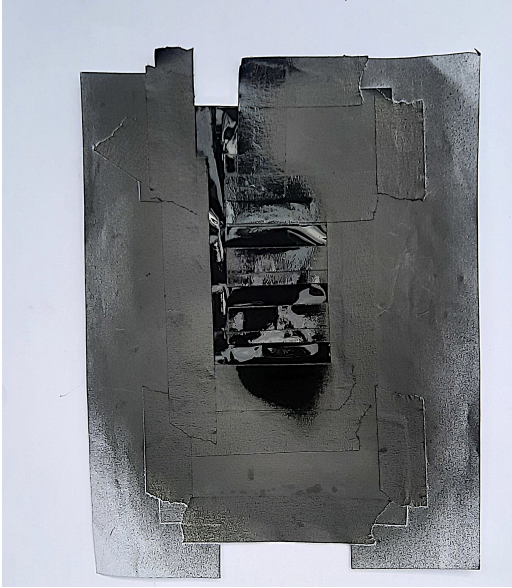
The optimization of the HASEL manufacturing was conducted as an iterative trial-and-error process. This means that the different attempts of improvement in the manufacturing process resulted in an actuator that had to be tested. Test failure led us to investigate the cause of the failure, propose a modification in the manufacturing and re-test the resulting new HASEL. Table 3 recapitulates the different tests that have been performed during this iterative process in chronological order.

The tests were performed on the same mount that we designed which is described in more detailed in Section 4. We also used a DC high-voltage power supply [23], able to deliver up to $35\text{kV}10\text{mA}$. To connect the actuator to the supply, we used cables with U-shaped tips that we clamped using a screw, a washer and a nut. For security, we linked the mount base to the ground to ensure no static electricity could build up. To avoid anyone touching it, we also built a casing made of plexiglass.

As a starting point, three Peano-HASELs created before the manufacturing process was finalized, corresponded to a pouch sealed at 220°C during 1s , with electrodes made of graphite liquid paint. For all of these three pouches, disclosed electrical arcing in the bond region when applying a $3.5 - 4\text{kV}$ voltage. These arcing caused the formation of holes in the plastic and pierced the pouches.

The fact that electrical arcing occurred in the bonded regions was also observed by Kellaris et al. [6]. To dive further on into this phenomenon, we decided to test strip bands made of unfilled Peano-HASELs cut in half. These HASELs were also heat-sealed at 220°C during

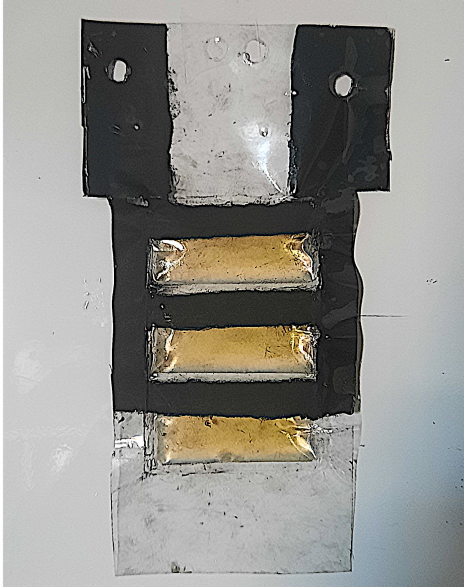
A.



B.



C.



D.



Figure 24: *Types of electrodes tested. (A) Canvas for graphite spray paint. We observe that the paint has a laquered aspect showing that it takes a liquid form. (B) Spray-painted electrodes. Its delimitations are not clean. We can also see traces laid when handling the HASEL. In fact, the paint does not adhere well to the plastic sheet. (C) Graphite liquid paint electrodes. We use the same type of canvas with tape for the electrode's shape. Delimitations are more clear but still vague. The liquid paint adheres a bit better than the spray but still comes off easily. We still have traces of graphite on the rest of the sheet. (D) Aluminium electrodes. The electrode's shape is cut before the positioning using a cardboard canvas. The delimitations are clear.*

n°	Geometry Description	Heat-sealing parameters	Filling conditions	Electrodes type	Results
1	3 pouches; $L_p = 20$ mm, $w = 40$ mm	BOPP 220°C/1s	1.4 ml/pouch	Liquid paint graphite	No actuation. Electric arcs occurred in the bonded region.
2	Strips	BOPP 220°C/1s	Not filled	Liquid paint graphite	Electric arcs occurred in the bonded region.
3	3 pouches; $L_p = 20$ mm, $w = 40$ mm	PP 190°C/4s	1.4 ml/pouch	Aluminium	No actuation. No electric arcs.
4	Two plastic sheets	Unsealed PP	/	Aluminium	Electrodes came together.
5	3 pouches; $L_p = 20$ mm, $w = 40$ mm	PP 190°C/4s	1 ml/pouch	Aluminium	No actuation. Electric arcs occurred in the sealed ports.
6	1 pouch; $L_p = 66$ mm, $w = 40$, mm	PP 190°C/4s	2 ml	Aluminium	Actuation.

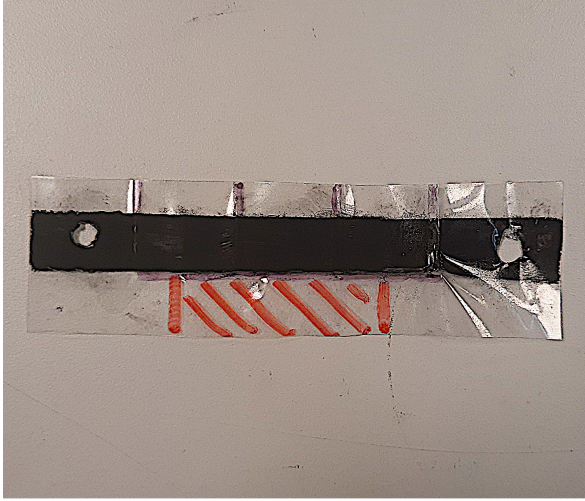
Table 3: List of carried out tests in chronological order.

1s. On each side of the strips, graphite electrodes were paint in a way they could overlap in the center of the strip, as illustrated on Figure 25A. A total of eight strips were produced and tested.

During these tests, the voltage was progressively increased until we started to observe electrical arcing. For many strips, electrical arcing stopped after a period where the voltage was maintained constant. Upon voltage re- increasing, electrical arcs started to reappear inducing the formation of holes that connected electrodes together and, as a result, created a permanent short-circuit in the strip. The maximum voltage tested was 12kV. Example of holes are shown in the Figure 25B. Out of the eight strips tested, only one did not produced electrical arcing and another one did not result with a permanent short-circuit. The results are plotted in the graph of Figure 26.

The average voltage at which electrical breakdowns started to occur is around $8kV$. This value is much smaller than the theoretical one reported for BOPP in Table 1 (52kV). This means that the heat-sealing affects the dielectric property of the plastic of the bonded region. Such reduction of the break-down voltage could be due to two effects: the reduction of the plastic thickness and the change in its chemical rearrangements. As a result, the theoretical value would not account for the real dielectric breakdown resistance of the actuator. A more representative value can be obtained by taking the average measured voltage V_{avg} divided by

A.



B.

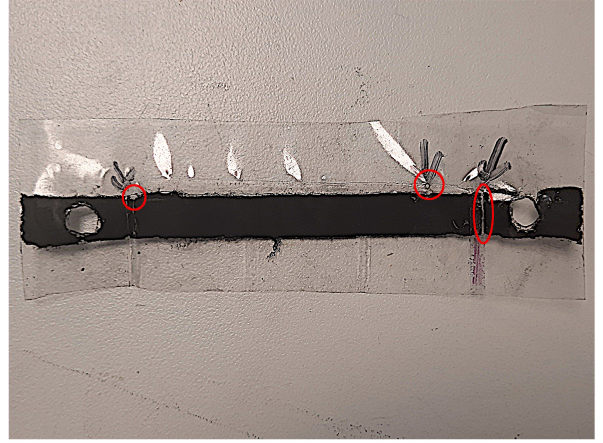


Figure 25: *Test strips made of a non-filled Peano-HASEL actuator cut in half. Electrodes are painted with graphite on each side of the strip overlapping in its center. (A) Test strip. The bonded region are shown in purple while the red area shows the region of overlapping electrodes. (B) Example of a short-circuited test strip. Holes are shown in the circled areas. These holes are formed by an electric arc passing through the plastic, melting it and therefore letting the electric current pass through.*

twice the thickness of the film t . We calculate this with :

$$E_c = \frac{V_{avg}}{2t} = \frac{8000}{2 \cdot 40 \cdot 10^{-6}} = 100kV/mm \quad (3.1)$$

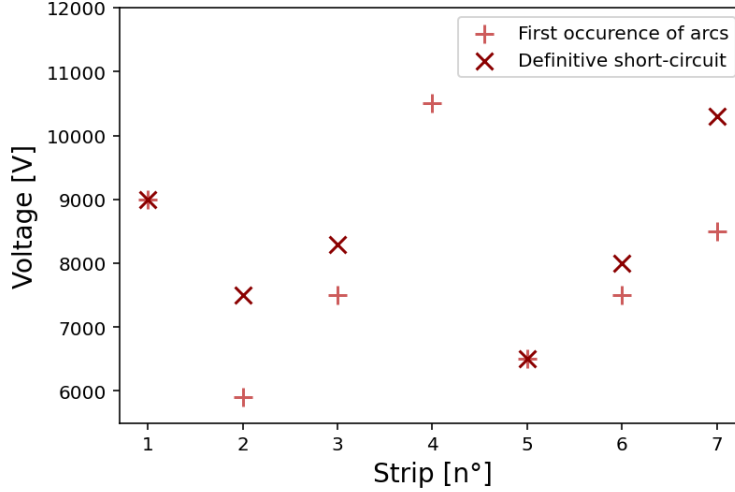


Figure 26: *Graph of the strips test's results. The first appearance of electric arcs are marked by the straight crosses and the appearance of the definitive short-circuits by the tilded cross. The strip without electrical breakdown is not represented in this graph. Strips n°1 and 5 produced directly a definitive short-circuit. Strip n°4 produced none.*

This breakdown voltage value E_c corresponds to the one of a bonded region made using non optimal settings. To get the right value corresponding to a properly sealed bond, this test should be performed on strips sealed with the optimized settings. Actually, this test could be used to determine the quality of the bonding. Indeed, it would give us a quantitative results on which we could rely on to select the best parameters in the heat-sealing step.

The second batch of actuators were created following the final manufacturing method presented. They were made of polypropylene with pouches thermally bonded at $190^{\circ}C$ during 4s. The pouches were filled with 1.4ml of olive oil and the port was sealed at $280^{\circ}C$ during 3s. Electrodes were made of aluminium foil glued to the plastic. These actuators were tested under voltage up to 12kV. A picture of the test is shown in Figure 27. During the test, no electrical arcing was observed, suggesting that the sealing parameters were compatible with a good quality of the bonds. Unfortunately, the HASELs did not actuate itself. At this stage, we formulated two hypothesis that could explain the absence of actuation: either the electrodes were not deformable enough and conferred a rigidity to the pouch, incompatible with a contraction or the oil was too viscous to permit a liquid motion.

To verify the first hypothesis, we tested the electrodes. The test, schematized in Figure 28, consisted of two sheets of plastic with an electrode on each one. We placed them at an approximate distance of 10mm. The goal was to see if the electrodes, under applied voltage, would attract each other. Around 2kV, the electrodes came into contact, proving that the electrodes could deform enough. Therefore, the suspected rigidity of the electrodes cannot account for the absence of actuation observed the prototype.

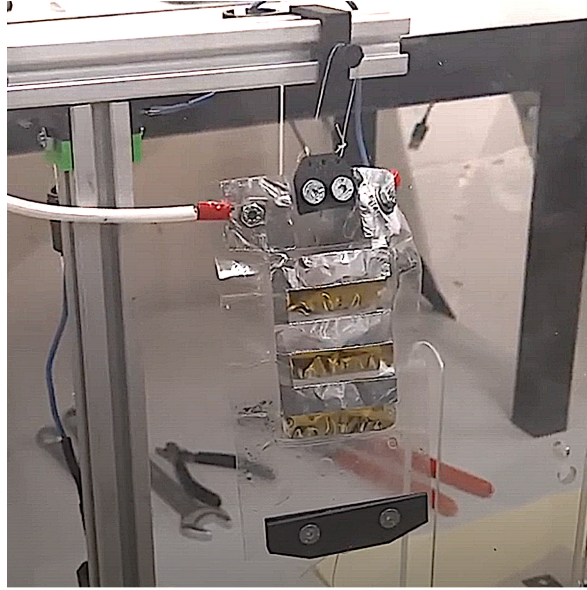


Figure 27: *Actuation test of Peano-HASEL actuator. The actuator was not actuated even under voltage up to 12kV.*

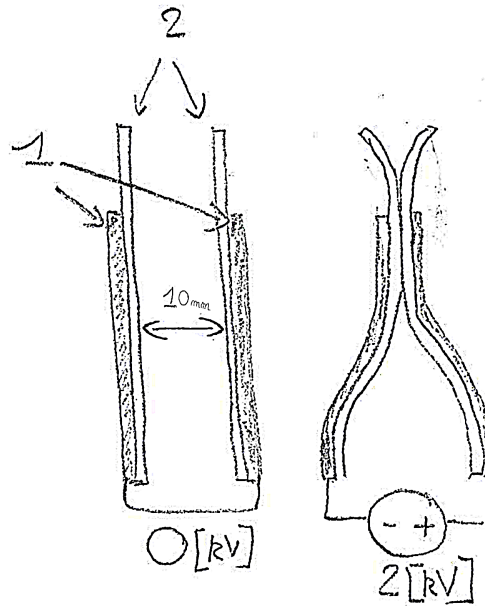


Figure 28: *Schematic of the aluminium electrodes' test. The electrodes (1) are disposed on the outside of each plastic sheet (2). The sheets are separated by a distance of 10mm. On the left, no voltage is applied. On the right, around 2kV, the electro-static force make the electrodes attract each other until they touches.*

For the second hypothesis, we simply recreated Peano-HASELs the same way but with a reduced volume inside the pouches ($1ml$ instead of $1.4ml$). However, these actuators did not actuate either, and electrical arcs occurred in the sealed port around the $5kV$. Since at this stage the pouches were not damaged and in order to see if the actuator would be able to actuated under higher voltages, we decided to fold the electrodes in a way that they would not be as close to the ports. However, the actuator produced an arc around in the top right corner of the top pouch around $8kV$, creating an irreversible damage.

To further investigate the hypothesis of an excessive viscosity of the medium,, we tested a single pouch of width $w = 4mm$ and a length $L_p = 6.3mm$ (heat-sealed by removing the inside L-shaped profiles on the die). The setup is schematized in Figure 29. To avoid creating arcs, the electrodes were placed at the center of the pouch, which was supposed to create a pull-in transition, contrary to the zipping actuation. Before filling, we applied a weight of $\sim 85g$ ($0.83N$) on the surface of the electrodes. We then filled the pouch until the oil started to lift the weight. This method was used to evaluate the electro-static force. To estimate this force before the test, we measured the capacitance of the pouch with a RC-meter. The obtained values averaged at $13pF$. The equation of the electro-static force is given by:

$$F = \frac{QE}{2} = \frac{CV^2}{d} \quad (3.2)$$

where Q is the electric charge, E the electric field, C the capacitance, V is the voltage applied and d is the distance between the electrodes. Using this relation, we estimated that the liquid in the pouch would create a distance d of around $1mm$. When calculated for $V = 7kV$, we obtained an estimated force around $0.6N$. When tested, the pouch was actuated at $7kV$, proving that the electro-static force exceeded at least $0.83N$. However, the electrodes did not go into contact homogeneously on their all area they bent.

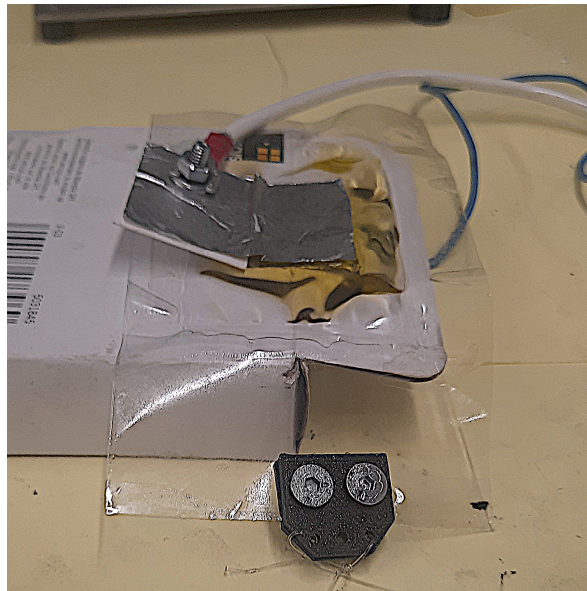


Figure 29: *Test with one pouch and central electrodes. The size of the pouch is $L_p = 63\text{mm}$ and $w = 40\text{mm}$. The volume is around the 2ml. The contact between the electrode and the cable is reinforced with cardboard. It is placed on a box to place it as flat as possible. The bottom electrodes passes through a hole. The actuation is not clearly visible in the pictured taken, but was observed at the naked eye.*

4 Demonstrator

A part of this work was to design a demonstrator that could be able to illustrate some interesting properties of the HASEL actuator. Since the HASELs are considered as a soft actuator, we decided to demonstrate the phenomenon of co-contraction.

Co-contraction refers to the simultaneous activation of two antagonistic muscles or actuators that pull in opposite directions. Rather than producing movement, this opposing action increases the stiffness of the joint or structure, enhancing its stability, resistance to disturbances, and precision of control. In biological systems, co-contraction is a common strategy for stabilizing joints during demanding or unpredictable tasks, such as maintaining balance or keeping a tool steady. In soft robotics, this phenomenon can be replicated using Peano-HASEL actuators. By placing them in an antagonistic arrangement, their ability to contract on demand allows the modulation of stiffness and damping in a manner analogous to biological muscles, enabling safer, smoother, and more adaptable interaction with the environment.

The principle for our demonstrator relies on linking the antagonistic HASELs to the same pulley. The pulley is linked to an arm that can show its rotation and that can be handled to verify the change in stiffness. The pulley and the muscles are all attached to a mount made of two aluminium profiles forming a T shape: the pulley on the vertical profile and the actuators on the horizontal one, as sketched in Figure 30.

To concretely achieve the designed prototype (Figure 30A), we would need an alimentation with two outputs. To simplify, the power supply used in the tests mentioned in Section 3.4 possesses only one, limiting the use to a single actuator. The issue could be overcome by using a spring that would mimic the effect of the missing muscle, as illustrated on Figure 30B.

The mount (disclosed on Figure 32) was built using two aluminum profiles. Since exact dimensions were not critical, we reused pre-cut pieces available in the workshop: each profile is $30mm$ wide, with lengths of $400mm$ for the vertical element and $150mm$ for the horizontal one. The base was made from a metal plate, machined with four central holes arranged in a square, along with three small corner holes and one larger corner hole. The larger hole was used to attach the ground cable to the base, preventing static electricity buildup. To connect the profiles to the base, we designed and 3D-printed custom joint pieces. Additional 3D-printed pads were added to slightly elevate the base, preventing direct contact with the table surface. On the horizontal profiles, 3D-printed pieces serve as attachments for the actuator and the spring.

The pulley assembly consisted of a $13mm$ external diameter ball bearing mounted on a linking piece fixed to the base. On top of the bearing, we placed a 3D-printed pulley featuring two grooves to guide the actuator and spring threads. This pulley also integrated a $150cm$ arm. We further printed guiding pieces to route the power supply cables. For operator safety,

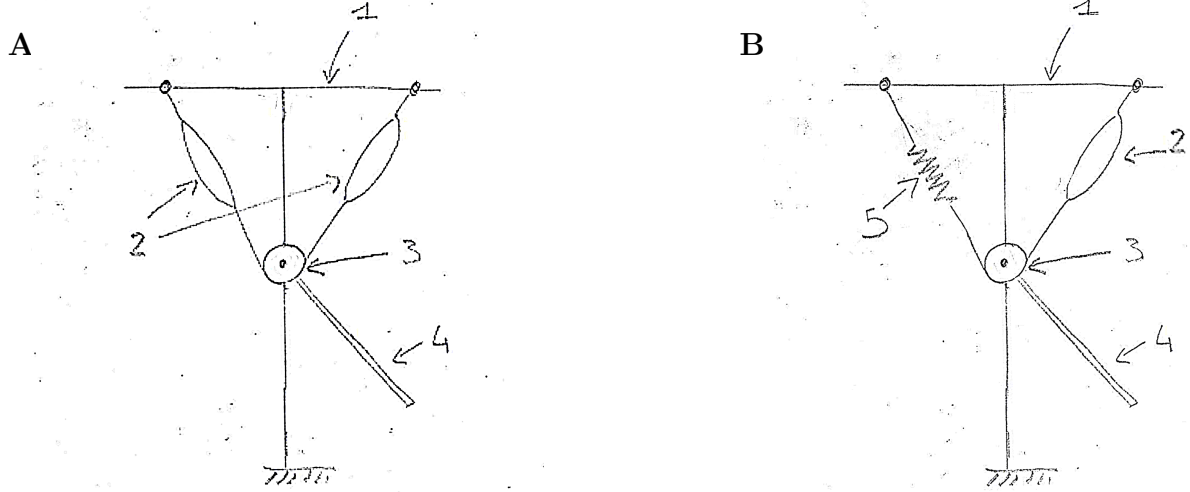


Figure 30: *Schematics of the demonstrator. In A, the initial demonstrator with two actuators. In B, the alternative demonstrator with one actuator and a spring. Legend: (1) aluminum profiles. (2) Peano-HASELs actuators. (3) Pulley. (4) Arm. (5) Spring.*

a plexiglass enclosure was built, endowed with small openings at the bottom for cables to pass and a larger opening to allow manual manipulation of the arm. The demonstrator and the casing are pictured in Figure 32 and .

To determine the maximum possible angle the pulley can rotate, we need to know the maximum displacement of the actuator. Since we were not able to actuate our Peano-HASEL, we can not get its force-strain curve. We then based this calculation according to the one established by Kellaris et al. [6] for 10kV, shown in Figure 33. In this study, they mentioned that the maximum actuation strain of 10% happens under a 0.2N load. Since the actuator is made of three pouches of length 20mm, this means that the maximum stroke is around 6mm. The inside radius of the pulley's groove r is 10mm. Therefore, we can calculate the maximum angle α using this equation:

$$\alpha \cdot r = x \equiv \alpha = \frac{x}{r} = \frac{6}{10} = 0.6rad \approx 34^\circ \quad (4.1)$$

We also can calculate the required stiffness of the spring K . By posing that the spring is at rest when not actuated, we know that the maximum stroke is 6mm. At this state, the spring should match or be lower than the acceptable load of the actuator which is 0.2N. To find the maximum stiffness of the spring for full actuation, we use this equation:

$$F = Kx \equiv K = \frac{F}{x} = \frac{0.2}{0.006} \approx 33.3N/m \quad (4.2)$$

Upon the achievement of a functional actuator, our demonstrator should constitute a valuable tool to illustrate the functioning of an artificial muscle. If a second power supply



Figure 31: *Demonstrator's mount. On the left, the backside shows the guiding pieces for the cables. The bigger screw with the washer are on the left bottom corner. On the right, the frontside shows the pulley with its arm lifted. Attachments pieces are on the horizontal profile at the top. The brackets and the 3D-printed base that join the profiles and the plate are in black and green. Screws with nuts clamp the mount together.*

can be obtained, the co-contraction elicited by the cooperation of 2 HASEL actuators could be nicely demonstrated.

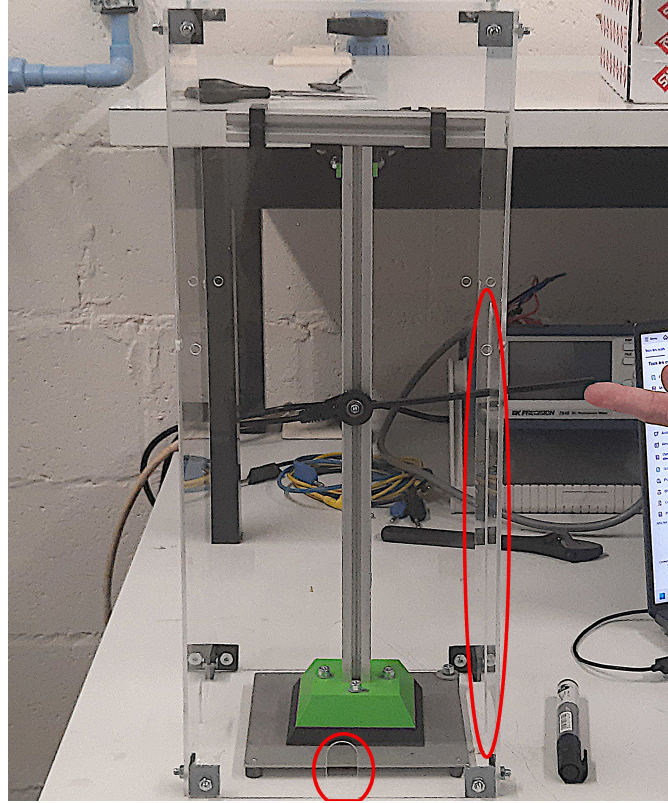


Figure 32: Demonstrator's mount inside the plexiglass casing. The opening for the cables is circled in red at the bottom and the one for the arm is on the right.

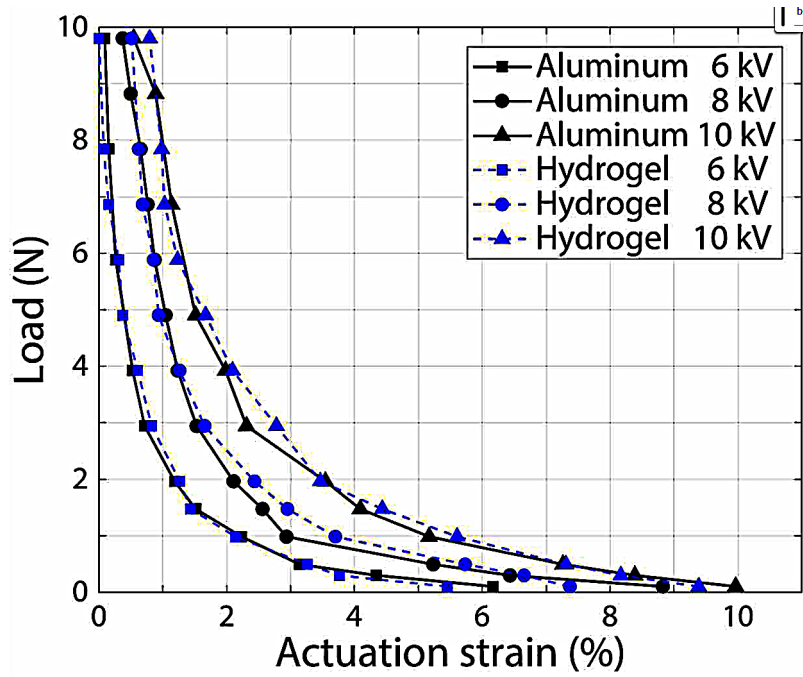


Figure 33: Experimental force-strain curve [6].

5 Possible improvements

5.1 Materials

As described in Section 3.4, we could not actuate our Peano-HASELs with the right amount of liquid inside the pouches. The reason of this lack of success can originate from the viscosity of the medium used to fill the pouch. Indeed, for their working actuator Kellaris et al. [6], who largely inspired our work, used the vegetable oil Envirottemp FR3 produced by Cargill whereas we chose to work with olive oil. The respective kinematic viscosity of Envirottemp FR3 and olive oil are of $32 - 34 \text{ mm}^2/\text{s}$ [22] and $43 \text{ mm}^2/\text{s}$ ⁵. In addition, the olive oil we used was purchased in a supermarket and we cannot guarantee that its properties are exactly the same as the one reported in [21]. The simplest solution would be to purchase the same oil. However, supplied by a limited number of distributors and sold only in bulk quantity (minimal amount = 185kg). Some alternatives such as mineral oils or silicone oils are listed in the literature [24]. Whatever the substitute for the liquid, it is essential that it matches the electrical and mechanical properties of the reference oil. These values are listed in Table 4.

Property	Typical Value / Limit
Breakdown voltage (2 mm gap)	$\geq 35 \text{ kV}$
Kinematic viscosity μ (40°C)	$32-34 \text{ mm}^2/\text{s}$
Relative density (15°C)	≤ 0.96
Relative permittivity ϵ_r (25°C)	~ 3.2

Table 4: *Typical electrical and physical properties of Envirottemp FR3 fluid, based on Soltex technical datasheet [25] and EPRI transformer fluids report [22].*

In general, transformer oils can be a good fit due to the dielectric properties as well as their low viscosity. As an example of this, we can cite the DIALA S4 ZX-I from Shell (See the datasheet: https://www.lubexcel.com/ressources/data/prod/document/17-8775-8775_DIALA%20S4%20ZX-I%20_%20FT.pdf). Its dielectric properties are less performant than FR3 [26] but it possesses a very low viscosity ($9.6 \text{ mm}^2/\text{s}$). This type of oil can be sold by smaller quantities (20L).

Another aspect that has been overlooked is the thickness of the plastic films. Indeed, as explained in Section 3.1, we used thicker plastic sheets. These films were selected based on their comparable electric properties and their availability. However, the electric field E in the zipped region depends on the thickness of the film t :

$$E = \frac{V}{2t} \quad (5.1)$$

We can therefore understand that a higher thickness reduces the electrostatic force under a similar voltage.

⁵https://www.engineeringtoolbox.com/kinematic-viscosity-d_397.html

The main solution to these issues would be to select other materials that better match the electrical and mechanical properties if the original is too difficult to get. Tests with these new materials could better match the conditions of those of the first studies. However, due to the lack of time, we were not able to carry out those tests. This could be a line of inquiry worth exploring in future research here at UCLouvain. A careful preselection of different surrogates for the liquid dielectric and for the envelope of the HASEL pouch and their testing in parallel would probably constitute a good strategy to increase the chance of success.

5.2 Process

While the manufacturing method developed in this work produces clean HASELs, we do not have the control over all the parameters that influence their quality. The pressure for the pouch formation by heat sealing and filling port sealing are not quantified, the duration of sealing is estimated by the operator, etc.

In parallel to the method presented above, we began to think about different solutions to implement a more controllable process. Although it did not permit to work ourselves on these aspects in the framework of this thesis, we hope that the following suggestions will inspire future works on the subject.

5.2.1 Press

The press described in the manufacturing method possesses some drawbacks that can affect the bonding of the plastic films. For example, its plates do not align in parallel while applying the pressure. This means that the pressure is not perfectly spread around the plates. The backside starts pressing before the frontside. This could result in inhomogeneous bond quality.

Other presses commercially available work with parallel plates, as shown in the example provided on Figure 34. It could be a better performing alternative to the press we used in the present work if we equip it with a similar device than the one we clamped. However, these presses present the rest of the same limitations as the current one. For example, there is no direct control of the pressure. The pressure is often set indirectly by a screw that actually sets the distance between the plates when actuated. According to the manufacturer when asked, the press can apply up to $150kg$, however there is no indicator on the press. A solution might be to use a separate pressure sensor so that we could manually set the exact pressure. The other problem about these parallel presses is the thickness of the material that can be introduced between the plates. The manufacturer recommends not exceeding the $3cm$, what our current tools do. Increasing this distance would mean cutting the rod to extend it.

⁶https://www.vevor.fr/presses-a-imprimer-c_11148/8-en-1-presse-a-chaud-t-shirts-casquettes-1250w-commande-numerique-a-led-220v-p_010412399683?utm_source=favorite&utm_campaign=010412399683&utm_medium=96787719&utm_co



Figure 34: *Commercially available press. The upper plate can rotate to let the operator place the products on the bottom plate. [Link](#)⁶*

The best solution to ensure the control of all the parameters is to create a press ourselves from scratch. At the beginning, we laid down the specifications of the press. These are listed in a document in Appendix B. Afterwards, we started to think about solutions. Out of these, two of them were retained, which would work according to the same principle.

The first one functions with the same rotating system than the press available on the market. However instead of a handle, the air-pressured cylinder is placed on the arm of the upper part and attaches its moving part to the plate. The force is therefore managed by the cylinder that we can control by pressure. The other implementation consists in fixing it on a frame that is placed over the down plate. To ensure the handling of the film safely, simple plexiglass plates can be mounted on the frame to avoid touching the heated plate. Both implementations are schematized in Figure 35 and 36.

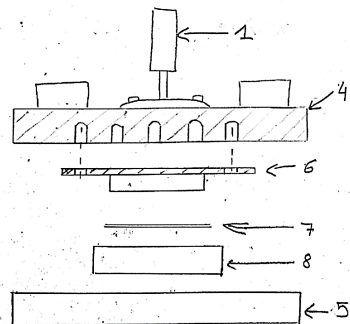
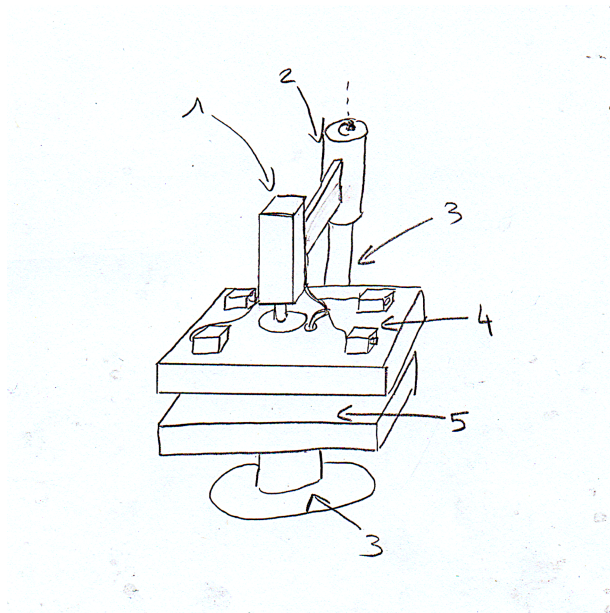


Figure 35: Home-made rotating press with disassembled view. Legend: (1) Air-pressured cylinder. (2) Turning arm. (3) Base with axle cylinder. (4) Upper plate. (5) Downer plate. (6) Dye. (7) BOPP films. (8) Solid gel.

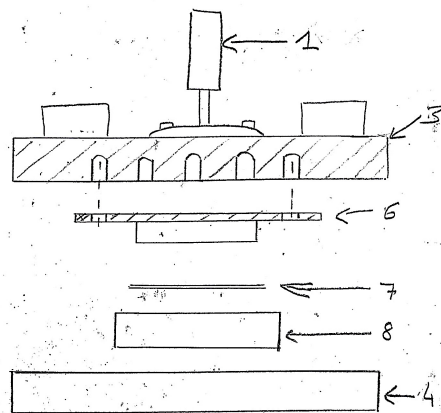
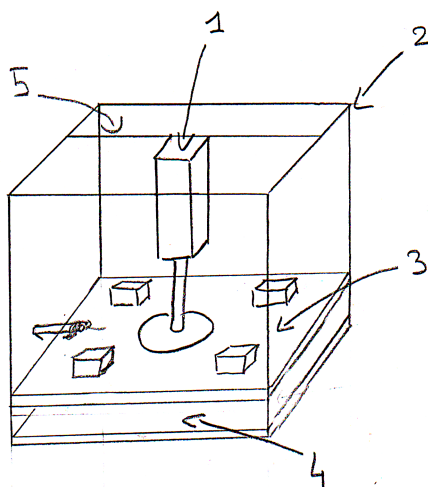


Figure 36: Home-made framed press with disassembled view. Legend: (1) Air-pressured cylinder. (2) Frame made of profiles. (3) Upper plate. (4) Downer plate. (5) Profile linking the cylinder to the frame (6) Dye. (7) BOPP films. (8) Solid gel.

In both implementations, the upper plate possesses a heating system on its top side. This system is made of heating resistances spread evenly on the surface so that the heat spreads homogeneously on the plate, making the temperature of the die evenly distributed.

A thermocouple is placed through a hole pierced on the plate to sense the temperature of its down side. A switch is also placed outside of the plate that is triggered when pressing in order to measure the pressing time. The detailed upper plate is depicted in Figure 37.

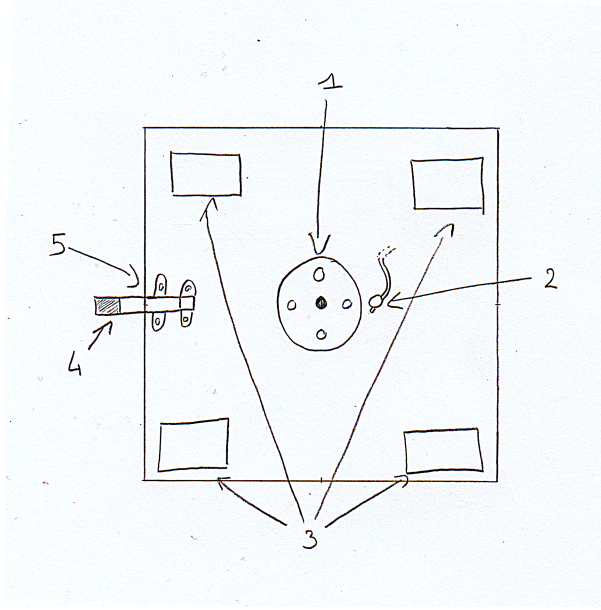


Figure 37: *Top side of the upper plate of the home-made presses. Legend: (1) Fixation with the air-pressured cylinder. (2) Thermocouple fixed in place with a screw. (3) Heating resistances. (4) Detection switch. (5) Fixed bar linking the switch to the plate.*

To complete the design, we can create an electronics that automate the system. By using a simple Arduino controller, we can control the temperature, the pressure of the cylinder and the duration of pressing. All the actuators and sensors have to be linked to the controller. With simple buttons and an LCD screen, we can set the different parameters. To ensure that the operator does not put his hands on the heating parts, we use two press buttons that start the process only when both are pressed. They are placed at a sufficient distance to force the operator to use both hands to operate the device. In this new device, the only requirement is to set the parameters, place the BOPP films and press the buttons. Other measures are included, such as an emergency stop button and indicators like LEDs and buzzers, for example to indicate an excessive temperature or any other type of dysfunction.

5.2.2 Die and punch

The die itself was thought separately from the press. Once again, two solutions were retained. The first is similar to the one used in our manufacturing method (see Section 3.1), but with a set of pieces of different sizes in order to create different geometries. They are placed on a multi-perforated plate. This idea is interesting for the reusability because a set of enough pieces can generate a lot of different dimensions. However, a problem could be the junctions between the borders of the pouch. With no link that associates the pieces together, it might create discontinuities between in the borders of the pouch. We need to

join them tightly together. For example, we could use corner pieces between perpendicular parts. However, the die used in this work does not possess such links, and no problem caused by the discontinuities was observed.

The other solution would consist in creating the die from one block and to cut the geometry in it. Alternatively, the die can be mounted on the same kind of plate as the other option. The different holes are for the different die sizes. In this case, the junctions are not an issue anymore, but a new piece needs to be recreated for each geometry change, adding costs and time.

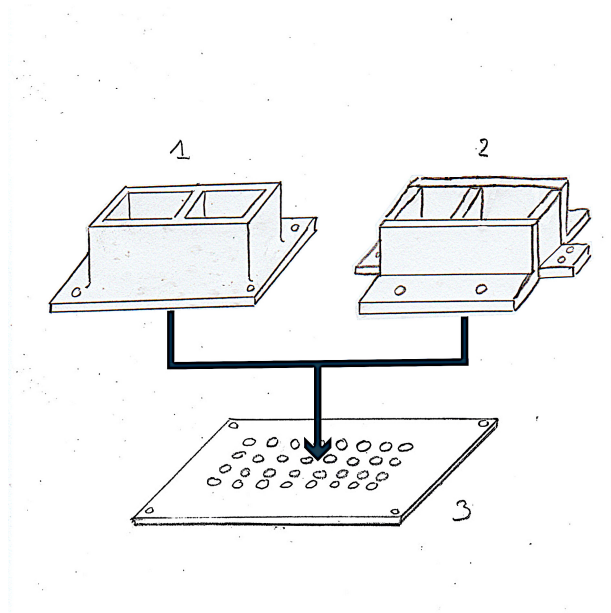


Figure 38: *Two die solutions. Legend: (1) Cut block. (2) L-shaped profiles set. (3) Mounting plate.*

The press can also be used for the sealing of the filling port. The idea is to create a small punch that seals the port. This punch can be mounted on the same pierced plate as the die, on specially dedicated position.

For the heat-sealing, a perfect placement of the films with respect to the die is not required. We can afford a small displacement and rotation because we can cut the BOPP film around the pouches afterward. However, it is not the case with the punch since the port is quite small (2 mm). The hole in the clamp that allows the sealing is quite small too, which means that a precise alignment between the punch and the clamp is mandatory. For this reason, a pierced plate has to be set on the bottom. The holes would need to respect the pattern made by the clamp's head screws on its bottom. This allows the clamp to be set in a fixed position relative to the bottom plate. The alignment between the plates needs to be calibrated on the first assembling to minimize as much as possible placement errors.

In addition to the above suggested improvements, other avenues remain to be explored for the constitution of an efficient HASEL manufacturing method. Examples like a better attachment system between the electrodes and the supply cables, a CNC heat-sealing machine for other geometries of pouches, etc., would be nice additions to the process.

6 Conclusion

In this work, we took an interest in HASEL actuators. We explained their working principle and their production process in order to develop our own manufacturing method here at UCLouvain. We described this method with its different stages in detail. We also looked at the design of a demonstrator showing an interesting principle enabled by soft actuators like HASELs, the co-contraction.

Unfortunately, we were not able to achieve the initial goals. We could not produce a Peano-HASEL that could reproduce the performances of the ones presented in the literature for different reasons. We were able to actuate a simpler version, proving that the materials possess the electrical properties essential for HASEL actuators. However, the mechanical properties were overlooked for the benefit of availability and might be the cause of the malfunctioning. Some alternative materials are proposed as solutions that could be explored in future works.

This work taught me the core method of experimental work in research. From the design to the tests, I was able to use key concepts that helped me for the realization of this work. The writing time was also important for me since it forced me to a questioning, not only on the technical options that have been chosen but also on the methodological choices. If the approach followed here was very similar to the successful one described in the literature, modifying simultaneously different parameters (plastic for the pouch constitution, dielectric liquid) is more difficult to manage than a step by step approach (working on HASEL preparation with a liquid dielectric that is reported to work, if OK, changing the liquid dielectric, etc). On the other hand, the different failures I had to face during this work forced me to explore possible solutions and alternative tests. And ultimately, it stimulated my creativity, possibly better than a straightforward and (too) well-working experimental scheme.

I also learned, in the different formations I followed, the importance of safety pertaining to electricity, especially in high voltage conditions. I found it profitable and tried to take security principles into account in the design of equipment I proposed.

Finally, achieving this master thesis work in a stimulating environment brought me one of the most sought-after value for an engineer: experience. And even if I can not consider myself as experienced, I find this to be a good starting point.

References

- [1] Allan Chapman. *England's Leonardo: Robert Hooke and the seventeenth-century scientific revolution*. CRC Press, 2004.
- [2] Ron Pelrine et al. “High-speed electrically actuated elastomers with strain greater than 100%”. In: *Science* 287.5454 (2000), pp. 836–839.
- [3] Justin Leclair, Marc Doumit, and Greg McAllister. “Analytical stiffness modeling and experimental validation for a pneumatic artificial muscle”. In: *ASME international mechanical engineering congress and exposition*. Vol. 46583. American Society of Mechanical Engineers. 2014, V009T12A089.
- [4] Mohsen Shahinpoor et al. “Ionic polymer-metal composites (IPMCs) as biomimetic sensors, actuators and artificial muscles-a review”. In: *Smart materials and structures* 7.6 (1998), R15.
- [5] Eric Acome et al. “Hydraulically amplified self-healing electrostatic actuators with muscle-like performance”. In: *Science* 359.6371 (2018), pp. 61–65.
- [6] Nicholas Kellaris et al. “Peano-HASEL actuators: Muscle-mimetic, electrohydraulic transducers that linearly contract on activation”. In: *Science Robotics* 3.14 (2018), eaar3276.
- [7] Gabor Kovacs et al. “Stacked dielectric elastomer actuator for tensile force transmission”. In: *Sensors and actuators A: Physical* 155.2 (2009), pp. 299–307.
- [8] Xiaofan Niu et al. “Synthesizing a new dielectric elastomer exhibiting large actuation strain and suppressed electromechanical instability without prestretching”. In: *Journal of Polymer Science Part B: Polymer Physics* 51.3 (2013), pp. 197–206.
- [9] Nicholas Kellaris et al. “An analytical model for the design of Peano-HASEL actuators with drastically improved performance”. In: *Extreme Mechanics Letters* 29 (2019), p. 100449.
- [10] Philipp Rothmund, Nicholas Kellaris, and Christoph Keplinger. “How inhomogeneous zipping increases the force output of Peano-HASEL actuators”. In: *Extreme Mechanics Letters* 31 (2019), p. 100542.
- [11] Philipp Rothmund, Sophie Kirkman, and Christoph Keplinger. “Dynamics of electrohydraulic soft actuators”. In: *Proceedings of the National Academy of Sciences* 117.28 (2020), pp. 16207–16213.
- [12] Alexandria Washington et al. “A physics-based modeling of a hydraulically amplified electrostatic actuator”. In: *Journal of Physics Communications* 6.8 (2022), p. 085007.
- [13] Shane K Mitchell et al. “An easy-to-implement toolkit to create versatile and high-performance HASEL actuators for untethered soft robots”. In: *Advanced Science* 6.14 (2019), p. 1900178.
- [14] Michel R. Vogt et al. “High-Frequency Capacitive Sensing for Electrohydraulic Soft Actuators”. In: *2024 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 2024, pp. 8299–8306. DOI: 10.1109/IROS58592.2024.10802777.

- [15] Zachary Yoder et al. “Design of a high-speed prosthetic finger driven by Peano-HASEL actuators”. In: *Frontiers in Robotics and AI* 7 (2020), p. 586216.
- [16] Zhaozhen Liu. “Design of a bio-inspired Peano-HASEL artificial muscle for lower limb prosthetics using finite element analysis”. PhD thesis. The University of Manchester (United Kingdom), 2024.
- [17] Fabian Sadi and Jan Holthausen. “HASEL-Actuated Pneumatic Valve for Image Guided Robotic Systems”. In: *ACTUATOR 2024; International Conference and Exhibition on New Actuator Systems and Applications*. 2024, pp. 199–202.
- [18] Isabel Hess and Patrick Musgrave. “A continuum soft robotic trout with embedded HASEL actuators: Design, fabrication, and swimming kinematics”. In: *Smart materials and structures* 33.10 (2024), p. 105043.
- [19] Nicholas Kellaris et al. “Spider-inspired electrohydraulic actuators for fast, soft-actuated joints”. In: *Advanced Science* 8.14 (2021), p. 2100916.
- [20] Thomas Pomponio. *HASEL’s manufacturing : test report n°2-6*. Internal report, UCLouvain-iMMC. Available at https://uclouvain-my.sharepoint.com/:f:/g/personal/raphael_veithen_student_uclouvain_be/EoPsaQsmNINCqx8vQ5c_pbsB9GIeLEx4m-snDcFZ4pmu6A?e=CSUQiG. 2024.
- [21] Abderrahim Reffas, Hocine Moulai, and Abderrahmane Beroual. “Comparison of dielectric properties of olive oil, mineral oil, and other natural and synthetic ester liquids under AC and lightning impulse stresses”. In: *IEEE Transactions on Dielectrics and Electrical Insulation* 25.5 (2018), pp. 1822–1830.
- [22] Cargill, Incorporated. *FR3 — The Original and Most Proven Natural Ester*. <https://www.cargill.com/bioindustrial/doc/1432243645220/fr3-most-proven-natural-ester.pdf>. Accessed: 2025-08-15. 2025.
- [23] FUG Elektronik GmbH. *HCN 350-35000 High Voltage Power Supply*. Accessed: 2025-08-10. Rosenheim, Germany, 2025. URL: <https://www.fug-elektronik.de/en/products/hcn-series>.
- [24] Philipp Rothmund et al. “HASEL artificial muscles for a new generation of lifelike robots—recent progress and future opportunities”. In: *Advanced materials* 33.19 (2021), p. 2003375.
- [25] Soltex, Inc. *Envirotemp FR3 Fluid Technical Data Sheet*. <https://soltexinc.com/wp-content/uploads/2024/01/FR3-Data-Sheet.pdf>. Accessed: 2025-08-12. 2024.
- [26] C Williamson et al. “Breakdown characteristics of natural and synthetic ester liquids when containing varying levels of moisture”. In: *2019 IEEE Pulsed Power & Plasma Science (PPPS)*. IEEE. 2019, pp. 1–6.
- [27] Xiying Dai et al. “The effect of annealing on the structure and electric performance of polypropylene films”. In: *International Journal of Polymer Science* 2022.1 (2022), p. 5970484.
- [28] Xingrui Wang et al. “High-strain peano-HASEL actuators”. In: *Advanced Functional Materials* 30.7 (2020), p. 1908821.

- [29] Travis Hainsworth et al. “Simulating electrohydraulic soft actuator assemblies via reduced order modeling”. In: *2022 IEEE 5th International Conference on Soft Robotics (RoboSoft)*. IEEE. 2022, pp. 21–28.
- [30] Yu Yeh et al. “Modeling and position control of the HASEL actuator via port-Hamiltonian approach”. In: *IEEE Robotics and Automation Letters* 7.3 (2022), pp. 7100–7107.
- [31] Clemens C Christoph et al. “Self-Sensing Feedback Control of an Electrohydraulic Robotic Shoulder”. In: *2024 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE. 2024, pp. 4679–4685.
- [32] Onat Halis Totuk and Selçuk Mistikoğlu. “Modeling and Optimization of a Peano-HASEL Actuator Peristaltic Pump”. In: (2023).
- [33] Christoph Keplinger et al. “Stretchable, transparent, ionic conductors”. In: *Science* 341.6149 (2013), pp. 984–987.
- [34] Qiaoxi Li et al. “Bottlebrush elastomers: A new platform for freestanding electroactuation”. In: *Advanced Materials* 29.2 (2017).

A Materials and tools

A.1 Lists of materials and tools

Material	Breakdown voltage	Dielectric constant ϵ_r	Additional properties	References
Biaxially oriented polypropylene (BOPP) sheets	$\sim 650kV/mm$	~ 2.2 [27]	Thickness : $40\mu m$	Link
Polypropylene (PP) sheets	$\sim 500kV/mm$	2.3	Thickness : $30\mu m$	Link
Olive oil	$> 80kV$ [21]	3.1	Viscosity: $43mm^2/s$	Link
Graphite spray paint	Conductive	$\sim 10 - 15$	/	Link
Graphite liquid paint	Conductive	$\sim 10 - 15$	/	Link
Aluminium foil	Conductive	$\rightarrow \infty$	/	Link
Glue	/	/	/	Link

Tool	Description	Dimensions	References
Heat press	Press available in the Makilab room	Plates: $400 \times 400mm^2$	Not found
Die	Die clamped on the upper plate of the press with the dimensions of the desired HASEL	Given in Appendix A.2	Made by Pomponio [20]
Syringe + needle	Syringe with flat tip needle to fill the oil in the pouches	Syringe's volume: $5ml$ Needle's diameter: $1mm$	Syringe and flat tip needle
Clamp	Clamp to avoid leakage when filling the pouch	Base plate: $103 \times 124mm^2$ L-shaped profile length: $87mm$ L-shaped profile width: $20mm$ Hole: $10 \times 5mm^2$	Made by Pomponio [20]
Soldering iron + mount	Soldering iron on a mount to seal the filling port of the pouch	Plate: $240 \times 160mm^2$ Vertical profile: $285mm$ Horizontal profile: $185mm$	Link

A.2 Die assembly drawing



B Specification of the heat-sealing process

Raphaël Veithen		Specifications Press	date: 15/01/2025 version : 3
Context : During the process, we need to thermally bond the plastic films together twice: for the delimitations of the pouches and for the sealing of the port.			
date	origin	Functions	
		F1 : Heats the plastic films F2 : Apply force on the plastic films during a given time F3 : Display the operating parameters F4 : Easy access to the heating surface	
		Functional Requirement (FR) criteria and levels FR 1.1 Temperature max. around 220°C FR 1.2 Sensing of the temperature FR 2.1 Adjustable Force up to 20N for a given entry	
		Constraints C1 : Security C2 : Use of BOPP (2 layers from 10 to 40 µm) C3 : Pouches filled with liquid C4 : Clamping device	
		Constraint Requirement (CR) criteria and levels CR1.1 : Must stop heating when shut down CR 1.2 : Simple release of the pressure CR 1.3 : No possibility of pressing when manipulating on the surface CR3.1 : No spilling of the liquid CR 4.1 : Must accommodate the clamping device and its dimensions	

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